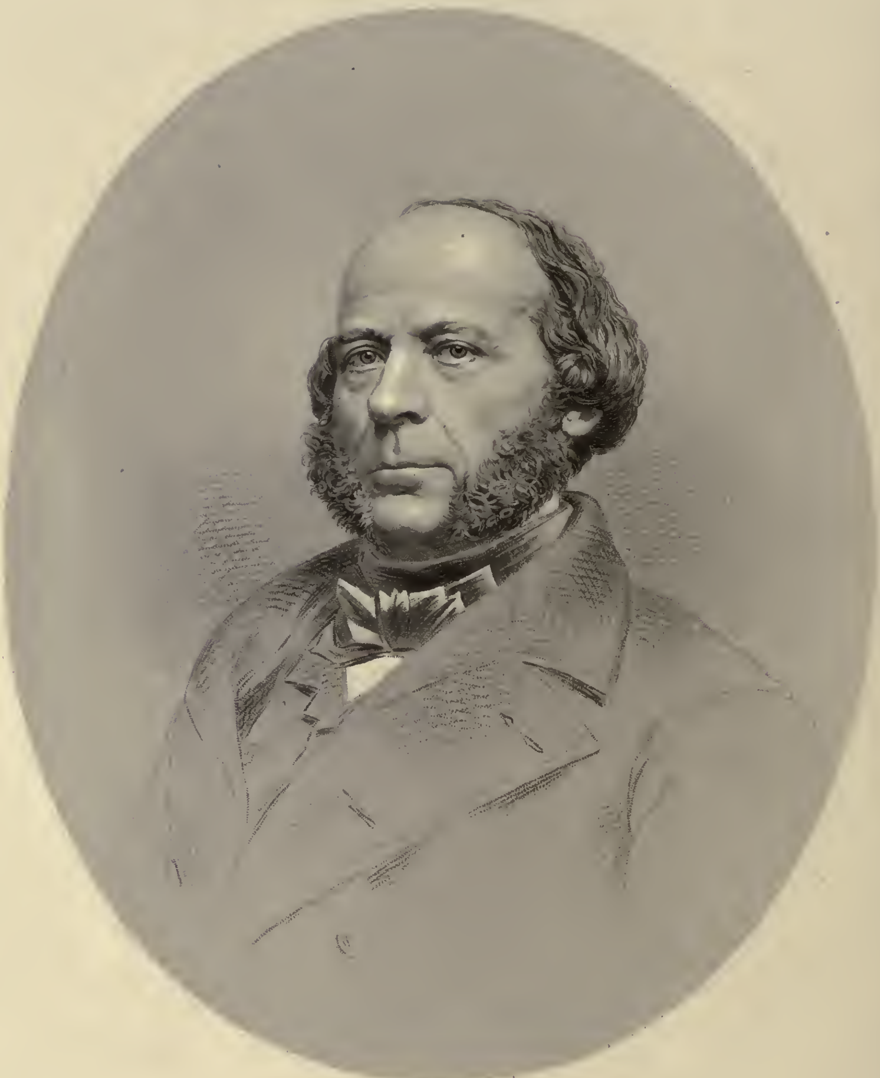

H. Adlard sc.

J. Ericsson

1865

CONTRIBUTIONS

TO THE

CENTENNIAL EXHIBITION.

BY

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1876.

INTRODUCTION.

The Commissioners of the Centennial Exhibition having omitted to invite me to exhibit the results of my labors connected with mechanics and physics, a gap in their record of material progress exceeding one-third of a century has been occasioned. I have therefore deemed it proper to publish a statement of my principal labors during the last third of the century, the achievements of which the promoters of the Centennial Exhibition have called upon the civilized world to recognize.

The nature of the labors referred to will be seen by the following account of philosophical instruments, engines, and other structures described and illustrated in this work —viz.: Apparatus for measuring the intensity of radiant heat at given distances. Instrument for measuring radiant heat emitted by concave spherical radiators within exhausted enclosures. Instrument showing the rate of cooling of a heated body within an exhausted cold enclosure. Instrument showing the rate of heating of a cold body within an exhausted heated enclosure. Instrument showing the rate of cooling of an incandescent sphere within an exhausted cold enclosure. Instrument for measuring the dynamic energy developed by radiant heat at different intensities. Actinometer, for measuring the temperature developed by solar radiation. Solar Calorimeter, for measuring the dynamic energy developed by solar radiation. Portable Solar Calorimeter. Parallactic mechanism, for measuring the intensity of radiation from different parts of the solar disc. Instrument for measuring the radiant power of the solar envelope. Instrument for measuring the actual intensity of the sun's rays. Solar Pyrometer, for measuring the temperature of the solar surface. Apparatus for measuring the radiant intensity of flames. Instrument for measuring radiation from incandescent planes at different angles. Instrument for measuring the radiation from different zones of incandescent spheres. Calorimeter, for measuring the dynamic energy developed by radiation from fused iron. Apparatus for measuring radiant heat by means of the thermo-electric pile. Barometric Actinometer, for measuring the temperature developed by solar radiation. Apparatus for ascertaining the conductivity of mercury. Concave spherical radiator, for testing the accuracy of the solar pyrometer. Instrument for measuring the reflective power of silver and other metals. Rapid-indication Actinometer, for measuring the temperature developed by solar radiation. Apparatus for ascertaining the diathermancy of flames. Dynamic Register, for measuring the relative power of currents of water and vapor. Distance-instrument, for measuring distances at sea. Steam fire-engine, designed 1841. Engines of the United States steamship *Princeton*, built at Philadelphia, 1842. Twelve-inch wrought-iron gun and carriage mounted on board the *Princeton*, 1843. Iron-clad cupola vessel, designed 1854. Surface-condenser for marine engines, patented 1849, built at New York. Experimental caloric engine, built at New York, 1851. Caloric engine for domestic purposes, extensively introduced in Europe and America. The iron-clad turret-vessel *Monitor*, built at New York, 1861. Turret-vessels of the *Passaic* class, built at New York and other places, 1862. The *Monitor* engine, applied to the entire iron-clad fleet of the United States during the war. The turret-vessel *Dictator*, built at New York, 1862. Carriages for heavy ordnance, designed 1861, built at numerous mechanical establishments in the United States. Pivot-carriages of the Spanish gunboats, built at New York, 1869. Rotary gun-carriage and transit platform, built at New York, 1873. Gun-carriage for coast defence, designed

1861, built at New York. Independent twin screw-engines of the thirty Spanish gunboats, built at New York, 1869. New system of naval attack, published 1870. Movable torpedo, built at New York, 1873. Air-compressor for the transmission of mechanical power, built at New York, 1873. Solar engine, actuated by the intervention of steam, built at New York, 1870. Solar engine, actuated by the intervention of atmospheric air, built at New York, 1872.

The foregoing, it should be observed, relates to work carried out by me on American soil. It has no reference to my labors in England from 1826 to 1839 connected with locomotion, steam navigation, motive engines, and other branches of mechanical and civil engineering. Nor does it contain a *complete* enumeration of the original mechanical inventions carried into practice by me in the United States—models of which would have been presented at the Centennial Exhibition had its promoters desired me to furnish a record of my share in the progress of mechanical engineering during the last thirty-seven years of the first century of the Republic.

As our space only admits of a brief reference to the mechanical inventions adverted to and not described or illustrated in this work, the following statement is appended, furnishing an outline of the principal structures omitted—viz.: Engines of the twin-screw steamship *Clarion*, built at

New York, 1840, consisting of two vertical cylinders, placed fore and aft in the vessel, actuating the cranks of the screw-shafts by inclined connecting-rods. Vertical single engines, actuating twin screws, built at New York, 1842, applied to several freight vessels on the Delaware and Raritan Canal. Single horizontal back-action engine, built 1843, applied to the United States screw-steamer *Legaré*. Inclined screw-engines, built 1843, applied to the steamship *Massachusetts*, the steam-cylinders of which were placed near the deck at the ship's sides, secured to diagonal timbers bolted to the planking. Centrifugal suction-fan, built 1843, operated by an independent engine, for producing draught in marine boilers by *drawing* the air through the furnaces and flues, and forcing the products of combustion into the chimney. Inclined engines, built 1844, applied to the bark *Edith*, the connecting-rods operating at right angles to each other and coupled to a common crank-pin on the propeller-shaft. Vertical engines, built 1844, applied to the twin-screw vessel *Midas* (the first screw-vessel to round the Cape of Good Hope), the power being transmitted to the propeller-shafts by vertical connecting-rods actuated by horizontal beams placed transversely under the deck. Vertical engines applied to numerous screw-vessels employed on the coast and inland waters of the United States, the cylinders being placed perpendicularly above the propeller-shaft, the connecting-rods acting downwards—a form of engine now employed in nearly all sea-going steamers, but at that time (about 1844) severely criticised by marine engineers. Engines of the twin-screw ship *Marmora*, built 1843, consisting of vertical steam-cylinders which, by means of beams working under the deck and vertical connecting-rods, imparted independent motion to the propeller-shafts. Horizontal high-pressure and condensing engine of the twin-screw steam-tug *R. B. Forbes*, built 1844, provided with detached condenser and air-pump actuated by an independent engine—a vessel which, during a series of years, rendered valuable service on the coast of Massachusetts by towing and relieving ships in distress. Compound stationary engine, actuated by very high pressure, in which the steam was expanded to the utmost extent, elaborately described by Dr. Lardner, who devoted much time to its theoretical consideration. Horizontal engine applied to the screw-vessel *Primero*, actuated by a mixture of steam and atmospheric air. Stationary engines actuated by highly superheated steam, the pistons of which were single-acting and thoroughly protected against the injurious effect of high temperature. Experimental street-car, propelled by a double caloric engine. Hoisting machines, actuated by cold compressed air, applied to several warehouses in New York. Small motors, actuated by cold compressed air, successfully applied to the sewing-machines of a large establishment in New York, intended to establish the fact that the present injurious physical exertion of sewing-women may economically be dispensed with.

Regarding the descriptions and illustrations of the caloric engines contained in this work, it is proper to observe that they relate only to some of the engines which I have built, at least ten different types, unlike those described, having been constructed and practically tested. Nor have I yet wholly suspended the labors connected with this safe and economical engine. The fact that it requires no water, and that its principle is not incompatible with the desirable employment of very high temperature—apart from the important circumstance that the use of atmospheric air admits of returning at each stroke, by the process of regeneration, the heat not converted into mechanical work during the previous movement of the working piston—justify continued endeavors to perfect this remarkable motor.

J. ERICSSON.

NEW YORK, September, 1876.

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CHAPTER I.

TRANSMISSION OF RADIANT HEAT.

No phenomenon connected with radiant heat supposed to have been thoroughly investigated is so imperfectly understood as its propagation through space. The recognized doctrine, which asserts that the temperature imparted to substances exposed to radiant heat diminishes in the inverse ratio of the square of the distance from the radiating body, is true only of a sphere of perfectly uniform temperature at the surface, if the distance be computed from the centre of the sphere. The temperature produced by radiation of spheres which are not uniformly heated at all points of their surface, and of other bodies of whatever form, we have no exact means of ascertaining, although the distance and the temperature of the radiating body be accurately known. Nor will it avail if, in addition to the assumed known uniform temperature and accurate knowledge of distance, we also know the dimensions of the radiator. In fine, notwithstanding our knowledge of these elements, an attempt to solve the problem will be fruitless, unless, as before stated, the radiation proceeds from a *sphere* of known diameter having a uniform temperature at its surface. According to Melloni's theory, which Professor Tyndall and some eminent French scientists assure us has been unanswerably demonstrated by the celebrated Italian, the matter is very simple, namely: the temperature at intermediate points between a heated body and a thermometer placed at a given distance, exposed to, and indicating the intensity of the radiant heat, may be determined by squaring the respective distances from the radiator. The products, it is asserted, will show the inverse ratio of the intensities, and consequently the temperature at the intermediate points, due to their distance from the radiating surface. The question being of great practical importance, I have examined the merits of Melloni's mode of establishing the infallibility of the propounded doctrine that the temperature imparted to bodies exposed to radiant heat are in the inverse ratio of the distances between the radiating surface and those bodies. The illustration shown on the first plate represents an apparatus constructed for the purpose of testing practically whether the experiment referred to by Professor Tyndall in "Heat as a Mode of Motion" really furnishes positive evidence of the correctness of Melloni's theory accepted by the distinguished experimentalist and by certain French authors. *a* represents the section of a rectangular vessel filled with hot water, the face *g k* being coated with lamp-black. A hollow cone *c*, lined with black paper on the inside, is secured to a thermo-electric pile *c'*, supported by an appropriate stand sliding in a groove formed at the top of, and parallel with, the centre line of the table on which the apparatus is placed. It will be evident that this arrangement prevents any change of direction of the axis of the cone which should be right angular to the heated vessel, during the movement of the pile. Melloni asserts that if the cone *c* be moved towards the heated vessel, say to the position *b*, the needle of the galvanometer connected with the pile will remain stationary. His accepted reasoning defining the law which governs the transmission of radiant heat being based solely on the correctness of this assumption, I have carried out an elaborate series of experiments to ascertain if the needle of the galvanometer remains absolutely stationary as shown by Prof. Tyndall during the exhibitions at the Royal Institution, mentioned in his work on heat before alluded to. The result establishes the fact most positively that the needle does not remain stationary as assumed, and that the deflection which takes place increases considerably as the pile is advanced towards the heated vessel. That such should be the case will be evident on due reflection. A careful inspection of the diagram shows that, because the points *g* and *d* of the radiating surface are not equidistant from *c′*, the radiant heat which they emit cannot affect the face of the pile alike. The extent of the irregularity may be approximately determined by squaring the distances *g c′* and *d c′*. Now, the proportion of these distances, as shown by the diagram, is 20 to 19, hence the radiant heat transmitted to the pile from the points *g* and *d* will vary in the inverse ratio of the products of the stated numbers, viz.: as 361 to 400. In view of this great difference of intensity of the heat transmitted to the face of the pile from different points of the radiating surface, the readers of "Heat as a Mode of Motion" may with propriety ask if the intensity indicated by the galvanometer connected with the thermo-electric pile during the reported experiments at the Royal Institution was that due to the radiant heat transmitted from *g* in the line of *g c′*, or that transmitted from *d* along *d c′*.

On theoretical grounds, therefore, Melloni's demonstration is quite unsatisfactory. Several imperfections of a practical nature, inseparable from the method adopted by the Italian physicist, demand consideration, all tending to aggravate the theoretical defects. The black paper which lines the inside of the hollow cone *b*, being very light and incapable of reflecting the radiant energy transmitted by the heat-rays *k r* and *m o*, will at once become heated, consequently the air contained within the cone will speedily have its temperature raised by convection. The heat thus received will radiate towards the face of the pile and thereby contribute to disturb the indication, already seriously affected by the difference of temperature consequent on the varying intensities of the radiant heat transmitted. The relative intensity imparted to the black paper within the cone *b*, and that transmitted to the pile *b′*, may be ascertained by squaring the length of the heat-rays *d o* and *d b′*. The diagram shows that these lengths are as 3 to 5; hence, by squaring and inversion, we find that the temperature imparted by the radiant heat at *o* will be greater than that at *b′* in the proportion of 25 to 9. Black paper being a powerful radiator, while air has very small specific heat, it will be perceived that the volume within the cone will rapidly become heated by convection, as already stated, and therefore the temperature of the face of the pile will be elevated to a degree far beyond that which it would attain by the direct radiation of the vessel *a*. Before presenting a demonstration proving the fallacy of Melloni's assertion, that the temperatures imparted to bodies exposed to radiant heat are "*inversely as the square of the distances between the radiating surface and those bodies*," I propose to give a detailed statement of the elaborate experiments before adverted to, instituted for the purpose of showing *practically* that the assertion which forms the basis of the accepted doctrine is false, and that the hollow cone *c* cannot be moved to the position *b* without increasing the deflection of the needle of the galvanometer connected with the thermo-pile. It has already been stated that, in order to insure perfect parallelism during the movement, the stand which supports the cone and pile slides in a groove parallel with the table on which the radiating vessel *a* is placed, and at right angles to the face of the latter. A scale *h*, divided into inches, is attached to the side of the table for the purpose of showing the distance between the pile and the vessel *a*, the face of the latter coinciding with the zero of the scale. The mode of conducting the experiment will be seen by the following brief explanation. The hollow cone *c* was placed so that the vertical line of the face *c′* corresponded with the last division of the scale, a screen being introduced for the purpose of shutting off the radiation from the blackened face of the vessel *a*. Maintaining the water in the latter at a constant temperature of 130° above that of the surrounding atmosphere, it was found on removing the screen that the needle of the galvanometer moved 4.7 deg. from zero during an interval of 30 seconds from the moment of exposing the face of the pile to the radiator. The vessel *a* was then removed and carried into an adjoining room to allow the pile to cool while thus thoroughly protected from the radiation of the heated vessel. In the meantime, a spirit-lamp was applied under the vessel in order to make good the heat lost during the preceding operation. Sufficient time having elapsed to allow the pile to cool, the vessel was again put in position on the table. The pile being then advanced to the 10th division, and the screen withdrawn, the needle moved 5.05 deg. from zero in the same time as before, viz., 30 seconds. The vessel was removed a third time into the adjoining room, the temperature raised to the fixed point, the pile allowed to cool, and the vessel placed in position as before. The pile being now advanced to the 5th division on the scale, and the screen raised, the needle moved 5.55 deg. from zero in the stipulated time of 30 seconds. It will be seen then that, so far from remaining stationary, the deflection of the needle of the galvanometer increases very considerably as the pile is advanced towards the radiator. The important fact remains to be noticed, that the needle continues to move rapidly after the expiration of 30 seconds from the time of exposing the pile to the radiator; a circumstance furnishing additional evidence of the unsatisfactory nature of

Melloni's method. In order to ascertain the exact extent of deflection of the needle, referred to, two distinct sets of experiments were made, the mean result of which is exhibited in the accompanying table. The position of the needle of the galvanometer, it will be seen, was recorded at the expiration of 30, 60, 90, and 120 seconds. A glance at the table proves the correctness of the objections previously raised against the detail of Melloni's arrangement, especially the disturbing influence of the rays projected against the interior of the cone from points *beyond* the area whose radiation is supposed alone to affect the pile. Having thus practically shown the fallacy of the assumption on which the Italian physicist bases his doctrine, I will now prove its unsoundness by the process of demonstration. For this purpose let us suppose that an incandescent cylindrical block *l* (see illustration Plate 1) composed of cast iron, 6 inches in diameter, be suspended at such a height that its axis passes through the centre of the bulb of a thermometer *m*, held by a bracket *m′* sliding in a groove

TIME.	DISTANCE AND DEFLECTION.		
	20 ins.	10 ins.	5 ins.
Seconds.	*Deg.*	*Deg.*	*Deg.*
30	4.70	5.05	5.55
60	4.30	5.00	6.75
90	4.50	5.70	8.25
120	4.75	6.25	10.15

similar to that formed at the opposite end of the table, before described. A scale *n*, divided into equal parts, is attached to the side of the table, the zero of this scale coinciding with the vertical line drawn from the face of the incandescent cylindrical block *l*; while the last division corresponds with the vertical line passing through the centre of the bulb of the thermometer *m*. Actual trial shows that, if the incandescent iron block be suspended while its temperature is 1,200°, the thermometer exposed to its radiant heat will indicate 22° above that of the surrounding atmosphere when the block has cooled so far that its differential temperature has become reduced to 1,000.° Now, agreeably to Melloni's doctrine, the thermometer *m*, if advanced to the 10th division of the scale, will indicate a differential temperature of $\frac{20^2 \times 22}{10^2} = 88°$; if advanced to the 5th division, $\frac{20^2 \times 22}{5^2} = 352°$; if further advanced to the 2d division, $\frac{20^2 \times 22}{2^2} = 2{,}200°$; and, lastly, if advanced to the 1st division on the scale, the thermometer will indicate an intensity of $\frac{20^2 \times 22}{1} = 8{,}800°$. The temperature of the incandescent radiating block being only 1,000°, we have thus demonstrated the utter fallacy of Melloni's theory, based on the result of imperfect experiments with hollow cones and thermopiles exposed to radiant heat. In view of the foregoing facts writers on radiant heat will do well to expunge this erroneous theory from their works. Practical men, not suspecting that the law of inverse squares is inapplicable to short distances, frequently commit serious mistakes in calculating the effect of placing incandescent bodies at certain distances from structures intended to be heated. But Melloni's device, although incapable of elucidating the principles which govern the transmission of radiant heat, possesses great value, as it proves the correctness of the apparently absurd proposition, that an increase of the surface of a radiator is capable of elevating the temperature of a substance exposed to radiant heat without increasing the temperature of the radiator. The importance of this fact cannot well be overstated. It contradicts certain modern speculations regarding radiant heat, and it affords a landmark which, though it does not point out what we seek, guards against taking the wrong course.

The defects of Melloni's method, and its inadequacy to solve the problem under consideration, suggest the question: Is it possible to determine, by calculation, what temperature substances will acquire by being placed at various distances from the surface of a heated body of known temperature and dimensions, the sides of which are straight and parallel? We are compelled to admit that the question thus presented cannot be satisfactorily answered, because each point of the radiating surface, in consequence of varying distance, transmits a different degree of intensity to the exposed substances. The difficulty of solution is increased on account of the stipulated form; the inferior intensity transmitted from the corners of the radiator rendering the question exceedingly complicated. A radiating plane surface of *circular* form somewhat simplifies the question; yet the difficulty remains of dealing with the inferior power of the heat-rays emanating from the circumference. To overcome this difficulty, I have constructed an instrument—shown by the illustrations on Plate 2, representing a longitudinal section and a perspective view (copied from a photograph)—in which the radiating surface is concave, forming part of a sphere whose centre is situated near the centre of the bulb of the thermometer employed to ascertain the intensity of the radiant heat. But this expedient of employing a concave spherical surface, every point of which is equidistant from the bulb of the thermometer, prevents any change of distance between the same and the radiator during experiments. I have accordingly introduced four distinct discs of varying spherical concavity, with a thermometer placed in the centre of curvature of each. These four concave discs form the sides of an open vessel filled with oil, heated by a gas flame. In order to facilitate comparison, a regular gradation of curvature has been adopted; the radius of the deepest concavity being 3 in., the next being 6 in., then 9 in., and, lastly, 12 in. for the least concavity. It will be evident that, owing to the difference of curvature, each disc will present a different extent of radiating surface, if a uniform size be employed, thereby rendering comparisons between the indicated intensities quite laborious. To obviate this, the diameters of the several discs have been so proportioned that the superficial measurement of each is precisely alike. The disc of the least curvature is 4 in. in diameter; the remaining three being respectively 3.982 in., 3.939 in., and 3.777 in. diameter. Much pains has been bestowed on the workmanship in order to obtain concavities of precisely equal areas. The objections raised in subsequent chapters against conducting experiments with the solar calorimeter and actinometer in the presence of the disturbing influence of the surrounding air, apply with equal force to the apparatus now being considered. Accordingly, the heater, with its four concave radiating discs and thermometers, are enclosed in an exhausted chamber, as will be seen by reference to the longitudinal section. Evidently, the heat reflected by the sides of this chamber towards the bulbs of the enclosed thermometers, will determine their zero precisely as in the instruments referred to; hence, it is indispensable that this chamber should be maintained at a constant temperature. This is effected by surrounding the same with an external open vessel filled with water kept at a temperature of 60 deg. Fahr. during experiments. The object of adopting 60 deg. is that of facilitating comparisons with solar intensity, the zero of my actinometer being also 60 deg. above Fahrenheit's zero. Let us now consider briefly the leading properties of the illustrated device. In the first place, the radiating concave surfaces, as well as the bulbs of the thermometers, are surrounded by the ether alone, and therefore cannot suffer any loss of heat by convection. Secondly, the intensity of the radiant heat received from all points of each concave surface will be precisely alike, because those points are equidistant from their respective thermometers. Thirdly, the concave surfaces presenting equal areas, being composed of the same materials of uniform thickness, and being heated by the same medium, will emit an equal amount of heat. Fourthly, as the several thermometers are exposed to the radiation of a surrounding vessel kept at 60 deg., they will acquire that temperature before fire is applied to the heater. In consequence of this, the increase of temperature, after heating, will furnish a true comparative measure of the energy of the radiant heat transmitted from the concave radiators to the bulbs of the thermometers.

The prevailing opinion that there is a concentration of heat in the focus of spherical radiators, will be urged as an objection against the described method of measuring radiant heat. A careful examination of this question will therefore be necessary. Fig. 4, Plate 3, represents a concave spherical radiator, *o* being the focus, *o c* the axis, and *a b* a section of the radiator. According to the accepted theory of radiation, rays of heat are projected in all directions from every point of the radiating surface. In order, therefore, to demonstrate that there is no concentration of heat in the focus, we have merely to draw radial lines representing the heat-rays from points *d* and *f* on the concave surface, as shown on the diagram. It will be seen on close examination that there is only a single ray *d c* emitted from the point *d*, which is directed towards the focus *c*; the ray *f c* being the only one directed from the point *f*. The other heat-rays from the points *d* and *f* diverge in all directions, and intersect every part of the field *k l*; thus dispersing the radiant heat nearly uniformly over a very large surface. The curve *c n*, struck from the point *f*, clearly shows that all the heat-rays below *c*, projected from *f*, are shorter than those directed to the *focus* from the same point, and therefore impart a *higher* temperature to the plane k l than that transmitted to the focus. It will be needless to enter on a detailed computation of the temperature at the intersections of the various rays with the plane k l, as a mere inspection of the diagram distinctly shows that the focus c receives no increase of heat on account of being the centre of the spherical radiator. Indeed, if we substitute a *plane* circular disc extending from a to b, a greater amount of heat will be transmitted to a thermometer placed at c, than with the spherical surface represented; the only important difference between a plane and a concave radiator being that a thermometer placed in the focus of the latter receives an equal degree of heat from each point of the concave surface.

Investigations conducted by means of the illustrated instrument prove that the intensity of heat transmitted by the radiation of concave spherical surfaces of equal temperature, presenting equal areas and having different curvature, is in the inverse ratio of the square of their radii, provided the substance which receives the radiant heat is placed in the focus of the radiating surface. This important fact in connection with the previous demonstrations showing the fallacy of the propounded doctrine that the intensity of radiation diminishes in the inverse ratio of the square of the distance, between plane radiators and the recipients of their radiant heat, enables us now to consider the proposition contained in our introductory remarks, viz., that the assumed law is true only of a sphere of perfectly uniform temperature at the surface, if the distance to the recipient of the radiating heat be computed from the *centre* of the heated sphere. Suppose that *s*, Fig. 5, represents a solid sphere of metal maintained at a constant temperature and suspended in the centre of an exhausted metallic spherical vessel *v*, the size of which is much greater than that of the solid sphere; *c a* and *c b* being radial lines drawn from the mutual centre *c* to the circumference of the exhausted vessel. The heated sphere being maintained at a uniform temperature while the spherical vessel is exhausted, and thereby freed from any disturbing influence of internal currents of air, it will be evident that the intensity of radiant heat, thus transmitted from the sphere through the ether alone, will be alike at every point of the surface of the surrounding spherical vessel. It needs no demonstration to prove that the temperature resulting from radiation against the latter will be less than that of the central sphere in proportion to the area presented by each. In other words, *the temperature will be inversely as the areas of the two spheres.* On the soundness of this proposition depends the correctness of the accepted doctrine relating to the propagation of heat and light through space. The remarkable fact must not be overlooked, that this proposition takes no cognizance of *distance;* and that it enables us to determine the temperature of the surrounding sphere if we know the temperature of the central one, merely by comparing their relative *areas*, basing our computation on the proportion they bear to each other; the intervening space, whether it be 1 mile, or 1,000 miles, being an element excluded from our calculation.

That rays of light and heat meet with no appreciable resistance in their passage through the ether is an irresistible inference to be drawn from the fact that the intensity bears a direct proportion to the *area over which the rays are dispersed.* The common expression that "the intensity of light and heat varies inversely as the square of the distances" leads to the supposition that *distance* is an element to be taken into account in estimating the intensity of radiant heat. That this is an error will be readily perceived if we reflect on the fact, just referred to, that the intensity of the rays diminishes in the *exact* proportion to the areas over which they are dispersed. It is self-evident that if distance, *per se*, in any way affected the question, the intensities could not thus depend solely on the extent of the *areas* over which the rays are diffused. Much misapprehension would be prevented if the law relating to radiant heat were thus expressed: *The intensities are inversely as the areas over which the rays are dispersed.* Sir Isaac Newton, referring to the intensity of the sun's radiant heat at different distances, thus clearly defines the question: "The heat of the sun (at various distances) is as the density of its rays." He also states that the densities of the diverging rays are "reciprocally as the square of the distance from the centre of the sun," a fact which obviously has nothing to do with the main proposition, as it simply results from certain geometrical relations, viz., that the areas of transverse sections of a cone are as the square of the distances from the apex.

I will now briefly show why the theory of Newton, supposed to have been proved by Melloni, is true, under certain conditions, as regards a uniformly heated sphere, although fallacious, under all circumstances, as regards plane surfaces. Referring again to Fig. 5, let us assume that the sphere *s* represents the sun, the semi-diameter of which is 426,292 miles; and that *a b v* represents the earth's orbit reduced to a circle whose radius corresponds with the earth's mean distance from the sun's centre, viz., 91,430,000 miles. Now, the arc *e f* is to the arc *a b* as the radial line *c e*, representing the sun's radius, is to *c a*, representing the earth's distance from the sun's centre. According to the stated dimensions, therefore, *c e* is to *c a* as 1 to 214.44; hence, regarding *a c b* as a cone of very small base, the area of *e f* is to that of *a b* as 1 to the square of 214.44 = 45,984. Accordingly, the temperature of the heated central sphere *s* will be 45,984 times greater than the temperature which it imparts by radiation to the surrounding sphere *a b v*.

We have now fully established the fact that, although the extent of the radiating and recipient surfaces, in connection with the temperature of the former, determines the temperature transmitted to the latter, wholly independent of distance, yet, as regards the sun, it is true that the temperature produced by the radiant heat of his rays is inversely as the square of the distance from his *centre*, the same law applying to all spheres having a uniform temperature at the surface.

CHAPTER II.

RADIATION AT DIFFERENT TEMPERATURES.

Sir Isaac Newton supposed that a heated body would lose by radiation at each instant a quantity of heat proportionate to the excess of its temperature above that of the surrounding medium. Modern physicists, basing their reasoning on the result of MM. Dulong and Petit's experiments, contend that Newton's supposition is erroneous. Prof. Balfour Stewart in his "Elementary Treatise on Heat," published at Oxford 1871, in support of his assertion that Newton's doctrine is false, presents the following extract from the work of Dulong and Petit:

Excess of Temperature of the Thermometer.	*Velocity of Cooling.*
° C.	° C.
240	10.69
220	8.81
200	7.40

Excess of Temperature of the Thermometer.	*Velocity of Cooling.*
° C.	° C.
180	6.10
160	4.89
140	3.88
120	3.02
100	2.30
80	1.74

"We see at once from this table," says the author of the "Elementary Treatise on Heat," "that the law of Newton does not hold, for according to it the velocity of cooling for an excess of 200 deg. should be precisely double of that for an excess of 100 deg.; now we find that it is more than three times as much." The rate of cooling exhibited in this table being at variance with the laws which govern the emission and absorption of radiant heat, I have instituted a series of experiments in order to test the correctness of the tabulated rates accepted by Prof. Stewart. The initiary proceeding of the investigation was that of ascertaining the rate of cooling at temperatures below 200° F., for which purpose I constructed the apparatus shown on Pl. 4, Fig. 1, representing three concentric spherical vessels placed within each other. As the drawing shows the detail of the entire mechanism, a brief description will suffice. *a a* is a spherical vessel 7 inches in diameter, applied within an exterior casing *b*. A spherical radiator *c*, 4 inches in diameter, composed of very thin copper, and coated with lamp-black, is sustained in the centre of the spherical vessel *a* by means of two vertical tubes *l* and *m*, composed of very thin metal, communicating with the interior of the radiator. The upper tube is large enough to admit the bulb of a thermometer, the lower one being only sufficiently large to accommodate a small axle, to which is attached a paddle-wheel provided with curved paddles arranged in such a manner that the bulb of the thermometer may be inserted considerably beyond the centre of the sphere, as shown in the illustration. The external casing *b* is provided with nozzles *g* and *d*, to which tubes are attached for circulating cold water through the intervening space during experiments. The air is exhausted from the spherical enclosure *a a* through the tube *k*, which passes across the said intervening space. The radiating sphere *c* being filled with water, it will be perceived that the centrifugal action of the paddles of the wheel applied within will produce a continuous current from the centre towards the circumference, the fluid successively passing over and coming in contact with the thin spherical shell, then returning to the centre to be again thrown off by the centrifugal action. The rotary motion of the water thus kept up without intermission round the cylindrical bulb of the thermometer, will evidently render its indication prompt and reliable. It is hardly necessary to observe that the rapid presentation of fresh particles of water, promoted by the action of the paddles, will effectually prevent the reduction of temperature proceeding faster at the circumference than at the centre; hence the radiation at the surface will, in virtue of the continuous interchange of particles, affect almost simultaneously every molecule within the sphere. It will be seen, therefore, that the total energy of radiation will be rendered available in reducing the temperature of the contents of the radiator, and that the central thermometer will indicate, at every instant, the precise degree of temperature of the entire mass. It might be supposed that the motion of the water within the sphere, consequent on the action of the paddle-wheel, would produce an elevation of temperature sufficient to render the indication of the thermometer inaccurate. Before commencing the experiments, several trials were accordingly instituted to ascertain if at the requisite speed, 20 turns per minute, heat could be produced. The result has proved positively that no appreciable elevation of temperature takes place. The diameter of the wheel being 3.4 ins., the maximum speed of the particles of water produced by the rotation scarcely reaches 3.5 ins. per second, a velocity evidently too small to generate appreciable heat.

The mode of conducting the experiment will be seen by the following statement: A capacious wooden cistern, charged with water and crushed ice, is connected by small flexible tubes to the nozzles *g* and *d* on opposite sides of the external vessel *b*, a pump being applied between the said nozzles and the cistern, by means of which the cold water is forced through the apparatus and ultimately returned to the source of supply.

In view of the great importance of the question at issue the investigation has been conducted with the utmost care, four operators having been employed to carry out the experiments, the labor being thus divided: 1st operator regulates the temperature of the water in the cistern by continual agitation and supply of crushed ice from time to time; 2d operator works the pump at a uniform rate; 3d operator, after having charged the central sphere with boiling water, turns the paddle-wheel, reads the thermometer, and announces the temperature for *each degree*, at the instant when the top of the mercurial column is covered by half the thickness of the line on the scale; the 4th operator, provided with a Casella chronograph, records the time and temperature. It should be observed that, notwithstanding this procedure, there is a slight irregularity in the ratio of temperature and time, the increment for each degree not being quite uniform. Obviously the most practised eye, though assisted by the magnifying-glass, cannot determine exactly at what moment the top of the falling column is half covered by the line on the thermometric scale. Again, a perfectly graduated thermometer cannot be obtained. The discrepancy referred to is, however, so small that it cannot readily be detected in the diagram. It will be proper to state that, in constructing the several tables contained in this chapter, a correction has been introduced agreeably to Regnault's method of correcting the irregularities inseparable from thermometric observations. Referring to the annexed tables, marked A, it will be noticed that the rate at which the spherical radiator cools has been recorded for each degree of differential temperature from 150° to 15°. The temperature of the surrounding cold vessel, it will be seen, is entered in the first column; the temperature of the radiating sphere in the second, and its excess of temperature in the third column. The number of seconds occupied in reducing the

A

Table showing the Rate of Cooling of a Heated Body suspended within a *Cold Enclosure.*

Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.
°*Fah.*	°*Fah.*	°*Fah.*	*Secs.*	*Secs.*	°*Fah.*	°*Fah.*	°*Fah.*	*Secs.*	*Secs.*
33	183	150	37.7	42.01	33	160	127	47.3	49.64
33	182	149	38.1	42.29	33	159	126	47.8	50.04
33	181	148	38.5	42.57	33	158	125	48.3	50.44
33	180	147	38.9	42.86	33	157	124	48.8	50.85
33	179	146	39.3	43.16	33	156	123	49.3	51.26
33	178	145	39.7	43.46	33	155	122	49.8	51.68
33	177	144	40.1	43.76	33	154	121	50.3	52.11
33	176	143	40.5	44.07	33	153	120	50.8	52.55
33	175	142	40.9	44.38	33	152	119	51.3	53.00
33	174	141	41.3	44.69	33	151	118	51.8	53.44
33	173	140	41.7	45.02	33	150	117	52.3	53.90
33	172	139	42.1	45.34	33	149	116	52.8	54.37
33	171	138	42.5	45.67	33	148	115	53.3	54.84
33	170	137	42.9	46.01	33	147	114	53.9	55.33
33	169	136	43.3	46.34	33	146	113	54.5	55.82
33	168	135	43.7	46.69	33	145	112	55.1	56.32
33	167	134	44.1	47.04	33	144	111	55.7	56.83
33	166	133	44.5	47.39	33	143	110	56.3	57.35
33	165	132	44.9	47.75	33	142	109	56.9	57.87
33	164	131	45.3	48.12	33	141	108	57.5	58.42
33	163	130	45.8	48.49	33	140	107	58.2	58.97
33	162	129	46.3	48.87	33	139	106	58.9	59.52
33	161	128	46.8	49.25	33	138	105	59.6	60.09

A

TABLE SHOWING THE RATE OF COOLING OF A HEATED BODY SUSPENDED WITHIN A *COLD ENCLOSURE.*

Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
33	137	104	60.3	60.67	33	114	81	80.8	78.01
33	136	103	61.0	61.27	33	113	80	81.9	78.99
33	135	102	61.7	61.87	33	112	79	83.1	80.00
33	134	101	62.4	62.48	33	111	78	84.3	81.03
33	133	100	63.2	63.11	33	110	77	85.5	82.09
33	132	99	64.0	63.76	33	109	76	86.7	83.18
33	131	98	64.8	64.41	33	108	75	88.0	84.29
33	130	97	65.6	65.08	33	107	74	89.3	85.44
33	129	96	66.4	65.76	33	106	73	90.6	86.62
33	128	95	67.2	66.46	33	105	72	91.9	87.83
33	127	94	68.0	67.16	33	104	71	93.3	89.08
33	126	93	68.9	67.89	33	103	70	94.7	90.36
33	125	92	69.8	68.63	33	102	69	96.1	91.68
33	124	91	70.7	69.39	33	101	68	97.5	93.04
33	123	90	71.6	70.17	33	100	67	99.0	94.44
33	122	89	72.5	70.96	33	99	66	100.5	95.88
33	121	88	73.5	71.77	33	98	65	102.0	97.36
33	120	87	74.5	72.60	33	97	64	103.6	98.89
33	119	86	75.5	73.45	33	96	63	105.2	100.48
33	118	85	76.5	74.32	33	95	62	106.9	102.11
33	117	84	77.5	75.21	33	94	61	108.6	103.80
33	116	83	78.6	76.12	33	93	60	110.4	105.55
33	115	82	79.7	77.05	33	92	59	112.3	107.35

A — Table showing the Rate of Cooling of a Heated Body suspended within a *Cold Enclosure.*

Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
33	91	58	114.3	109.22	33	69	36	189.9	176.90
33	90	57	116.4	111.15	33	68	35	195.4	182.03
33	89	56	118.6	113.15	33	67	34	201.2	187.46
33	88	55	120.9	115.23	33	66	33	207.2	193.23
33	87	54	123.3	117.38	33	65	32	213.5	199.36
33	86	53	125.8	119.62	33	64	31	220.2	205.90
33	85	52	128.4	121.94	33	63	30	227.4	212.88
33	84	51	131.1	124.35	33	62	29	235.1	220.35
33	83	50	133.9	126.87	33	61	28	243.4	228.36
33	82	49	136.8	129.48	33	60	27	252.3	236.98
33	81	48	139.9	132.21	33	59	26	261.9	246.27
33	80	47	143.1	135.05	33	58	25	272.2	256.32
33	79	46	146.5	138.02	33	57	24	283.3	267.23
33	78	45	150.0	141.12	33	56	23	295.4	279.11
33	77	44	153.7	144.37	33	55	22	308.7	292.09
33	76	43	157.5	147.76	33	54	21	323.4	306.34
33	75	42	161.5	151.32	33	53	20	339.7	322.05
33	74	41	165.7	155.06	33	52	19	357.9	339.46
33	73	40	170.1	158.99	33	51	18	378.3	358.86
33	72	39	174.7	163.12	33	50	17	401.2	380.60
33	71	38	179.5	167.47	33	49	16	426.9	405.16
33	70	37	184.6	172.06	33	48	15	455.7	433.10

temperature of the radiating sphere one degree is recorded in the fourth column. The fifth column contains the number of seconds which would be requisite to reduce the temperature one degree if the cooling proceeded at the rate shown by the Newtonian law.

Let us now examine the diagram Fig. 2, attached to the illustration, in which the length of the ordinates of the curve *b c* represent the observed time for each degree of differential temperature, while the ordinates of the curve *a d* represent the time that would elapse if the rate of cooling were in exact accordance with Newton's doctrine—namely, if the times were inversely as the differential temperatures. The vertical line in Fig. 2, on which the ordinates representing the time of cooling have been projected, is divided into degrees of Fahrenheit, showing the differential temperature, viz., the excess of temperature of the radiating sphere above that of the surrounding cold vessel. A careful inspection of this diagram and of the Tables A, renders argument unnecessary to show that our experimental investigation has established the correctness of Newton's assumption that a radiating body loses at each instant a quantity of heat proportionate to the excess of its temperature above that of the surrounding medium. It will be shown hereafter that the slight discrepancy indicated by the different length of the ordinates of the curves *a d* and *b c* is owing to the variation of emissive power of the radiator, caused by the difference of molecular motion resulting from change of temperature, and the consequent change of dimensions, of the radiator. Dulong and Petit's formula being based on the table presented at the commencement of this chapter, copied from Prof. Stewart's "Elementary Treatise on Heat" (compared also with the French original), I have deemed it important to examine carefully whether the rates of cooling presented in the said table are consistent. The result of this examination is shown in the accompanying table, in which the 1st column contains the differential temperature of the radiator, the 2d column contains the corresponding rate of cooling for each minute, established by Dulong and Petit; while the 3d and 4th columns show the ratio of difference.

240°	10°.69		
		1.88	
220	8.81		0.47
		1.41	
200	7.40		0.11
		1.30	
180	6.10		0.09
		1.21	
160	4.89		0.20
		1.01	
140	3.88		0.15
		0.86	
120	3.02		0.14
		0.72	
100	2.30		0.16
		0.56	
80	1.74		
1	2	3	4

The inconsistency and irregularity of the rates of cooling exhibited by the figures in the two last columns prove the unreliable character of the temperatures inserted in the two first columns. We are warranted in concluding that a doctrine

B

Table showing the Rate of Cooling of a Heated Body suspended within a *Cold Enclosure*.

Differential temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.	Differential temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.	Differential temperature of enclosed body.	Observed time cooling enclosed body one deg.	Time agreeably to Newton's law.
Cent.	*Secs.*	*Secs.*	*Cent.*	*Secs.*	*Secs.*	*Cent.*	*Secs.*	*Secs.*
83	38.1	42.29	57	61.6	61.75	31	119.9	114.39
82	38.8	42.81	56	62.9	62.86	30	124.3	118.27
81	39.5	43.34	55	64.3	64.01	29	128.9	122.41
80	40.3	43.89	54	65.7	65.21	28	133.9	126.87
79	41.0	44.45	53	67.2	66.46	27	139.3	131.65
78	41.7	45.02	52	68.7	67.74	26	145.2	136.81
77	42.4	45.60	51	70.3	69.09	25	151.5	142.40
76	43.1	46.20	50	72.0	70.48	24	158.3	148.46
75	43.8	46.82	49	73.7	71.94	23	165.7	155.06
74	44.5	47.46	48	75.5	73.45	22	173.8	162.27
73	45.3	48.12	47	77.3	75.02	21	182.6	170.18
72	46.1	48.80	46	79.2	76.68	20	192.1	178.91
71	47.0	49.49	45	81.2	78.40	19	202.4	188.59
70	47.9	50.20	44	83.3	80.20	18	213.5	199.36
69	48.8	50.93	43	85.5	82.09	17	225.7	211.44
68	49.8	51.68	42	87.7	84.07	16	239.4	225.08
67	50.7	52.45	41	90.0	86.14	15	255.2	240.61
66	51.6	53.25	40	92.4	88.32	14	273.6	258.44
65	52.5	54.09	39	94.9	90.62	13	295.4	279.11
64	53.5	54.94	38	97.5	93.04	12	321.1	303.38
63	54.5	55.82	37	100.2	95.58	11	351.6	332.27
62	55.6	56.73	36	103.0	98.28	10	388.1	367.25
61	56.7	57.67	35	106.0	101.12	9	432.5	410.45
60	57.8	58.64	34	109.1	104.15	8	487.9	465.11
59	59.0	59.64	33	112.3	107.35	7	558.0	536.71
58	60.3	60.47	32	115.9	110.76	6	656.3	634.33

based on such unsatisfactory premises cannot be sound. How far this inference is correct will be seen presently, by a comparison between the ratio of cooling at high temperatures, deduced from MM. Dulong and Petit's formula, and the *actual* rate shown by an incandescent cast-iron sphere enclosed within a vacuum; also by the amount of mechanical energy developed by the radiation of fused cast iron. The temperatures inserted in the table marked B, relating to the experiments under consideration, have been reduced to the Centigrade scale for the purpose of facilitating direct comparison with the result of Dulong and Petit's researches.

The question has frequently been asked, whether Newton's law holds for *increase* of temperature when a cold body is exposed to the radiation of a surrounding hot medium. In order to decide the question, experimentally, whether the times occupied in *heating* a certain body are equal, for corresponding differential temperatures, to the times occupied in cooling the same body, a modified apparatus has been constructed (see illustration shown on Plate 5, Fig. 3). The means adopted for measuring the temperature and producing circulation within the central sphere being identical with those of the apparatus already described, it will only be necessary to point out that the exhausted vessel *a a* which surrounds the central sphere *c* is immersed in water contained in a cylindrical vertical boiler *b*, open at the top and heated by means of a spirit-lamp applied under its bottom. The experiments with this modified apparatus have been conducted in the following manner: The water in the boiler having been brought to

C

TABLE SHOWING THE RATE OF HEATING OF A COLD BODY SUSPENDED WITHIN A *HEATED ENCLOSURE.*

Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosure.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosure.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
212	37	175	29.1	29.08	212	64	148	35.6	34.41
212	38	174	29.3	29.25	212	65	147	35.9	34.64
212	39	173	29.5	29.42	212	66	146	36.3	34.88
212	40	172	29.7	29.59	212	67	145	36.5	35.12
212	41	171	29.9	29.76	212	68	144	36.8	35.36
212	42	170	30.1	29.94	212	69	143	37.1	35.61
212	43	169	30.3	30.12	212	70	142	37.4	35.86
212	44	168	30.5	30.29	212	71	141	37.7	36.12
212	45	167	30.7	30.48	212	72	140	38.0	36.38
212	46	166	30.9	30.66	212	73	139	38.3	36.64
212	47	165	31.1	30.85	212	74	138	38.6	36.91
212	48	164	31.3	31.04	212	75	137	38.9	37.18
212	49	163	31.5	31.23	212	76	136	39.2	37.46
212	50	162	31.7	31.42	212	77	135	39.5	37.74
212	51	161	31.9	31.62	212	78	134	39.8	38.02
212	52	160	32.1	31.82	212	79	133	40.1	38.30
212	53	159	32.3	32.02	212	80	132	40.4	38.59
212	54	158	32.6	32.22	212	81	131	40.7	38.88
212	55	157	32.9	32.43	212	82	130	41.0	39.18
212	56	156	33.2	32.64	212	83	129	41.3	39.49
212	57	155	33.5	32.85	212	84	128	41.6	39.80
212	58	154	33.8	33.06	212	85	127	41.9	40.12
212	59	153	34.1	33.28	212	86	126	42.2	40.44
212	60	152	34.4	33.50	212	87	125	42.5	40.76
212	61	151	34.7	33.72	212	88	124	42.8	41.09
212	62	150	35.0	33.95	212	89	123	43.1	41.43
212	63	149	35.3	34.18	212	90	122	43.5	41.77

C	TABLE SHOWING THE RATE OF HEATING OF A COLD BODY SUSPENDED WITHIN A *HEATED ENCLOSURE.*								
Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosure.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosure.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
212	91	121	43.9	42.12	212	118	94	55.4	54.28
212	92	120	44.3	42.47	212	119	93	55.9	54.86
212	93	119	44.7	42.83	212	120	92	56.4	55.46
212	94	118	45.1	43.19	212	121	91	56.9	56.08
212	95	117	45.5	43.56	212	122	90	57.4	56.70
212	96	116	45.9	43.94	212	123	89	57.9	57.33
212	97	115	46.3	44.32	212	124	88	58.5	58.00
212	98	114	46.7	44.71	212	125	87	59.1	58.68
212	99	113	47.1	45.11	212	126	86	59.7	59.36
212	100	112	47.5	45.51	212	127	85	60.3	60.06
212	101	111	47.9	45.93	212	128	84	60.9	60.78
212	102	110	48.3	46.35	212	129	83	61.5	61.51
212	103	109	48.7	46.78	212	130	82	62.1	62.27
212	104	108	49.1	47.21	212	131	81	62.7	63.04
212	105	107	49.5	47.65	212	132	80	63.4	63.84
212	106	106	49.9	48.10	212	133	79	64.1	64.65
212	107	105	50.3	48.56	212	134	78	64.8	65.48
212	108	104	50.7	49.03	212	135	77	65.5	66.34
212	109	103	51.1	49.51	212	136	76	66.2	67.22
212	110	102	51.5	50.00	212	137	75	66.9	68.12
212	111	101	51.9	50.50	212	138	74	67.7	69.05
212	112	100	52.4	51.01	212	139	73	68.5	70.00
212	113	99	52.9	51.52	212	140	72	69.3	70.98
212	114	98	53.4	52.05	212	141	71	70.1	71.98
212	115	97	53.9	52.59	212	142	70	70.9	73.02
212	116	96	54.4	53.14	212	143	69	71.8	74.09
212	117	95	54.9	53.70	212	144	68	72.7	75.19

C	TABLE SHOWING THE RATE OF HEATING OF A COLD BODY SUSPENDED WITHIN A *HEATED ENCLOSURE.*								
Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosure.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed body.	Excess of temperature of enclosure.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
212	145	67	73.6	76.32	212	172	40	118.7	128.48
212	146	66	74.5	77.48	212	173	39	121.6	131.82
212	147	65	75.5	78.68	212	174	38	124.6	135.33
212	148	64	76.5	79.92	212	175	37	127.8	139.04
212	149	63	77.5	81.20	212	176	36	131.2	142.96
212	150	62	78.6	82.52	212	177	35	134.8	147.10
212	151	61	79.7	83.88	212	178	34	138.6	151.49
212	152	60	80.8	85.29	212	179	33	142.6	156.15
212	153	59	82.0	86.75	212	180	32	146.9	161.11
212	154	58	83.2	88.26	212	181	31	151.5	166.39
212	155	57	84.5	89.82	212	182	30	156.4	172.03
212	156	56	85.8	91.44	212	183	29	161.6	178.07
212	157	55	87.2	93.12	212	184	28	167.1	184.54
212	158	54	88.6	94.86	212	185	27	172.9	191.51
212	159	53	90.1	96.66	212	186	26	179.1	199.01
212	160	52	91.7	98.54	212	187	25	185.7	207.14
212	161	51	93.4	100.50	212	188	24	192.7	215.95
212	162	50	95.2	102.53	212	189	23	200.3	225.55
212	163	49	97.1	104.64	212	190	22	208.7	236.05
212	164	48	99.1	106.84	212	191	21	218.1	247.56
212	165	47	101.2	109.14	212	192	20	228.7	260.26
212	166	46	103.4	111.54	212	193	19	240.7	274.32
212	167	45	105.7	114.05	212	194	18	254.7	289.99
212	168	44	108.1	116.66	212	195	17	269.6	307.57
212	169	43	110.6	119.41	212	196	16	287.0	327.42
212	170	42	113.2	122.29	212	197	15	306.8	350.00
212	171	41	115.9	125.31					

C 2

TABLE SHOWING THE RATE OF HEATING OF A COLD BODY SUSPENDED WITHIN A *HOT ENCLOSURE.*

Differential temperature of enclosed body.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.	Differential temperature of enclosed body.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.	Differential temperature of enclosed body.	Observed time heating enclosed body one deg.	Time agreeably to Newton's law.
° Cent.	*Secs.*	*Secs.*	*° Cent.*	*Secs.*	*Secs.*	*° Cent.*	*Secs.*	*Secs.*
97	29.3	29.22	67	44.2	42.40	37	74.4	77.24
96	29.6	29.52	66	44.9	43.04	36	76.1	79.42
95	30.0	29.83	65	45.6	43.71	35	78.0	81.72
94	30.3	30.15	64	46.4	44.40	34	79.9	84.16
93	30.7	30.48	63	47.1	45.11	33	82.0	86.75
92	31.1	30.81	62	47.8	45.84	32	84.2	89.50
91	31.4	31.15	61	48.5	46.60	31	86.6	92.44
90	31.8	31.50	60	49.3	47.38	30	89.2	95.57
89	32.2	31.86	59	50.0	48.19	29	92.0	98.92
88	32.6	32.22	58	50.7	49.03	28	95.2	102.53
87	33.1	32.60	57	51.4	49.90	27	98.7	106.39
86	33.6	32.99	56	52.2	50.80	26	102.5	110.56
85	34.2	33.38	55	53.1	51.73	25	106.6	115.04
84	34.8	33.78	54	54.0	52.69	24	111.1	119.97
83	35.3	34.18	53	54.9	53.70	23	115.9	125.31
82	35.8	34.59	52	55.7	54.74	22	121.0	131.13
81	36.4	35.02	51	56.6	55.83	21	126.6	137.53
80	36.9	35.46	50	57.6	56.96	20	132.7	144.58
79	37.4	35.91	49	58.6	58.13	19	139.4	152.40
78	38.0	36.38	48	59.7	59.36	18	146.9	161.11
77	38.5	36.86	47	60.8	60.63	17	155.4	170.87
76	39.0	37.34	46	61.9	61.96	16	164.9	181.89
75	39.6	37.84	45	63.0	63.35	15	175.4	194.44
74	40.1	38.35	44	64.2	64.81	14	187.1	208.84
73	40.7	38.88	43	65.5	66.34	13	200.3	225.55
72	41.2	39.42	42	66.8	67.91	12	216.3	245.16
71	41.8	39.98	41	68.2	69.61	11	235.9	268.52
70	42.3	40.56	40	69.6	71.37	10	260.7	296.77
69	42.9	41.16	39	71.1	73.23	9	291.0	331.69
68	43.5	41.77	38	72.7	75.19	8	327.3	375.90

the boiling point, cold water, as near the freezing point as possible, is pumped into the central sphere, through suitable pipes (the thermometer having been previously removed). The operation of charging with cold water should be performed quickly, and the thermometer inserted as soon as the sphere is full. The reading should then commence without a moment's delay, the temperature being announced for each degree, and, together with the time, recorded by the operator attending the chronograph, precisely as before stated with reference to the process of ascertaining the time of cooling. The result of the experiment with the apparatus under consideration will be found by inspecting the annexed tables C together with the diagram attached to the illustration, see Fig. 4, in which the ordinates of the curve *a b′ b* represent the observed time for each degree of differential temperature, while the ordinates of the curve *a c′ c* represent the time that would elapse if the rate of heating were in exact accordance with Newton's doctrine. The small amount of the discrepancy shown by the diagram and table, at differential temperatures exceeding 75° F., proves that the energy varies in accordance with dynamical laws, whether heat be parted with by radiation towards a cooler body, or whether heat be received from a radiating surrounding medium of higher temperature. The perceptible discrepancy at low differential temperature exhibited in the diagram, namely, the observed times being shorter than the theoretical times, is owing to the unavoidable conduction of heat from the boiler to the cold central sphere through the connecting tubes

l and m. Obviously the prolonged period of heating consequent on low differential temperature renders the effect of conduction appreciable, as indicated by the diagram. Our experiments, then, establish the fact that until the emissive power is changed by disturbing causes, the energy developed by radiation increases in the exact ratio of the differential temperatures.

It is proper to mention that one of the principal objects of my investigations relating to the velocity of cooling by radiation, has been that of disproving the correctness of the assumption which certain eminent physicists have based on Dulong and Petit's estimates of the increase of radiant energy developed at high temperatures. Radiation, in a dynamic point of view, being merely transmission of mechanical power, it will be evident, on reflection, that we need only ascertain the number of thermal units developed in a given time, by a given amount of radiating surface maintained at a certain temperature, in order to determine the intensity which Dulong and Petit endeavored to deduce from the velocity of cooling shown by the contraction of mercury and other fluids. It must be inferred, from their having adopted a method so unsatisfactory, that these physicists overlooked the fact that radiant intensity is most accurately measured by ascertaining the amount of thermal energy developed in a given time; and that they deemed it impossible to determine, by direct means, the velocity of cooling of *incandescent* bodies. It cannot be supposed that such skilful experimentalists as Dulong and Petit questioned the practicability of suspending an incandescent body within a vacuum surrounded by a cooling medium. Why, then, it may be asked, did they not resort to that obvious method which, if adopted, would at once have convinced them of the fallacy of their formula assigning a fabulous rate of velocity of cooling to *incandescent* bodies? We must infer that they did not deem it practicable to construct an instrument by which the temperature of the enclosed incandescent body could be accurately measured. It will be urged in defence of Dulong and Petit's method, that the time occupied in cooling cannot be ascertained exactly unless an instrument can be devised capable of showing the temperature of incandescent bodies. This objection, apparently valid since we possess no reliable and delicate pyrometer, falls to the ground before the fact that, at a constant distance, the temperatures imparted to a thermometer by radiation are proportionate to the temperatures of the radiator; and that consequently the velocity of cooling of a radiator at any temperature whatever may be ascertained by a *distant* thermometer as correctly as by one in actual contact. Before entering on a description of the method, before referred to, of measuring the radiant energy at high temperatures by ascertaining the amount of thermal energy developed in a given time by a given area, I will now briefly describe an instrument constructed in accordance with the fact just mentioned, that the temperatures of a recipient of radiant heat are proportionate to the temperatures of the radiator. The illustration on Plate 6, Fig. 5, represents a vertical section and top view of the instrument referred to, by means of which the velocity of cooling of an incandescent body may be ascertained with perfect accuracy. *Description : a a*, spherical vessel composed of thin copper, coated with lamp-black on the inside and provided with a cover *b* fitting air-tight against the top side of a ring secured to the upper part of the spherical vessel, the cover and the ring being ground together in order to dispense with packing. *c c*, an open cylindrical vessel through which a constant stream of cold water is circulated by means of a force-pump and flexible tubes attached at *d* and *e*, these tubes communicating with a cistern in which water is maintained at a constant temperature of 33° F. *K* is a solid sphere of cast iron suspended by means of a lug formed at the upper part of the sphere, secured under the cover *b* as shown by the drawing. A brass stopple *g*, fitting air-tight in a conical socket formed in the before-mentioned ring, supports a Casella thermometer *f*. The cover *b* is provided with a vertical handle *b′* in order to facilitate the operation of inserting the solid sphere *K*, after being heated and suspended under the cover. The air is exhausted from the spherical vessel by means of a large air-pump, a stopcock being inserted in the exhaust pipe at *l*. The mode of operation will be readily understood by the following explanation. The solid cast-iron sphere being brought to nearly white heat in an air-furnace, is removed by suitable tongs and suspended under the cover *b*, which latter is quickly put in position over the opening of the spherical vessel. The air-pump is put in rapid motion immediately after putting on the cover; a few strokes of the water-pump being required to fill the cistern *c c* to the height shown in the drawing. These operations being performed with due diligence, practice has shown that the temperature of the incandescent sphere will not fall below 1,600° F. before the vacuum is sufficiently complete to admit of recording the indicated temperatures. The thermometer *f* being secured firmly in the stopple *g*, may of course be inserted very quickly, an important circumstance, since the bulb, in order to save time, should be previously heated to nearly maximum temperature. We have already pointed out that, agreeably to the laws which govern the transmission of radiant heat, the temperatures produced by radiation at constant distances are proportionate to the temperatures of the radiating body. It will be readily perceived, therefore, that the thermometer *f* will correctly indicate the *rate* of cooling of the suspended incandescent sphere. But in order to prove the fallacy of Dulong and Petit's estimate of the rate of cooling at high temperatures, we must also ascertain the temperature of the sphere itself. Bearing in mind that the temperature of the recipient of radiant heat is proportionate to that of the radiator, it will be perceived, on reflection, that we can previously determine the ratio between the temperature of the sphere *K* and that of the recording thermometer *f*. Evidently this ratio may be ascertained at temperatures which admit of the employment of ordinary mercurial thermometers, hence the determination may be very exact. It will be readily understood that the thermometer intended for our investigation may be placed at such a distance from a radiating spherical vessel containing mercury maintained at a temperature of 400°, that its indication shall be exactly 100°. In other words, the distance between the radiator and the recording thermometer may be such that the temperature of the former shall be exactly four times greater than the temperature of the latter. Now, if we remove the spherical vessel referred to and substitute an incandescent sphere whose diameter corresponds with the outside diameter of the said vessel, the indication of the recording thermometer multiplied by 4 will show the temperature of the incandescent sphere. It is hardly necessary to point out, that much time would be wasted in the tedious process of determining experimentally the distance between the recording thermometer and the radiator, necessary to cause an indication of the former exactly one-fourth of the temperature of the latter. Obviously a less symmetrical coefficient will answer nearly as well as the one mentioned. Let us therefore ascertain, approximately, how near the recording thermometer may be placed from an incandescent sphere of the intended size, in order that the mercury in the bulb may not be brought to boiling heat. Having determined the distance of the thermometer as stated, we may, without further experimenting, construct our instrument as shown by the illustration. The spherical vessel containing mercury being then introduced and a vacuum formed within the surrounding enclosure, the temperature of the said spherical vessel, compared with the temperature indicated by the recording thermometer, will of course determine the coefficient of the instrument. The following brief explanation of the procedure will suffice. Suppose that the temperature of the mercury in the spherical vessel is 409°, while that indicated by the recording thermometer is 98°. The ratio of temperature between the radiator and the recording thermometer will then be as 409 to 98; and hence the coefficient sought will be $\frac{409}{98} = 4.173$. Consequently, if we suspend the incandescent sphere K within the enclosure as before directed, and find by observation that the recording thermometer indicates 401°, we then learn that the temperature of the enclosed incandescent body, at the moment of observation, is $4.173 \times 401 = 1{,}673°$ F. The means thus afforded of measuring, with great exactness, the temperature and radiant intensity of incandescent bodies, cannot fail to facilitate future thermic investigations.

The result of our experiments with the suspended incandescent sphere, will be found recorded in the annexed set of tables, the first series, marked D, being constructed to the Fahrenheit scale, while the second series E has been reduced to the Centigrade scale. The first column in Table D shows the temperature of the enclosure, the temperature of the radiating sphere being inserted in the second column. The excess of temperature of the radiator over that of the surrounding cold vessel will be found in the third column, the time actually occupied in reducing the temperature of the radiator 10° F. being entered in the fourth column. The time of cooling, agreeably to the Newtonian law, will be found in the fifth and last column. The mode of constructing the tables will be readily comprehended by referring to previous explana-

D

TABLE SHOWING THE RATE OF COOLING OF AN INCANDESCENT SOLID SPHERE SUSPENDED WITHIN A *COLD ENCLOSURE*.

Temperature of enclosure.	Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere ten degs.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere ten degs.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
34	1600	1566	22.24	21.97	34	1320	1286	30.77	26.65
34	1590	1556	22.48	22.11	34	1310	1276	31.17	26.85
34	1580	1546	22.72	22.25	34	1300	1266	31.58	27.06
34	1570	1536	22.96	22.39	34	1290	1256	32.00	27.27
34	1560	1526	23.21	22.54	34	1280	1246	32.42	27.48
34	1550	1516	23.46	22.68	34	1270	1236	32.85	27.70
34	1540	1506	23.72	22.83	34	1260	1226	33.28	27.92
34	1530	1496	23.98	22.98	34	1250	1216	33.72	28.15
34	1520	1486	24.25	23.13	34	1240	1206	34.16	28.38
34	1510	1476	24.52	23.28	34	1230	1196	34.61	28.61
34	1500	1466	24.80	23.44	34	1220	1186	35.06	28.84
34	1490	1456	25.08	23.60	34	1210	1176	35.52	29.08
34	1480	1446	25.37	23.76	34	1200	1166	35.99	29.32
34	1470	1436	25.66	23.92	34	1190	1156	36.47	29.57
34	1460	1426	25.96	24.08	34	1180	1146	36.95	29.82
34	1450	1416	26.26	24.25	34	1170	1136	37.44	30.08
34	1440	1406	26.57	24.42	34	1160	1126	37.94	30.34
34	1430	1396	26.88	24.59	34	1150	1116	38.44	30.61
34	1420	1386	27.20	24.77	34	1140	1106	38.95	30.88
34	1410	1376	27.52	24.95	34	1130	1096	39.47	31.15
34	1400	1366	27.85	25.13	34	1120	1086	40.00	31.43
34	1390	1356	28.18	25.30	34	1110	1076	40.54	31.71
34	1380	1346	28.52	25.48	34	1100	1066	41.08	32.00
34	1370	1336	28.87	25.67	34	1090	1056	41.63	32.30
34	1360	1326	29.23	25.86	34	1080	1046	42.19	32.60
34	1350	1316	29.60	26.05	34	1070	1036	42.76	32.91
34	1340	1306	29.98	26.25	34	1060	1026	43.34	33.22
34	1330	1296	30.37	26.45	34	1050	1016	43.93	33.54

D

TABLE SHOWING THE RATE OF COOLING OF AN INCANDESCENT SOLID SPHERE SUSPENDED WITHIN A *COLD ENCLOSURE.*

Temperature of enclosure.	Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere ten degs.	Time agreeably to Newton's law.	Temperature of enclosure.	Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere ten degs.	Time agreeably to Newton's law.
° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*	° *Fah.*	° *Fah.*	° *Fah.*	*Secs.*	*Secs.*
34	1040	1006	44.53	33.80	34	760	726	72.05	46.42
34	1030	996	45.15	34.19	34	750	716	73.66	47.04
34	1020	986	45.79	34.53	34	740	706	75.33	47.68
34	1010	976	46.45	38.87	34	730	696	77.06	48.34
34	1000	966	47.12	35.22	34	720	686	78.85	49.01
34	990	956	47.81	35.58	34	710	676	80.70	49.71
34	980	946	48.52	35.94	34	700	666	82.61	50.43
34	970	936	49.24	36.31	34	690	656	84.58	51.16
34	960	926	49.98	36.69	34	680	646	86.61	51.92
34	950	916	50.74	37.08	34	670	636	88.71	52.70
34	940	906	51.53	37.48	34	660	626	90.88	53.50
34	930	896	52.35	37.89	34	650	616	93.12	54.33
34	920	886	53.20	38.30	34	640	606	95.43	55.18
34	910	876	54.08	38.72	34	630	596	97.81	56.07
34	900	866	54.99	39.15	34	620	586	100.26	56.98
34	890	856	55.93	39.59	34	610	576	102.78	57.92
34	880	846	56.90	40.04	34	600	566	105.37	58.90
34	870	836	57.91	40.51	34	590	556	108.03	59.91
34	860	826	58.96	40.98	34	580	546	110.76	60.95
34	850	816	60.05	41.47	34	570	536	113.56	62.03
34	840	806	61.18	41.97	34	560	526	116.43	63.15
34	830	796	62.36	42.48	34	550	516	119.37	64.30
34	820	786	63.59	43.00	34	540	506	122.38	65.50
34	810	776	64.87	43.53	34	530	496	125.46	66.75
34	800	766	66.20	44.08	34	520	486	128.61	68.05
34	790	756	67.58	44.65	34	510	476	131.83	69.40
34	780	746	69.01	45.22	34	500	466	135.13	70.80
34	770	736	70.50	45.81					

E

TABLE SHOWING THE RATE OF COOLING OF AN INCANDESCENT SOLID SPHERE SUSPENDED WITHIN A *COLD ENCLOSURE.*

Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere five degs.	Time agreeably to Newton's law.	Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere five degs.	Time agreeably to Newton's law.
° Cont.	*° Cent.*	*Secs.*	*Secs.*	*° Cont.*	*° Cent.*	*Secs.*	*Secs.*
890	771.12	22.18	21.94	735	716.12	30.63	26.58
885	776.12	22.39	22.06	730	711.12	30.99	26.76
880	761.12	22.61	22.19	725	706.12	31.36	26.95
875	756.12	22.83	22.32	720	701.12	31.73	27.13
870	751.12	23.05	22.44	715	696.12	32.11	27.32
865	746.12	23.27	22.57	710	691.12	32.49	27.51
860	741.12	23.49	22.70	705	686.12	32.87	27.71
855	736.12	23.73	22.83	700	681.12	33.26	27.91
850	731.12	23.96	22.97	695	676.12	33.65	28.12
845	726.12	24.20	23.11	690	671.12	34.05	28.32
840	721.12	24.44	23.25	685	666.12	34.45	28.53
835	716.12	24.69	23.39	680	661.12	34.86	28.74
830	711.12	24.94	23.53	675	656.12	35.27	28.95
825	706.12	25.20	23.67	670	651.12	35.69	29.17
820	701.12	25.46	23.81	665	646.12	36.11	29.39
815	696.12	25.73	23.96	660	641.12	36.54	29.61
810	691.12	26.00	24.11	655	636.12	36.98	29.84
805	686.12	26.28	24.26	650	631.12	37.42	30.07
800	681.12	26.56	24.41	645	626.12	37.87	30.30
795	676.12	26.84	24.57	640	621.12	38.32	30.54
790	671.12	27.13	24.72	635	616.12	38.78	30.78
785	766.12	27.42	24.88	630	611.12	39.24	31.03
780	761.12	27.71	25.04	625	606.12	39.71	31.28
775	756.12	28.01	25.20	620	601.12	40.19	31.53
770	751.12	28.31	25.36	615	596.12	40.67	31.79
765	746.12	28.62	25.53	610	591.12	41.16	32.05
760	741.12	28.93	25.70	605	586.12	41.65	32.31
755	736.12	29.25	25.87	600	581.12	42.15	32.58
750	731.12	29.58	26.04	595	576.12	42.66	32.85
745	726.12	29.92	26.22	590	571.12	43.18	33.13
740	721.12	30.27	26.40	585	566.12	43.71	33.42

E

TABLE SHOWING THE RATE OF COOLING OF AN INCANDESCENT SOLID SPHERE SUSPENDED WITHIN A *COLD ENCLOSURE.*

Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere five degs.	Time agreeably to Newton's law.	Temperature of enclosed sphere.	Excess of temperature of enclosed sphere.	Observed time cooling enclosed sphere five degs.	Time agreeably to Newton's law.
° *Cent*	° *Cent.*	*Secs.*	*Secs.*	° *Cent.*	° *Cent.*	*Secs.*	*Secs.*
580	561.12	44.25	33.71	425	406.12	71.19	46.08
575	556.12	44.80	34.01	420	401.12	72.61	46.63
570	551.12	45.37	34.31	415	396.12	74.08	47.20
565	546.12	45.95	34.61	410	391.12	75.60	47.78
560	541.12	46.54	34.92	405	386.12	77.17	48.37
555	536.12	47.15	35.24	400	381.12	78.78	48.98
550	531.12	47.77	35.56	395	376.12	80.44	49.60
545	526.12	48.41	35.89	390	371.12	82.14	50.24
540	521.12	49.06	36.22	385	366.12	83.89	50.90
535	516.12	49.72	36.56	380	361.12	85.69	51.58
530	511.12	50.40	36.91	375	356.12	87.55	52.27
525	506.12	51.10	37.26	370	351.12	89.47	52.98
520	501.12	51.82	37.62	365	346.12	91.44	53.71
515	496.12	52.56	37.99	360	341.12	93.47	54.46
510	491.12	53.32	38.36	355	336.12	95.55	55.23
505	486.12	54.11	38.74	350	331.12	97.69	56.02
500	481.12	54.93	39.13	345	326.12	99.89	56.84
495	476.12	55.78	39.53	340	321.12	102.15	57.68
490	471.12	56.65	39.94	335	316.12	104.46	58.55
485	466.12	57.55	40.35	330	311.12	106.83	59.45
480	461.12	58.48	40.77	325	306.12	109.26	60.37
475	456.12	59.44	41.20	320	301.12	111.74	61.32
470	451.12	60.44	41.64	315	296.12	114.28	62.30
465	446.12	61.47	42.10	310	291.12	116.87	63.31
460	441.12	62.54	42.56	305	286.12	119.52	64.36
455	436.12	63.65	43.03	300	281.12	122.23	65.44
450	431.12	64.80	43.51	295	276.12	125.00	66.56
445	426.12	65.99	44.00	290	271.12	127.83	67.72
440	421.12	67.22	44.50	285	266.12	130.71	68.92
435	416.12	68.50	45.01	280	261.12	133.65	70.52
430	411.12	69.82	45.54	275	256.12		

tions. It will be seen that the time occupied in cooling the radiating sphere through a range of ten degrees forms the basis, the temperature being of course deduced from the indication of the thermometer *f*. The advocates of Dulong and Petit's doctrine will be surprised to find by our tables that the *incandescent* sphere enclosed in a vacuum surrounded by a cooling medium maintained at a very low temperature, requires upwards of twenty seconds to cool five degrees Centigrade, while agreeably to Dulong's formula the stated reduction of intensity takes place during an interval occupying only a very small fraction of one second. Again, our tables show that the fall of temperature from 1,600° F. to 500° F. requires the considerable lapse of ninety-seven *minutes*, a fact which alone proves that the celebrated formula of Dulong is grossly erroneous.

We have before adverted to the fact that physicists have supposed that the rate of cooling of a body approaching white heat cannot be ascertained practically, because we possess no reliable instrument for measuring high temperatures. MM. Dulong and Petit, apparently impressed with this idea, confined their researches, as before stated, to temperatures below that of boiling mercury, imagining that by observing the rate of cooling up to a differential temperature of 240° C. they would be enabled to establish a law which would determine radiant energy for all intensities. Unfortunately, physicists have accepted the result of those researches, Dulong's formula being now the guide which the student is taught to follow in calculating the energy of radiant heat. Probably no doctrine in physics has occasioned such serious misconception as that propounded by MM. Dulong and Petit. The advance of every branch of knowledge connected with radiant heat has been retarded by the adoption of their doctrine regarding its transmission. Among other important matters, the question relating to the temperature of the sun has become seriously entangled by its adoption. It has led such eminent men as Pouillet to assume that the emission of heat at the surface of the sun is so rapid that the ascertained enormous development of 300,000 thermal units in a minute, on one square foot, may be accounted for by the accepted doctrine, even supposing the temperature of the surface of the photosphere to be only 1,461° C. A glance at the preceding Table E, which is based on actual trial, shows the velocity of cooling to be so moderate at the high temperature of 890° C., that the fall only amounts to $\frac{60.0}{22.18} \times (890 - 885) = 13.5°$ C. in one minute, instead of 1,876.6° C. for the stated temperature, shown by Dulong and Petit's formula $V = 2.037\ (1.0077^t - 1)$. It is surprising that the true character of this palpably erroneous formula, so often applied by engineers and physicists, has never been subjected to *practical* investigation. A positive test might have been applied in various ways, although not with that degree of exactness which is attainable by the means we have just described. The fallacy of the assumption, that an increase of a few hundred degrees of temperature suffices to augment the rate of cooling a thousand fold, becomes self-evident if we consider that an increased rate of cooling means a proportionate increase of the capability of communicating mechanical energy. Practical engineers who have observed the short time required to raise a mass of red-hot metal to the melting point, are familiar with the fact that the heat imparted to the metal by the combustibles during the short interval necessary to reach the point of fusion, from that of red heat, is wholly insufficient to communicate the enormous amount of energy assumed by those who accept MM. Dulong and Petit's formula. This practical mode of testing the correctness of the accepted doctrine demands serious reflection. Let us consider that bright-red heat indicates a temperature of 1,000° C., while welding or white heat indicates 1,500° C. Now, according to the formula $V = 2.037 (1.0077^t - 1)$, the velocity of cooling at 1,000° is represented by a fall of temperature of one degree in the short time of $\frac{1}{4{,}356}$ of a minute, while the velocity of cooling at 1,500° C., assigned by the same formula, will be at the rate of one degree in the exceedingly brief period of $\frac{1}{202{,}710}$ of a minute; hence the energy imparted to the heated metal while its temperature is being raised from 1,000° to 1,500°—viz., 500° C.—will be $\frac{202{,}710}{4{,}356} = 46$ times greater than the energy imparted during the *longer* period required to attain bright-red heat. Let us also consider that, owing to the diminished differential temperature between the burning combustible and the metal, the latter will absorb proportionably less heat from the former while attaining white heat than before red heat is reached;

thus the fallacy of the formula becomes yet more apparent. We have already stated that the rate of cooling at high temperatures may be determined with perfect accuracy, by measuring the number of thermal units which a certain amount of radiating surface develops in a given time. It will be shown in Chapter XIII. that fused iron maintained at a temperature of 2,940° F. above the surrounding air, develops 1,013 thermal units per minute upon an area of one square foot; the means employed to ascertain this fact being a calorimeter floating on the surface of the fused metal, nearly in contact with the same. The illustration shown on Plate 6, Fig. 6, represents a vertical section of a calorimeter for measuring the radiant energy of incandescent metals. It is placed on the top of a block of cast iron brought to white heat, in an air-furnace, the bottom of the instrument being nearly in contact with the top of the incandescent metal. The nature of the device, and the mode of conducting the experiment, being precisely the same as shown with great minuteness in Chapter XIII., it will only be necessary to observe, with reference to the apparently unprotected condition of the heater, that the initial temperature of the water contained in the same is equal to the atmospheric temperature, while the powerful radiation from the incandescent block, together with the intervention of the double casing, effectually prevents cooling by external currents of air. Again, the duration of the experiments being restricted to a few minutes, the refrigerating influence of the surrounding air will be practically inappreciable.

The result of numerous experiments conducted in order to ascertain the amount of radiant energy developed at various differential temperatures from 100° F. to 2,900° F., will be found by inspecting the annexed Table F, which shows the number of thermal units developed in one minute by a radiating surface of one square foot. The ordinates of the curves *a b* (see diagrams Fig. 7 and Fig. 8 attached to the illustration Plate 7) represent the radiant energy developed by the differential temperatures marked on the vertical base-line upon which the ordinates have been projected. It should be stated that the thermal units represented by the ordinates in Fig. 7 correspond with the energy developed by raising the temperature of a quantity of water weighing 1 lb. avoirdupois 1° F.; while the units ("caloris") expressed by the ordinates in Fig. 8 correspond with the energy developed by raising the temperature of 1 kilogramme of water 1° Centigrade. The spaces between the ordinates Fig. 8, of course, mark intervals of 100° Centigrade, the spaces between the ordinates in Fig. 7 marking intervals of 100° Fahrenheit. Referring to Table F, it will be seen that the number of thermal units entered in the third column is that developed during one minute on an area of one square foot; the corresponding temperature of the radiating body being entered in the second column. The fourth column shows the increment of dynamic energy for each 100° increase of temperature, also expressed in thermal units. The fifth column contains the rate of increment, assuming the minimum energy as unit. Regarding the diagrams Figs. 7 and 8, let us clearly understand that the length of the ordinates of the curves *a*

F TABLE SHOWING THE MECHANICAL ENERGY DEVELOPED BY RADIANT HEAT AT DIFFERENT INTENSITIES.

Temperature of surrounding air.	Differential temperature of heated body.	Energy developed in one minute by 1 sq. foot of surface.	Rate of increment of the energy developed for intervals of 100°.	Rate of increment, assuming the minimum energy as unit.	Temperature of surrounding air.	Differential temperature of heated body.	Energy developed in one minute by 1 sq. foot of surface.	Rate of increment of the energy developed for intervals of 100°.	Rate of increment, assuming the minimum energy as unit.
° *Fah.*	° *Fah.*	*Thermal units.*	*Thermal units.*	*Ratio.*	° *Fah.*	° *Fah.*	*Thermal units.*	*Thermal units.*	*Ratio.*
60	2900	980.2	81.7	12.38	60	1500	209.5	27.9	4.22
60	2800	898.5	77.2	11.70	60	1400	181.6	25.0	3.79
60	2700	821.3	72.8	11.03	60	1300	156.6	22.3	3.38
60	2600	748.5	68.5	10.38	60	1200	134.3	19.8	3.00
60	2500	680.0	64.3	9.74	60	1100	114.5	17.5	2.65
60	2400	615.7	60.2	9.12	60	1000	97.0	15.4	2.33
60	2300	555.5	56.2	8.51	60	900	81.6	13.5	2.05
60	2200	499.3	52.3	7.92	60	800	68.1	11.8	1.79
60	2100	447.0	48.5	7.35	60	700	56.3	10.3	1.56
60	2000	398.5	44.8	6.79	60	600	46.0	9.1	1.38
60	1900	353.7	41.2	6.24	60	500	36.9	8.2	1.24
60	1800	312.5	37.7	5.71	60	400	28.7	7.6	1.15
60	1700	274.8	34.3	5.20	60	300	21.1	7.3	1.10
60	1600	240.5	31.0	4.70	60	200	13.8	7.2	1.09
					60	100	6.6		
° *Centigrade.*					° *Centigrade.*				
15	1600	242.9	36.0	11.61	15	800	48.5	11.3	3.64
15	1500	206.9	32.1	10.35	15	700	37.2	9.3	3.00
15	1400	174.8	28.8	9.29	15	600	27.9	7.4	2.39
15	1300	146.0	25.5	8.22	15	500	20.5	5.7	1.84
15	1200	120.5	22.3	7.19	15	400	14.8	4.6	1.48
15	1100	98.2	19.5	6.29	15	300	10.2	3.7	1.19
15	1000	78.7	16.4	5.29	15	200	6.5	3.4	1.09
15	900	62.3	13.8	4.46	15	100	3.1		

b represent the number of thermal units actually transferred from one square foot of radiating surface to the fluid contained in the calorimeter, during one minute, the temperature of the radiator being that marked on the vertical line. It should be particularly noticed that, while the energy transferred at 100° C. is 3.1 thermal units (caloris), see Table F, it amounts to 242.9 such units at 1,600° C.; hence the energy will be $\frac{242.9}{3.1} = 78.3$ times greater at a differential temperature of 1,600° C. than at 100° C. Newton's law shows that the radiant energy augments in the ratio of 1,600 : 100 = 16 : 1. It will thus be seen that the actual increase of energy is $\frac{78.3}{16} = 4.89$ times greater than that assigned by the doctrine the correctness of which our investigations tend to prove. The fact should not be overlooked that the stated discrepancy refers to the maximum intensity of overheated fused cast iron just before the internal molecular arrangement is broken up and the metal dissipated. Besides, we have already pointed out that the expansion of metals is accompanied by molecular change within the mass, augmenting the energy of radiation. Nor should the fact be lost sight of that Newton's doctrine takes no cognizance of such molecular change or disturbance within the heated body. The insignificance of the apparent error of the Newtonian law referred to will be seen by a practical application of the rival theory of MM. Dulong and Petit. Let us compare the difference of energy produced at the extremes of 100° C.

and 1,500° C. differential temperature established by their researches. According to the tables, accepted by Prof. Stewart and others, contained in the second part of Dulong and Petit's famous work, "The Laws of Refrigeration," the rate of cooling at a differential temperature of 100° C. is 2°.30 C. in one minute (the surrounding medium being maintained at the freezing point of water); while at a differential temperature of 240° C. the rate is stated to be 10°.69 C. Applying these rates to the formula of Dulong and Petit, it will be found that when the differential temperature is 1,500° C. the fall will be 202,710° C. in one minute. The radiant energy parted with at 1,500° C. will accordingly be $\frac{202{,}710}{2.30} = 88{,}135$ times greater than at 100° C. But our tables and diagrams, based on actual trial, show that the radiant energy at 1,500° C. is only $\frac{206.9}{3.1} = 66.7$ times greater than at 100° C. Hence the radiant energy at 1,500° C., agreeably to Dulong and Petit's theory, will be $\frac{88{,}135}{66.7} = 1{,}321$ times higher than that established by our elaborate practical investigation.

CHAPTER III.

INTENSITY OF SOLAR RADIATION.

THE illustration shown on Plate 8 represents a vertical section of an instrument constructed for ascertaining, by a new and exact method, the intensity of solar radiation at the surface of the earth, specially arranged for revolving observatories. Sir John Herschel's definition of the word *actinometer*—" an instrument for measuring the intensity of heat in the sun's rays "—warrants the adoption of that term.

The causes which modify the intensity of solar radiation are chiefly: the position of the earth in its orbit, the sun's zenith distance—on which depends the depth of the atmosphere to be penetrated by the rays—and vapors in the atmosphere. The temperature of surrounding objects which radiate towards substances exposed to the sun's rays, and the heat abstracted from such substances by currents of air, present serious disturbing elements, rendering an accurate determination of the radiant intensity by ordinary thermometers practically impossible. It is hardly necessary to point out that solar intensity cannot be satisfactorily ascertained by the old method of deducting the temperature of a thermometer in the shade from that of another thermometer exposed to the sun. The investigations of Daniell relating to the sun's radiant heat, frequently referred to in works on meteorology, conducted in the latitude of London, where the depth of the atmosphere at noon, during the summer solstice, is 0.57 greater than on the ecliptic, merit serious consideration. The subjoined table contains the result of his observations on solar radiation throughout a day in the month of June.

A glance at this table shows that, according to the adopted method of determining the intensity of solar radiation by deducting the temperature indicated by a thermometer in the shade from the temperature attained in the sun, the radiant heat is considerably less before than after noon. The differential temperature, or solar intensity, at 9 A.M., according to this table, is 25°, while at 3 P.M., with an equal zenith distance and equal depth of atmosphere to penetrate, the solar intensity is stated to be 62°, thus exhibiting the enormous difference of 27°. An explanation of the causes of the extraordinary errors of Daniell's table is scarcely needed, but attention should be called to the gross imperfection of such a mode of determining solar radiation as that of noting the different indications of shaded and exposed thermometers. During the early stages of my investigation relating to the mechanical properties of the sun's radiant heat, I adopted this mode of ascertaining the temperature produced by solar radiation; but notwithstanding numerous expedients resorted to in order to prevent

Time of observation.	TEMPERATURE, A.M.				Differential temperature or solar intensity.	
	In the sun.		In the shade.			
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
9.00	93	33.88	68	20.00	25	13.88
9.30	103	39.44	69	20.55	34	18.89
10.00	111	43.88	70	21.11	41	22.77
10.30	119	48.33	71	21.66	48	26.67
11.00	124	51.11	71	21.66	53	29.45
11.30	125	51.66	72	22.21	53	29.45
12.00	129	53.88	73	22.77	56	31.11

Time of observation.	TEMPERATURE, P.M.				Differential temperature or solar intensity.	
	In the sun.		In the shade.			
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
12.30	132	55.55	74	23.33	58	32.22
1.00	141	60.55	74	23.33	67	37.22
1.30	140	60.00	75	23.88	65	36.12
2.00	143	61.66	75	23.88	68	37.78
2.30	138	58.88	76	24.44	62	34.44
3.00	138	58.88	76	24.44	62	34.44
3.30	132	55.55	77	25.00	55	30.55
4.00	124	51.11	76	24.44	48	26.67
4.30	123	50.55	77	25.00	46	25.55
5.00	112	44.44	76	24.44	36	20.00
5.30	106	41.11	75	23.88	31	17.23
6.00	100	37.77	73	22.77	27	15.00

the thermometers from being unduly influenced by the radiant heat of the air and surrounding objects, I failed to secure satisfactory results. The most important point—the controlling the irregular action of the surrounding air, which affects the exposed as well as the shaded thermometer—having presented obstacles which no mechanical arrangement whatever could overcome, I adopted the method of wholly excluding the atmosphere. By this expedient the bulb of the thermometer within the instrument becomes surrounded by ether only; hence the energy transmitted by the sun's rays determines the temperature freed from atmospheric influence. It will be objected that the thermometer cannot be applied within a vacuum without the employment of some transparent covering, and that, consequently, the energy of the rays will suffer considerable loss before reaching the bulb. This objection is readily met by applying a thin lens of about 50 ins. focus, inserted at such a distance from the bulb that the gain effected by concentrating the rays will exactly balance the loss of calorific energy attending their passage through the lens. It is evident, however, that a plane crystal might be employed in place of the lens, provided its absorptive power were known. I have accordingly constructed an apparatus for measuring the loss of calorific energy attending the passage of the sun's rays through plane crystals of adequate thickness to resist the atmospheric pressure when the air is withdrawn from the interior chamber of the instrument. It should be mentioned that many of the observations recorded in this work have been made with an actinometer provided with a plane crystal, the absorptive power of which amounts to 0.066. Very little trouble has been experienced in recording observations made with this instrument, the indicated differential temperatures having simply been multiplied by the coefficient 1.066.

Careful inspection of our illustration, together with the foregoing explanations regarding the nature of the lens and its substitute, and the object of applying the recording thermometer within a vacuum, render a minute description of the detail of the device unnecessary. Like the solar calorimeter, Plate 10, particularly described in Chapter V., the actinometer is attached to a table, the face of which is kept perpendicular to the sun during observations. It is also provided with a graduated arc and stationary index, similar to those applied to the solar calorimeter, by means of which the sun's zenith distance may be ascertained at every instant. The chamber containing the bulb of the thermometer is 4¾ ins. in diameter, plated with polished nickel and surrounded with a double casing, through which a current of water is circulated by means precisely like those employed in the solar calorimeter, the vacuum being also produced in a similar manner, and flexible tubes employed for connecting the instrument with the stationary pump. The cistern which supplies the circulating water is kept at a constant temperature of 60° F., and, in order to secure perfect accuracy, the thermometer employed for regulating this temperature is so applied that the return current from the actinometer to the cistern circulates round its bulb. A thin metallic screen of annular form, supported by four columns, and plated with silver, protects the instrument from the sun's radiant heat, for the purpose of economizing the cooling medium required to keep the circulating water at the proper temperature. The opening in the screen corresponds with the size of the lens. The bulb of the thermometer is 3 ins. in length, in order to expose a relatively large surface to the action of the solar rays; the proportion of heating surface to the contents of the bulb being thus much greater than in ordinary thermometers. The upper half of the bulb is coated with lamp-black, the lower half being exposed to the action of the reflected rays from the bottom of the chamber, in such a manner that the radiation of this lower bright half of the bulb is neutralized by reflected heat. Much pains has been bestowed in order to attain this desirable object. Before making an observation with the actinometer, the vacuum gauge should be inspected, and the water from the cistern be permitted to run freely through the casing for several minutes until the temperature of the return current and that indicated by the enclosed thermometer correspond. The observatory being then turned to the sun, and the declination table on which the actinometer stands adjusted to the proper angle, the cover over the lens should be removed. The height of the mercurial column of the enclosed thermometer will then, in due time, indicate with absolute certainty the intensity of the sun's radiant heat, independent of atmospheric temperature and other disturbing causes which render the indications of solar intensity by common thermometers mere approximations. It will be evident that, since the instrument is kept at a constant temperature of 60°, it continually radiates heat of that intensity towards the bulb of the enclosed thermometer; hence the *zero* of the thermometric scale of the actinometer will mark 60° above Fahrenheit's zero. Obviously, the point reached by the mercurial column of the enclosed thermometer above the stated zero on exposure to the sun's rays can only be attained in virtue of the power of unaided solar radiation. In support of this assertion it may be well to repeat the explanation already given, namely, that the bulb is surrounded by ether alone, freed from all disturbing influences of ponderous matter, and that the heat which determines the zero of the actinometer is supplied by radiation from the instrument itself. The important question of actual intensity with reference to the adopted "absolute" zero will be discussed in Chapters IX. and XVI.; but it may be well to state in this place that the actinometer merely shows the thermometric interval of solar intensity on Fahrenheit's scale, without reference to the position of that interval on a scale which commences at the accepted "absolute zero." I regard this absolute zero, however, as an *ignis-fatuus*, retreating as fast as we approach it.

It should be observed that all the actinometric observations contained in this work have been made in lat. 40 deg. 42 min., thus only 17 deg. 12 min. from the tropic of Cancer. The depth of atmosphere so near the tropics being, at midsummer, only 0.047 greater than on the ecliptic, while the sun's zenith distance on lat. 40 deg. 42 min. during the winter solstice is only 2 deg. 18 min. less than at the pole at midsummer, I have been enabled to determine the maximum intensity of solar radiation for all latitudes from the equator to the pole. The diagram represented on Pl. 9, Fig. 1, shows the relations of atmospheric depth and solar intensity for each degree of zenith distance from the vertical to the 75th degree. A brief description will suffice to render this diagram readily understood. The ordinates between the curve *e a* and the base line *f g* exhibit the true proportions of the depth of the atmosphere penetrated by the rays from the vertical to 75 deg. zenith distance; while the ordinates of the curve *c a* indicate the relative intensity of the sun's radiant heat at the summer solstice for each degree of the sun's zenith distance from the vertical to 75 deg. The straight line *b a* is the tangent of the curves *e a* and *c a*. It will be seen by closely examining these curves, and the ordinates resting on the base line *f g* (comparing the same with the figures in the tables of this chapter), that the intensities of solar radiation vary nearly in the inverse ratio of the cube roots of the atmospheric depth for all zenith distances not exceeding 75 deg. The ordinates between the irregular line *d d d* and the base line *f g* show the solar intensity for each degree of zenith distance from 23 deg. to 75 deg., ascertained by actinometric observation during a day in the month of August when the sun was obscured by *cirri* of average density. With reference to the solar engine this irregular line *d d d* possesses great interest, as it indicates the available solar energy, for mechanical purposes, during a day when the sun is partially obscured.

The engineer will regard this diagram as a solar indicator-card, the space below the line *d d d* representing the available power, while the space contained between that line and the curve *c a* indicates the loss. For the purpose of elucidation, the North Pole, together with the cities of Edinburgh, London, Paris, and New York, have been introduced on this diagram, their positions having reference solely to the depth of atmosphere and solar intensity during the summer solstice. The annexed Tables A, B, and C show the relative depth of atmosphere and maximum solar intensity at midsummer for each degree of the sun's zenith distance from the vertical to 75 deg.

Referring to the second part of the diagram, it will be found that Fig. 2 contains a delineation of the graduated plate specially mentioned in Chapter V. This plate is furnished with a movable radial index, to enable the observer to ascertain quickly the depth of atmosphere corresponding with observed zenith distances. The graduated plate is constructed to a scale of 24 miles to the inch, the curvature of the earth's surface and the atmospheric boundary (supposed to extend 42 miles above the earth) being accurately laid down according to the said scale. The vertical depth of the atmosphere, it will be seen, has been divided into 100 equal parts, the same graduation having been introduced on the movable index. Accordingly, by placing this index at angles corresponding with the observed zenith distance, the intersection of its upper edge with the top line of the atmosphere will show the proportion of diagonal and vertical

A

TABLE SHOWING THE INTENSITY OF SOLAR RADIATION AND THE ATMOSPHERIC DEPTH FOR GIVEN ZENITH DISTANCES.

Zenith distance.	Atmospheric depth.	Increment of atmospheric depth.	Maximum intensity.		Observed intensity during a partially cloudy day.	
Deg.	*Relative.*	*Relative.*	*° Fah.*	*° Cent.*	*° Fah.*	*° Cent.*
0	1.000	0.000	67.20	37.33	...	...
1	1.000	0.000	67.19	37.33	...	...
2	1.000	0.000	67.18	37.32	...	...
3	1.001	0.001	67.16	37.31	...	...
4	1.002	0.002	67.14	37.30	...	...
5	1.003	0.003	67.11	37.28	...	...
6	1.005	0.005	67.07	37.26	...	...
7	1.007	0.007	67.02	37.24	...	...
8	1.010	0.010	66.97	37.21	...	...
9	1.013	0.013	66.91	37.17	...	...
10	1.016	0.016	66.84	37.13	...	...
11	1.019	0.019	66.77	37.09	...	...
12	1.023	0.023	66.69	37.05	...	...
13	1.027	0.027	66.60	37.00	...	...
14	1.031	0.031	66.51	36.95	...	...
15	1.036	0.036	66.41	36.89	...	...
16	1.041	0.041	66.30	36.83	...	...
17	1.046	0.046	66.19	36.77	...	...
18	1.051	0.051	66.07	36.70	...	...
19	1.057	0.057	65.94	36.63	...	...
20	1.063	0.063	65.80	36.56	...	...
21	1.070	0.070	65.66	36.48	...	...
22	1.077	0.077	65.51	36.40	...	...
23	1.085	0.085	65.36	36.31	59.5	33.05
24	1.093	0.093	65.20	36.22	58.4	32.44
25	1.102	0.102	65.03	36.13	57.7	32.04

B

Table showing the Intensity of Solar Radiation and the Atmospheric Depth for given Zenith Distances.

Zenith distance.	Atmospheric depth.	Increment of atmospheric depth.	Maximum intensity.		Observed intensity during a partially cloudy day.	
Deg.	*Relative.*	*Relative.*	*° Fah.*	*° Cent.*	*° Fah.*	*° Cent.*
26	1.111	0.111	64.85	36.03	58.4	32.44
27	1.121	0.121	64.67	35.93	57.5	31.95
28	1.132	0.132	64.48	35.82	57.7	32.05
29	1.141	0.141	64.29	35.72	57.7	32.05
30	1.152	0.152	64.08	35.60	57.8	32.11
31	1.164	0.164	63.87	35.49	56.9	31.61
32	1.176	0.176	63.66	35.36	56.9	31.61
33	1.189	0.189	63.43	35.24	56.7	31.50
34	1.203	0.203	63.20	35.11	57.0	31.66
35	1.217	0.217	62.96	34.98	56.8	31.55
36	1.232	0.232	62.72	34.84	56.4	31.33
37	1.248	0.248	62.47	34.70	56.2	31.22
38	1.265	0.265	62.21	34.56	55.8	31.00
39	1.283	0.283	61.94	34.21	56.1	31.17
40	1.302	0.302	61.67	34.26	55.0	30.55
41	1.322	0.322	61.39	34.11	54.8	30.44
42	1.342	0.342	61.10	33.95	54.8	30.44
43	1.363	0.363	60.81	33.78	54.9	30.50
44	1.384	0.384	60.51	33.62	54.6	30.34
45	1.406	0.406	60.20	33.45	54.7	30.40
46	1.431	0.431	59.88	33.27	54.5	30.28
47	1.457	0.457	59.56	33.09	54.4	30.22
48	1.485	0.485	59.23	32.91	53.4	29.66
49	1.514	0.514	58.89	32.72	53.0	29.44
50	1.545	0.545	58.54	32.52	53.2	29.55

C

TABLE SHOWING THE INTENSITY OF SOLAR RADIATION AND THE ATMOSPHERIC DEPTH FOR GIVEN ZENITH DISTANCES.

Zenith distance.	Atmospheric depth.	Increment of atmospheric depth.	Maximum intensity.		Observed intensity during a partially cloudy day.	
Deg.	*Relative.*	*Relative.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
51	1.577	0.577	58.18	32.32	50.7	28.16
52	1.612	0.612	57.81	32.12	50.6	28.11
53	1.648	0.648	57.44	31.91	45.8	25.44
54	1.686	0.686	57.05	31.70	45.4	25.22
55	1.726	0.726	56.66	31.48	44.6	24.77
56	1.769	0.796	56.25	31.25	44.6	24.77
57	1.815	0.815	55.82	31.02	47.0	26.11
58	1.864	0.864	55.39	30.77	48.0	26.66
59	1.916	0.916	54.94	30.52	47.3	26.27
60	1.970	0.970	54.47	30.26	47.4	26.32
61	2.037	1.037	53.99	29.99	46.4	25.77
62	2.098	1.098	53.48	29.72	46.8	26.00
63	2.164	1.164	52.96	29.42	46.8	26.00
64	2.235	1.235	52.41	29.12	46.4	25.77
65	2.312	1.312	51.85	28.81	46.1	25.50
66	2.398	1.398	51.26	28.48	45.0	25.00
67	2.490	1.490	50.63	28.13	42.6	23.66
68	2.591	1.591	49.96	27.76	43.1	23.94
69	2.701	1.701	49.24	27.36	43.2	24.00
70	2.821	1.821	48.43	26.93	42.8	23.77
71	2.952	1.952	47.67	26.46	41.9	23.27
72	3.097	2.097	46.72	25.96	40.4	22.44
73	3.255	2.255	45.72	25.40	33.5	18.61
74	3.428	2.428	44.61	24.79	36.3	20.16
75	3.624	2.624	43.39	24.11	32.4	18.00

atmospheric depth. The important relations of solar intensity, zenith distance, atmospheric depth, and latitude, being exhibited by the diagram under consideration, let us now consider the mode adopted in constructing the same.

The data indispensable in constructing the curve *c a*, the ordinates of which represent the maximum solar intensity for given zenith distances when the earth is in aphelion, first claim our attention. It will be perceived, on reflection, that, owing to the varying intensity resulting from change of distance between the sun and the earth, the temperature produced by solar radiation varies from day to day with the altered position of the earth in its orbit. Consequently, observed deficiency of solar intensity at any given zenith distance does not always furnish, as supposed by certain meteorologists, a correct indication of the amount of absorption caused by the presence of vapor in the atmosphere. Obviously, the observed deficiency of intensity may result partially from the earth's proximity to the aphelion. It will be seen by reference to Chapter IV. that for equal zenith distance a diminution of temperature of 4°.66 F. takes place during the summer solstice, compared with the intensity of the radiant heat at midwinter. Consequently, if we omit to make a proper allowance for the difference of intensity resulting from the sun's distance at the time of observation, no satisfactory record can be produced. It is hardly necessary to point out that, unless we establish some fixed position of the earth in its orbit, as a zero, it will be impossible to construct tables of varying solar intensity capable of being employed as a means of correction.

I have accordingly adopted the *aphelion* as the controlling zero, all my tables relating to this subject having reference to *maximum solar intensity when the earth is furthest from the sun.* The reader will find the question of solar distance fully discussed in the next chapter.

Regarding the observations which have furnished the data on which our diagram has been constructed and the annexed tables calculated, it will be necessary to state, for the information of those who are not familiar with the subject, that observations of maximum solar intensity should be continued during a series of years. It sometimes happens that an entire season elapses without a single opportunity for a satisfactory observation presenting itself. Records of solar observations are therefore exceedingly irregular; during some seasons reliable observations may be made from day to day; then again a considerable period intervenes during which the work must be wholly suspended. Indeed, the difficulties inseparable from investigations of *maximum* solar energy can hardly be exaggerated. A complete record requires that the sun should be *perfectly clear* while we observe the temperature produced by the rays for each degree of the sun's zenith distance, upon each degree of latitude, for each day in the year. Now, observations continued during a century would not suffice to produce such a record; hence I have had recourse to the graphic method, projecting from a base line drawn on a large diagram ordinates representing the maximum intensity shown by each satisfactory observation. The position of the ordinates thus projected, it is scarcely necessary to observe, depends on the zenith distance under which the respective observations are made, while their length will be determined by the observed maximum temperature, to be marked on the diagram in accordance with a fixed scale. As the recorded investigations extend from the vertical to 75 deg. zenith distance, it will be evident that the base line should be divided into 75 equal parts, each division representing one degree of zenith distance. For each successful observation an ordinate will be projected at a position on the base corresponding with the zenith distance under which the successful observation has been made; the length of the ordinate being marked off according to the fixed scale mentioned. It will be perceived, therefore, that, at the termination of a series of observations, the base line on the diagram, with its 75 equal divisions, representing degrees of zenith distance, subdivided into minutes, will be studded with a number of perpendicular lines of unequal length, placed at irregular distances. In accordance with the rules of the graphic system, the terminations of the several irregularly-spaced perpendicular lines will then be connected by a curved line which, if uniform and nearly parabolic when completed, proves that the observations have been accurate. Should it, however, contain breaks, or should its curvature not be gradually increasing with increased zenith distance, in accordance with an ascending series, fresh observations must be made at zenith distances embracing the defective portions. Again, it may happen that in connecting the terminations of the ordinates considerable gaps present themselves; in other words, that want of observation occurs for several succeeding degrees of zenith distance. These gaps must be filled by fresh observations, unless the completed parts of the curve on both sides of the gap, when extended over it, meet in such a manner as to produce a consistent curve. Our small diagram (Plate 9) has been copied from a large diagram constructed in accordance with the foregoing explanation of the plan adopted. The scale employed in laying down the observed temperatures, viz., marking off the length of the ordinates, being sufficiently large to admit of showing fractions of a degree of Fahrenheit, the temperatures entered in the Tables A, B, and C, for given zenith distances, will be found very precise. In view of the foregoing explanation of the procedure resorted to, the reader need not be reminded that the temperatures appearing in the tables have not all been determined by actual observation. Agreeably to the graphic system, several of these temperatures have been determined by *measuring* the height of the ordinates in the diagram. It needs no demonstration, however, to prove that intensities ascertained by measurement, in the manner pointed out, are as reliable as if ascertained directly by the actinometer, provided the curve be perfect which connects the termination of the ordinates obtained by actual observation. It should be stated that, during a period embracing many years, but few favorable opportunities have been neglected of verifying the correctness of the preceding tables. No material discrepancies having been observed, future investigations are not likely to lead to any important modifications of these tables.

Possibly observations conducted on the table-lands of India might show somewhat higher intensities for given zenith distances; but tables modified agreeably to such observations would not be as useful for meteorological investigations concerning the effects of solar intensity in America and Europe as those here presented. It may be mentioned that it was my original intention to extend the observations of zenith distance and solar intensity from the 75th deg. to the horizon; but experience has shown that both the eastern and western horizon, viewed from my present observatory, are so seldom free from clouds and haze that too long a time would elapse before the investigations of atmospheric absorption at extreme zenith distance could be completed. It will be found, however, on mature reflection, that the most important meteorological phenomena connected with solar heat are confined within the vertical segment of 150 deg., which embraces the result of my actinometric observations.

With reference to the maximum intensity of solar radiation on each degree of latitude, it will be evident that, since we possess an accurate knowledge of the relation of zenith distance and temperature, we can readily determine the maximum intensity for different latitudes during the summer solstice. For instance, we know, by referring to the preceding Table B, that, when the earth is in aphelion and the zenith distance is 43 deg., the temperature produced by solar radiation is 60°.81 F.; hence we know that this temperature marks maximum solar intensity on the Arctic Circle, the latter being 43 deg. from the ecliptic at the summer sol-

TABLE D, SHOWING THE TEMPERATURE PRODUCED BY SOLAR RADIATION AT NOON FOR EACH DEGREE OF LATITUDE WHEN THE EARTH IS IN APHELION. NORTHERN HEMISPHERE.

	Lat.	Solar intensity at noon.		Lat.	Solar intensity at noon.	
	Deg.	*° Fah.*	*° Cent.*	*Deg.*	*° Fah.*	*° Cent.*
Equator........ ...	0	65.30	36.28	24	67.20	37.33
	1	65.45	36.36	25	67.19	37.32
	2	65.60	36.44	26	67.18	37.32
	3	65.75	36.52	27	67.17	37.31
	4	65.89	36.60	28	67.14	37.30
	5	66.02	36.68	29	67.10	37.28
	6	66.15	36.75	30	67.05	37.25
	7	66.27	36.82	31	66.99	37.21
	8	66.39	36.88	32	66.93	37.18
	9	66.49	36.94	33	66.87	37.15
	10	66.58	36.99	34	66.80	37.11
	11	66.66	37.03	35	66.73	37.07
	12	66.73	37.07	36	66.66	37.03
	13	66.80	37.11	37	66.58	36.99
	14	66.87	37.15	38	66.49	36.94
	15	66.93	37.18	39	66.39	36.88
	16	66.99	37.21	40	66.27	36.81
	17	67.05	37.25	41	66.15	36.75
	18	67.10	37.28	42	66.02	36.68
	19	67.14	37.30	43	65.89	36.60
	20	67.17	37.31	44	65.75	36.52
	21	67.18	37.32	45	65.60	36.44
	22	67.19	37.32	46	65.45	36.36
	23	67.20	37.33	47	65.30	36.28
Tropic of Cancer	23.30	67.20	37.33	48	65.13	36.18

TABLE E, SHOWING THE TEMPERATURE PRODUCED BY SOLAR RADIATION AT NOON FOR EACH DEGREE OF LATITUDE WHEN THE EARTH IS IN APHELION. NORTHERN HEMISPHERE.

	Lat.	Solar intensity at noon.		Lat.	Solar intensity at noon.	
	Deg.	° Fah.	° Cent.	Deg.	° Fah.	° Cent.
	49	64.95	36.08	69	59.76	33.20
	50	64.77	35.98	70	59.42	33.01
	51	64.58	35.88	71	59.06	32.81
Greenwich.........	51.28	64.48	35.82	72	58.69	32.61
	52	64.38	35.77	73	58.31	32.39
	53	64.17	35.65	74	57.92	32.18
	54	63.96	35.53	75	57.52	31.95
	55	63.74	35.41	76	57.10	31.72
	56	63.51	35.28	77	56.67	31.48
	57	63.28	35.15	78	56.24	31.24
	58	63.04	35.02	79	55.79	30.99
	59	62.79	34.88	80	55.32	30.73
	60	62.53	34.74	81	54.84	30.46
	61	62.25	34.58	82	54.35	30.19
	62	61.96	34.42	83	53.84	29.91
	63	61.65	34.25	84	53.32	29.62
	64	61.34	34.08	85	52.78	29.32
	65	61.03	33.91	86	52.23	29.02
	66	60.72	33.73	87	51.68	28.71
Arctic Circle.....	66.30	60.57	33.65	88	51.11	28.39
	67	60.41	33.56	89	50.52	28.07
	68	60.09	33.38	90	49.91	27.73

stice. Again, the North Pole being 66 deg. 30 min. from the ecliptic at the same time, we learn, by referring to Table C, that the maximum solar intensity at the said pole will be 50°.95 F., that being the temperature produced by solar radiation when the zenith distance is 66 deg. 30 min.

The Tables D and E contain the maximum solar intensities for all latitudes from the Equator to the North Pole, determined agreeably to the foregoing explanation. The difference of atmospheric density towards the pole calls for a trifling correction of the temperature entered in the table; but the data not being sufficiently well known, I have deemed it best to present the theoretical temperatures without correction.

As far as ascertained by means of the actinometer, there is an appreciable difference in the sun's energy for corresponding zenith distances early in the morning and late in the afternoon, which cannot be traced to any adequate physical cause. I have accordingly attempted to explain the discrepancy on the ground that the orbital motion of the earth occasions a very considerable advance towards, and retreat from, the solar wave early A.M. and late P.M. The subject will be readily understood by reference to Fig. 3, which represents a section of the earth through the plane of the ecliptic, the line *d e* indicating the orbit, and the straight arrow the earth's course, while the curved arrow shows the direction of rotation; *a b c*, etc., represent the sun's rays, the orbital velocity during a definite period being represented by *f g* and *k l*. Let us assume that the latitude of the point *f*, on the earth's surface, is such that the prolongation of the ray *a h* to *g* makes *h g* three times longer than *f g*. It will now be evident that the ray *a h*, which has been arrested at *h*, must, while the earth advances from *f* to *g*, continue its course at a rate three times greater than the earth's orbital velocity, in order to reach *g* simultaneously with *f*. Assuming the mean distance of the earth from the sun to be 91,430,000 miles, the orbital velocity will be 96,120 ft. per second; hence the ray *a h*, to keep up with the retreating western quarter of the globe, must move at the rate of 288,360 ft. per second. The advancing eastern quarter obviously imparts a retrograde movement to the solar wave, consequently the ray *m l* will, on grounds already set forth, be pushed towards the sun at the rate of 288,360 ft. per second. We have thus established a difference of advancing and retreating velocity exceeding 600,000 ft. per second for the lower altitudes, which unquestionably interferes with the regularity of the solar wave, and thereby tends to disturb the uniformity of the intensity of the sun's radiant heat towards evening. Meteorologists will account

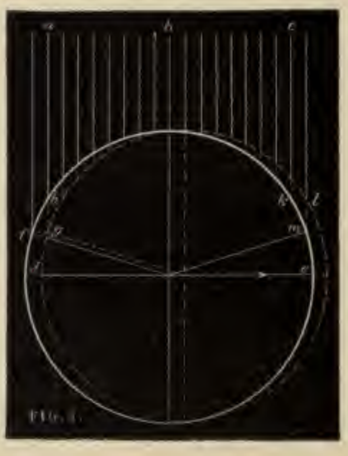


FIG. [illegible]

for the observed diminution by pointing to the fact that during sunshine—without which the actinometer cannot be used—the atmosphere, in most localities, gradually becomes charged with vapor as the day advances; and that dust and other light dry particles are carried up into the atmosphere by the ascending heated current of air, thus obstructing the sun's rays. These plausible reasons lose their force if we consider that, during the season most favorable for actinometric observations, the vapors are held fast within icy boundaries, and that the dust is buried under the snow.

The extraordinary velocity of light—nearly 1,700 times greater than the velocity shown by the foregoing demonstration—will be urged as a reason why the disturbance of the solar wave could not be practically appreciable. This objection cannot be deemed valid unless it can be shown that the dynamic energy imparted by solar heat is not partially the result of arresting the motion of the rays. The following facts connected with the subject demand serious consideration. Owing to the orbital motion of the earth, the lens of a solar calorimeter, while exposed to the radiant heat, sweeps across the path of the sun's rays at the rate of 96,120 ft. per second; hence the fluid contained within the instrument receives the energy of a countless number of rays following each other in an inconceivably rapid succession.

Pouillet, having ascertained the number of thermal units imparted to the water in his pyrheliometer of 3.93 ins. diameter, imagined that he had measured only the energy of the rays contained in a pencil of 11.9 square inches section;

whereas, in reality, he had, at the end of his experiment of five minutes' duration, subjected his instrument to the action of the entire number of rays contained in a passing pencil or sunbeam, the section of which we ascertain by multiplying the orbital advance of the earth during five minutes, 28,836,000 ft., by the diameter of the pyrheliometer, 0.305 ft.

CHAPTER IV.

PERIODIC VARIATION OF THE INTENSITY OF SOLAR RADIATION.

The preceding chapter has made the reader familiar with the construction of the actinometer, and with the leading results of the investigations conducted by means of that instrument, relating to the variations of temperature consequent on the sun's varying zenith distance. Let us now consider the variation of solar intensity consequent on the varying distance between the sun and the earth from day to day. Meteorologists, in recording the temperature produced by solar radiation, have hitherto taken no notice of the position of the earth in its orbit at the time of making their observations. At the commencement of my investigation of the mechanical properties of solar heat, I committed the same oversight; but finding that the result of my observations frequently presented discrepancies that could not be accounted for on the ground of different zenith distance and presence of vapor in the atmosphere, I was led to examine systematically and very carefully the effect on solar intensity produced by the variation of the sun's distance from the earth. Sir John Herschel, in "Outlines of Astronomy," says, regarding the effect of the sun's varying distance: "The angular velocity of the earth in its orbit is not uniform, but varies in the inverse ratio of the square of the sun's distance—that is, in the same precise ratio as his heating power. The momentary supply of heat, then, received by the earth in every point of its orbit varies exactly as the momentary increase of its longitude; from which it obviously follows that equal amounts of heat are received from the sun in passing over equal angles round it, in whatever part of the ellipse those angles may be situated." As regards the temperature developed by the sun at different periods, the author of the "Outlines of Astronomy" calculates that there is a difference of one-fifteenth; but, in judging of the effect of this difference on the temperature produced by solar radiation, he says: "We have to consider as our unit, not the number of degrees above a purely arbitrary zero point (such as the freezing point of water or the zero of Fahrenheit's scale) on which a thermometer stands on a hot summer day, as compared with a cold winter one, but the thermometric interval between the temperatures it indicates in the two cases, and that it would indicate did the sun not exist, which there is good reason to believe would be at least as low as 239° *below zero* of Fahrenheit. And as a temperature of 100° F. *above* zero is no uncommon one in a fair shade exposure under a sun nearly vertical, we have to take one-fifteenth of the sum of these intervals (339°), or 23° F., as the least variation of temperature under such circumstances which can reasonably be attributed to the actual variation of the sun's distance." Adopting the stated calculation, without reflecting on the erroneous grounds upon which it rests, I introduced corrections of the observed temperatures according to the supposed augmentation of radiant intensity, viz., 23° F. when the earth is in perihelion. The application of these corrections proved that the discrepancies in my records, before adverted to, amounted to only one-fifth of that which, agreeably to Sir John Herschel's theory, ought to have appeared. Fully convinced, however, that the difference of solar intensity resulting from the variation of distance between the sun and the earth was the true cause of the irregularity and breaks in the curve which I had constructed according to the observed temperatures, I availed myself of every favorable opportunity to ascertain the maximum intensity produced *during the summer and winter solstices.* It will be well to state, for the information of those who have not paid special attention to the subject, that *mean results* of observation are inadmissible in records intended to establish solar energy. The superior intensity ascertained at a single observation will set aside the result of previous observations continued for many years. It will be well also to correct the prevailing erroneous supposition that solar intensity cannot be ascertained during the summer months, owing to vapor in the atmosphere. There are short intervals at all seasons when polar winds prevail, during which the sun is perfectly clear. Those who have paid close attention to this matter will say that they have seen as bright a solar disc in August as in

January. This fact has been repeatedly verified by the indications of my solar calorimeter, an unerring test, since it records the number of units of heat developed by the sun in a given time on a given area. Obviously the smallest increase of the absorptive power of the atmosphere will be detected by this method. It will be perceived from the foregoing remarks that the records of solar intensity connected with the solstices, kept during a series of years, possess no material interest regarding the question at issue—namely, the true maximum difference of intensity of solar radiation when the earth is in aphelion and in perihelion. The reader, therefore, instead of being called upon to examine an extended record of observations, will simply have his attention directed to the fact that January 7, 1871, the earth being then, of course, very near perihelion, the temperature produced by solar radiation, indicated by the actinometer, reached 57°.25 F. at noon; the zenith distance being 63 deg. 15 min. Referring to the table of temperatures for given zenith distances (Chap. III.), it will be seen that the temperature produced by solar radiation when the earth is in *aphelion* is 52°.84 F. at a zenith distance of 63 deg. 15 min.; consequently, an augmentation of solar intensity of 57.25 – 52.84 = 4°.41 F. takes place when the earth is in perihelion. The result of my actinometric observations, continued through a series of years, recorded in Chap. III., shows that when the earth is in aphelion the maximum solar intensity on the ecliptic is 67°.20 F. The law of inverse squares being true for spherical radiators and for radiating circular discs subtending small angles, the stated intensity of solar radiation when the earth is in aphelion enables us to determine with absolute certainty what temperature will be produced when the earth is in perihelion. The ratio of the earth's distance from the sun at the two opposite points of the orbit, in aphelion and in perihelion, being 218.1 : 210.9, while the temperature produced by solar radiation during the summer solstice, as stated, is 67°.2 F., the radiant intensity during the winter solstice will be $\frac{218.1^2 \times 67.2}{210.9^2} = 71°.86$ F. The temperature produced by solar radiation at the surface of the earth will thus, agreeably to the laws which govern the transmission of radiant heat, be $71.86 - 67.20 = 4°.66$ F. higher when the earth is nearest the sun than when furthest from it. The actinometric observation, Jan. 7, 1871, having established a differential temperature of 4°.41 F., it will thus be seen that a discrepancy exists amounting to 0°.25 F. That is, the observed solar intensity, 57°.25, Jan. 7, was 0°.25 less than the calculated intensity. A closer agreement between computed and observed increment of solar intensity consequent on the eccentricity of the earth's orbit could not reasonably be expected. Besides, the record shows that, although the sun was exceptionally clear on the day mentioned, there was a perceptible mist round the solar disc, indicating that the full radiant power was not transmitted to the actinometer. In constructing the tables appended to this chapter I have, therefore, based my calculations of diurnal variation of solar intensity on the differential temperature, 4°.66 F., determined by computations founded on the distance of the earth from the sun at the opposite points of the orbit. Referring to the tables, it will be seen that the maximum temperature produced by solar radiation has been entered for each day throughout the year; also the increment of solar intensity for each day, consequent on the varying distance of the sun. The principal object of the tables being that of enabling the meteorologist to ascertain to what extent the result of his observations of solar radiation is influenced by the distance of the sun, it will be evident that some zero having a fixed relation to the position of the earth in its orbit should be adopted, in order to render comparisons possible. Accordingly, the appended tables have reference to the maximum temperature produced by solar radiation when the earth is in *aphelion*. The utility of adopting a fixed zero will be seen by the following explanation: Suppose that we find by observation, during bright sunshine, January 20, that, under a zenith distance of 68 deg., the actinometer indicates 54°.5 F. Suppose, also, that our records of solar intensity during summer show that, June 15, the actinometer indicated 49°.9 F. at equal zenith distance—viz., 68 deg. Leaving the influence of solar distance out of sight, the inference would be that the diminished intensity of $54.5 - 49.9 = 4°.6$ F., observed June 15, was owing to the presence of vapor in the atmosphere. Secchi and others, who suppose that the absorptive power of the atmosphere called forth by vapor prevents the full development of solar radiation at all times during summer, would not hesitate to ascribe the observed diminution of radiant intensity to that cause. But a glance at our table at once discloses the true cause of the observed difference of solar intensity under equal zenith distance in January and in June. Consulting the table for January, and running the eye down the column headed "Increment," the temperature 4°.6 will be found opposite the date 20th in the first column. Accordingly, the feebleness of solar radiation observed in the middle of June, instead of being caused by atmospheric absorption, is solely due to the *increased distance of the earth from the sun.* It should be observed that the assumed temperature of 49°.9 F., at a zenith distance of 68 deg. in the middle of June, is not imaginary, having frequently been observed during my investigations of solar energy. Again, temperatures exceeding 54° F. have been observed during mid-winter at a zenith distance of 68 deg.

It will be proper to remind meteorologists accustomed to observe the intensity of solar radiation, hence familiar with the extraordinary discrepancy of observations made with ordinary "solar radiation thermometers," that the invariably consistent indications, and the freedom from conflicting results, in my actinometric observations of solar energy, are chiefly due to the fact that the bulb of the recording thermometer is enclosed within an exhausted vessel, maintained at a constant temperature of 60° F. during observations. Hence, whether the investigation be conducted in calms or high winds, or whether the thermometer marks 100° in the shade or the temperature of the air be below zero, no material error is possible. This fact merits special consideration on the part of those who have questioned the possibility of determining *practically* to what degree the temperature produced by solar radiation is increased when the earth is in perihelion. And those who have adopted Herschel's conclusion, that "23° Fahrenheit is the least variation of temperature which can reasonably be attributed to the actual variation of the sun's distance," will do well to contrast the reasoning of the great astronomer with the reasoning which assigns 5° Fahrenheit as the utmost increment of solar intensity in the southern hemisphere, consequent on the proximity of the luminary during our midwinter.

Regarding the construction of the appended tables of solar intensity, the following explanation and recapitulation will suffice: Having determined the maximum solar intensity when the earth is in aphelion, in accordance with the data furnished in Chap. III., the maximum intensity in perihelion was determined by computation in the manner already pointed out. The result, as we have seen, has been fully corroborated by actinometric observation. The maximum increment of temperature produced by solar radiation when the earth is in perihelion having been fixed at 4°.66 F., the increment of temperature for each day throughout the year was determined by inverting the ratio of the square of the sun's distance from day to day.

We have already pointed out that investigations of solar intensity which do not take cognizance of the influence of the sun's distance are of no value. Obviously, the difference of temperature produced by solar radiation furnishes an infallible index of atmospheric absorption, provided we make due allowance for the sun's zenith distance and the *position of the earth in its orbit* at the time of making our observation. But, unless such allowance be made, the inference we draw from the indicated temperatures will prove wholly erroneous.

Respecting the mode of applying the tables, it will be evident, on reflection, that, if we desire to ascertain whether vapors are present in the atmosphere, the temperature contained in the column headed "Increment," for the day on which the observation is made, should be deducted from the temperature indicated by the actinometer. Suppose, for instance, that the indicated solar intensity, Aug. 26, is 58° F. at a zenith distance of 40 deg. Deducting from 58° the increment of temperature entered in the table for Aug. 26—viz., 0°.96—consequent on the diminished distance from the sun, we obtain 58 − 0.96 = 57°.04. Now, if we consult the table of temperatures for given zenith distance (see page 62, Chap. III.), it will be found that the maximum solar temperature for a zenith distance of 40 deg. should be 61°.67. Our observation of Aug. 26, therefore, shows that the vapors contained in the atmosphere have absorbed 61.67 − 57.04 = 4°.63 of the sun's radiant heat. The advantage of this positive mode of ascertaining the absorptive power—*i.e.*, the presence of vapor in the atmosphere—meteorologists cannot fail to appreciate.

The close agreement between the computed and observed increment of the temperature produced by solar radiation when the earth is in perihelion, before adverted to, calls for special notice in this place, since it proves the correctness of the actinometric observations recorded in Chap. III., on which our determination of the varying intensity of the sun's radiant heat is based. It will be evident that, if our determination of maximum solar intensity when the earth is in aphelion (based solely on our observations) were incorrect, the infallible test of applying the law of inverse squares would at once expose the error. Now, this test has been applied; we have inverted the squares of the relative aphelion and perihelion distance of the earth, and we find that in the latter position an increment of 4°.66 F. results from the proximity of the sun. Our *observations* show an increment of 4°.41 difference = 0°.25 Fahrenheit.

TABLE SHOWING THE MAXIMUM INTENSITY OF SOLAR RADIATION ON THE ECLIPTIC.

Date.	*JANUARY.*				*FEBRUARY.*			
	Maximum.		Increment.		Maximum.		Increment.	
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
1	71.94	39.97	4.66	2.59	71.59	39.77	4.31	2.39
2	71.94	39.97	4.66	2.59	71.57	39.76	4.29	2.38
3	71.94	39.97	4.66	2.59	71.54	39.74	4.26	2.36
4	71.93	39.97	4.65	2.59	71.52	39.73	4.24	2.35
5	71.93	39.97	4.65	2.59	71.50	39.72	4.22	2.34
6	71.92	39.96	4.64	2.58	71.47	39.71	4.19	2.33
7	71.92	39.96	4.64	2.58	71.45	39.69	4.17	2.31
8	71.91	39.95	4.63	2.57	71.42	39.68	4.14	2.30
9	71.91	39.95	4.63	2.57	71.40	39.67	4.12	2.29
10	71.90	39.94	4.62	2.56	71.38	39.65	4.10	2.27
11	71.90	39.94	4.62	2.56	71.35	39.64	4.07	2.26
12	71.89	39.93	4.61	2.55	71.32	39.62	4.04	2.24
13	71.88	39.93	4.60	2.55	71.29	39.60	4.01	2.22
14	71.87	39.92	4.59	2.54	71.27	39.59	3.99	2.21
15	71.86	39.92	4.58	2.54	71.24	39.58	3.96	2.20
16	71.85	39.91	4.57	2.53	71.20	39.56	3.92	2.18
17	71.84	39.91	4.56	2.53	71.17	39.54	3.89	2.16
18	71.82	39.90	4.54	2.52	71.14	39.52	3.86	2.14
19	71.81	39.90	4.53	2.52	71.11	39.50	3.83	2.12
20	71.80	39.89	4.52	2.51	71.08	39.49	3.80	2.11
21	71.78	39.88	4.50	2.50	71.05	39.47	3.77	2.09
22	71.77	39.87	4.49	2.49	71.02	39.45	3.74	2.07
23	71.76	39.87	4.48	2.48	70.98	39.43	3.70	2.05
24	71.74	39.86	4.46	2.47	70.95	39.42	3.67	2.04
25	71.72	39.84	4.44	2.46	70.92	39.40	3.64	2.02
26	71.70	39.83	4.42	2.45	70.88	39.38	3.60	2.00
27	71.68	39.82	4.40	2.44	70.85	39.36	3.57	1.98
28	71.67	39.81	4.39	2.43	70.82	39.34	3.54	1.96
29	71.65	39.80	4.37	2.42				
30	71.63	39.79	4.35	2.41				
31	71.61	39.78	4.33	2.40				

Table showing the Maximum Intensity of Solar Radiation on the Ecliptic.

Date.	*MARCH.*				*APRIL.*			
	Maximum.		Increment.		Maximum.		Increment.	
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
1	70.79	39.33	3.51	1.95	69.60	38.67	2.32	1.29
2	70.75	39.31	3.47	1.93	69.56	38.64	2.38	1.26
3	70.72	39.29	3.44	1.91	69.52	38.62	2.24	1.24
4	70.68	39.27	3.40	1.89	69.48	38.60	2.20	1.22
5	70.65	39.25	3.37	1.87	69.44	38.58	2.16	1.20
6	70.61	39.23	3.33	1.85	69.40	38.56	2.12	1.18
7	70.58	39.21	3.30	1.83	69.36	38.53	2.08	1.15
8	70.54	39.19	3.26	1.81	69.32	38.51	2.04	1.13
9	70.50	39.17	3.22	1.79	69.28	38.49	2.00	1.11
10	70.46	39.14	3.18	1.76	69.24	38.47	1.96	1.09
11	70.42	39.12	3.14	1.74	69.20	38.44	1.92	1.06
12	70.38	39.10	3.10	1.72	69.16	38.42	1.88	1.04
13	70.35	39.08	3.07	1.70	69.13	38.40	1.85	1.02
14	70.31	39.06	3.03	1.68	69.09	38.38	1.81	1.00
15	70.27	39.04	2.99	1.66	69.05	38.36	1.77	0.98
16	70.23	39.02	2.95	1.64	69.01	38.34	1.73	0.96
17	70.19	38.99	2.91	1.61	68.97	38.32	1.69	0.94
18	70.15	38.97	2.87	1.59	68.93	38.29	1.65	0.91
19	70.12	38.95	2.84	1.57	68.89	38.27	1.61	0.89
20	70.08	38.93	2.80	1.55	68.85	38.25	1.57	0.87
21	70.04	38.91	2.76	1.53	68.81	38.23	1.53	0.85
22	70.00	38.89	2.72	1.51	68.78	38.21	1.50	0.83
23	69.96	38.87	2.68	1.49	68.74	38.19	1.46	0.81
24	69.92	38.84	2.64	1.46	68.70	38.17	1.42	0.79
25	69.88	38.82	2.60	1.44	68.66	38.14	1.38	0.76
26	69.84	38.80	2.56	1.42	68.63	38.12	1.35	0.74
27	69.80	38.78	2.52	1.40	68.59	38.10	1.31	0.72
28	69.76	38.75	2.48	1.37	68.55	38.08	1.27	0.70
29	69.72	38.73	2.44	1.35	68.52	38.06	1.24	0.68
30	69.68	38.71	2.40	1.33	68.48	38.04	1.20	0.66
31	69.64	38.69	2.36	1.31				

TABLE SHOWING THE MAXIMUM INTENSITY OF SOLAR RADIATION ON THE ECLIPTIC.

Date.	*MAY.*				*JUNE.*			
	Maximum.		Increment.		Maximum.		Increment.	
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
1	68.45	38.03	1.17	0.65	67.58	37.54	0.30	0.16
2	68.41	38.01	1.13	0.63	67.56	37.53	0.28	0.15
3	68.38	37.99	1.10	0.61	67.54	37.52	0.26	0.14
4	68.35	37.97	1.07	0.59	67.52	37.51	0.24	0.13
5	68.32	37.95	1.04	0.57	67.51	37.50	0.23	0.12
6	68.28	37.93	1.00	0.55	67.49	37.49	0.21	0.11
7	68.25	37.92	0.97	0.54	67.47	37.48	0.19	0.10
8	68.22	37.90	0.94	0.52	67.46	37.48	0.18	0.10
9	68.19	37.88	0.91	0.50	67.44	37.47	0.16	0.09
10	68.16	37.87	0.88	0.49	67.43	37.46	0.15	0.08
11	68.13	37.85	0.85	0.47	67.42	37.45	0.14	0.07
12	68.10	37.83	0.82	0.45	67.40	37.44	0.12	0.06
13	68.06	37.81	0.78	0.43	67.39	37.44	0.11	0.06
14	68.03	37.79	0.75	0.41	67.38	37.43	0.10	0.05
15	68.00	37.78	0.72	0.40	67.37	37.43	0.09	0.05
16	67.97	37.76	0.69	0.38	67.36	37.42	0.08	0.04
17	67.94	37.74	0.66	0.36	67.35	37.42	0.07	0.04
18	67.91	37.73	0.63	0.35	67.34	37.41	0.06	0.03
19	67.89	37.72	0.61	0.34	67.33	37.40	0.05	0.02
20	67.86	37.70	0.58	0.32	67.32	37.40	0.04	0.02
21	67.84	37.69	0.56	0.31	67.32	37.40	0.04	0.02
22	67.81	37.67	0.53	0.29	67.31	37.39	0.03	0.01
23	67.79	37.66	0.51	0.28	67.30	37.39	0.02	0.01
24	67.77	37.65	0.49	0.27	67.30	37.39	0.02	0.01
25	67.75	37.64	0.47	0.26	67.29	37.38	0.01	0.00
26	67.72	37.62	0.44	0.24	67.29	37.38	0.01	0.00
27	67.70	37.61	0.42	0.23	67.28	37.38	0.00	0.00
28	67.67	37.59	0.39	0.21	67.28	37.38	0.00	0.00
29	67.65	37.58	0.37	0.20	67.28	37.38	0.00	0.00
30	67.63	37.57	0.35	0.19	67.28	37.38	0.00	0.00
31	67.60	37.55	0.32	0.17				

TABLE SHOWING THE MAXIMUM INTENSITY OF SOLAR RADIATION ON THE ECLIPTIC.

Date.	*JULY.*				*AUGUST.*			
	Maximum.		Increment.		Maximum.		Increment.	
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
1	67.28	37.38	0.00	0.00	67.58	37.54	0.30	0.16
2	67.28	37.38	0.00	0.00	67.60	37.55	0.32	0.17
3	67.28	37.38	0.00	0.00	67.63	37.57	0.35	0.19
4	67.28	37.38	0.00	0.00	67.65	37.58	0.37	0.20
5	67.28	37.38	0.00	0.00	67.67	37.59	0.39	0.21
6	67.28	37.38	0.00	0.00	67.70	37.61	0.42	0.23
7	67.29	37.38	0.01	0.00	67.72	37.62	0.44	0.24
8	67.29	37.38	0.01	0.00	67.75	37.64	0.47	0.26
9	67.30	37.39	0.02	0.01	67.77	37.65	0.49	0.27
10	67.30	37.39	0.02	0.01	67.79	37.66	0.51	0.28
11	67.31	37.39	0.03	0.01	67.81	37.67	0.53	0.29
12	67.32	37.40	0.04	0.02	67.84	37.69	0.56	0.31
13	67.32	37.40	0.04	0.02	67.86	37.70	0.58	0.32
14	67.33	37.41	0.05	0.03	67.89	37.72	0.61	0.34
15	67.34	37.41	0.06	0.03	67.91	37.73	0.63	0.35
16	67.35	37.42	0.07	0.04	67.94	37.74	0.66	0.36
17	67.36	37.42	0.08	0.04	67.97	37.76	0.69	0.38
18	67.37	37.43	0.09	0.05	68.00	37.78	0.72	0.40
19	67.38	37.43	0.10	0.05	68.03	37.79	0.75	0.41
20	67.39	37.44	0.11	0.06	68.06	37.81	0.78	0.43
21	67.40	37.44	0.12	0.06	68.10	37.83	0.82	0.45
22	67.42	37.45	0.14	0.07	68.13	37.85	0.85	0.47
23	67.43	37.46	0.15	0.08	68.16	37.87	0.88	0.49
24	67.44	37.47	0.16	0.09	68.19	37.88	0.91	0.50
25	67.46	37.48	0.18	0.10	68.22	37.90	0.94	0.52
26	67.47	37.48	0.19	0.10	68.25	37.92	0.97	0.54
27	67.49	37.49	0.21	0.11	68.28	37.93	1.00	0.55
28	67.51	37.50	0.23	0.12	68.32	37.95	1.04	0.57
29	67.52	37.51	0.24	0.13	68.35	37.97	1.07	0.59
30	67.54	37.52	0.26	0.14	68.38	37.99	1.10	0.61
31	67.56	37.53	0.28	0.15	68.41	38.01	1.13	0.63

TABLE SHOWING THE MAXIMUM INTENSITY OF SOLAR RADIATION ON THE ECLIPTIC.

Date.	*SEPTEMBER.*				*OCTOBER.*			
	Maximum.		Increment.		Maximum.		Increment.	
	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*	° *Fah.*	° *Cent.*
1	68.45	38.03	1.17	0.65	69.60	38.67	2.32	1.29
2	68.48	38.04	1.20	0.66	69.64	38.69	2.36	1.31
3	68.52	38.06	1.24	0.68	69.68	38.71	2.40	1.33
4	68.55	38.08	1.27	0.70	69.72	38.73	2.44	1.35
5	68.59	38.10	1.31	0.72	69.76	38.75	2.48	1.37
6	68.63	38.12	1.35	0.74	69.80	38.78	2.52	1.40
7	68.66	38.14	1.38	0.76	69.84	38.80	2.56	1.42
8	68.70	38.17	1.42	0.79	69.88	38.82	2.60	1.44
9	68.74	38.19	1.46	0.81	69.92	38.84	2.64	1.46
10	68.78	38.21	1.50	0.83	69.96	38.87	2.68	1.49
11	68.81	38.23	1.53	0.85	70.00	38.89	2.72	1.51
12	68.85	38.25	1.57	0.87	70.04	38.91	2.76	1.53
13	68.89	38.27	1.61	0.89	70.08	38.93	2.80	1.55
14	68.93	38.29	1.65	0.91	70.12	38.95	2.84	1.57
15	68.97	38.32	1.69	0.94	70.15	38.97	2.87	1.59
16	69.01	38.34	1.73	0.96	70.19	38.99	2.91	1.61
17	69.05	38.36	1.77	0.98	70.23	39.02	2.95	1.64
18	69.09	38.38	1.81	1.00	70.27	39.04	2.99	1.66
19	69.13	38.40	1.85	1.02	70.31	39.06	3.03	1.68
20	69.16	38.42	1.88	1.04	70.35	39.08	3.07	1.70
21	69.20	38.44	1.92	1.06	70.38	39.10	3.10	1.72
22	69.24	38.47	1.96	1.09	70.42	39.12	3.14	1.74
23	69.28	38.49	2.00	1.11	70.46	39.14	3.18	1.76
24	69.32	38.51	2.04	1.13	70.50	39.17	3.22	1.79
25	69.36	38.53	2.08	1.15	70.54	39.19	3.26	1.81
26	69.40	38.56	2.12	1.18	70.58	39.21	3.30	1.83
27	69.44	38.58	2.16	1.20	70.61	39.23	3.33	1.85
28	69.48	38.60	2.20	1.22	70.65	39.25	3.37	1.87
29	69.52	38.62	2.24	1.24	70.68	39.27	3.40	1.89
30	69.56	38.64	2.28	1.26	70.72	39.29	3.44	1.91
31	...	...	...	...	70.75	39.31	3.47	1.93

TABLE SHOWING THE MAXIMUM INTENSITY OF SOLAR RADIATION ON THE ECLIPTIC.

Date.	*NOVEMBER.*				*DECEMBER.*			
	Maximum.		Increment.		Maximum.		Increment.	
	° Fah.	*° Cent.*	*° Fah.*	*° Cent.*	*° Fah.*	*° Cent.*	*° Fah.*	*° Cent.*
1	70.79	39.33	3.51	1.95	71.63	39.79	4.35	2.41
2	70.82	39.34	3.54	1.96	71.65	39.80	4.37	2.42
3	70.85	39.36	3.57	1.98	71.67	39.81	4.39	2.43
4	70.88	39.38	3.60	2.00	71.68	39.82	4.40	2.44
5	70.92	39.40	3.64	2.02	71.70	39.83	4.42	2.45
6	70.95	39.42	3.67	2.04	71.72	39.84	4.44	2.46
7	70.98	39.43	3.70	2.05	71.74	39.86	4.46	2.47
8	71.02	39.45	3.74	2.07	71.76	39.87	4.48	2.48
9	71.05	39.47	3.77	2.09	71.77	39.87	4.49	2.49
10	71.08	39.49	3.80	2.11	71.78	39.88	4.50	2.50
11	71.11	39.50	3.83	2.12	71.80	39.89	4.52	2.51
12	71.14	39.52	3.86	2.14	71.81	39.90	4.53	2.52
13	71.17	39.54	3.89	2.16	71.82	39.90	4.54	2.52
14	71.20	39.56	3.92	2.18	71.84	39.91	4.56	2.53
15	71.24	39.58	3.96	2.20	71.85	39.91	4.57	2.53
16	71.27	39.59	3.99	2.21	71.86	39.92	4.58	2.54
17	71.29	39.60	4.01	2.22	71.87	39.92	4.59	2.54
18	71.32	39.62	4.04	2.24	71.88	39.93	4.60	2.55
19	71.35	39.64	4.07	2.26	71.89	39.93	4.61	2.55
20	71.38	39.65	4.10	2.27	71.90	39.94	4.62	2.56
21	71.40	39.67	4.12	2.29	71.90	39.94	4.62	2.56
22	71.42	39.68	4.14	2.30	71.91	39.95	4.63	2.57
23	71.45	39.69	4.17	2.31	71.91	39.95	4.63	2.57
24	71.47	39.71	4.19	2.33	71.92	39.96	4.64	2.58
25	71.50	39.72	4.22	2.34	71.92	39.96	4.64	2.58
26	71.52	39.73	4.24	2.35	71.93	39.97	4.65	2.59
27	71.54	39.74	4.26	2.36	71.93	39.97	4.65	2.59
28	71.57	39.76	4.29	2.38	71.94	39.97	4.66	2.59
29	71.59	39.77	4.31	2.39	71.94	39.97	4.66	2.59
30	71.61	39.78	4.33	2.40	71.94	39.97	4.66	2.59
31	...	...	...	...	71.94	39.97	4.66	2.59

CHAPTER V.

MECHANICAL ENERGY OF SOLAR RADIATION.

The mechanical energy developed by solar radiation cannot be accurately determined unless we possess means of ascertaining (1) the energy actually called forth by the sun's radiant heat at the surface of the earth, and (2) the energy lost during the passage of the rays through our atmosphere. The illustration shown on Plate 10 represents a *solar calorimeter*, an instrument constructed for measuring the energy actually developed near the earth's surface. An instrument for measuring the amount of radiant heat absorbed by the atmosphere, the *actinometer*, has been fully described in Chapter III. Evidently, if we possess reliable means of ascertaining the heat developed on a given area at the surface of the earth, and that lost by atmospheric absorption, we can state positively what amount of dynamic energy is developed on a given area by solar radiation at the boundary of the terrestrial atmosphere. And since we know the true relation between the semi-diameter of the sun and the distance from the sun's centre to the earth, we can calculate the exact degree of dispersion of the solar rays on reaching the atmospheric boundary. Accordingly, we possess all the elements necessary to compute the amount of mechanical energy transmitted by radiation from a given area of the surface of the sun. Now, it will be found, on referring to Chap. VI., that the sun emits heat of equal energy in all directions; hence we are enabled to estimate the total amount of mechanical power developed and transmitted by the sun as a motor.

Sir John Herschel and M. Pouillet conceived the idea, nearly at the same time, of measuring the energy of solar radiation by exposing a given quantity of water, presenting a given area, to the sun's rays. Having ascertained the elevation of temperature of the water acquired in a given time, and added the energy supposed to be lost by atmospheric absorption, together with the loss consequent on the dispersion of the rays, they computed the total dynamic energy developed by the sun. Herschel employed a small, stationary, open vessel, which he termed an actinometer; while Pouillet resorted to a close, movable vessel, the well-known "pyrheliometre." The simple instrument devised by the great English astronomer, although very defective and incapable of furnishing exact data, demands particular notice, since it was employed in the first investigation of a practical nature intended to solve the important problem of solar energy. The result of the investigation of Herschel, it will be remembered, startled the world by the inconceivable magnitude of solar energy which it disclosed. The *actinometer*, agreeably to the following lucid statement, furnished by the distinguished designer himself, consisted of "a light cylindrical vessel of tinned iron, open at the top, 3¾ inches in diameter and 2.4 inches in depth, weighing 1,069 grains, nearly filled with water moderately darkened by a slight admixture of ink. This vessel was placed on a light wooden support, covered with cotton cloth, and touching it only in a narrow ring (to avoid the communication of heat by conduction), in the interior of an iron cylinder of much larger diameter, to protect it from wind and external radiation, the upper part of which was covered by an iron plate well protected from sunshine by several separate diaphragms of paper laid lightly one over the other thereon. This plate had a circular aperture somewhat wider than that of the tin cylinder, and vertically over it, centre corresponding to centre. The mouth of the tin cylinder was covered with a circle of stiff paper, having an aperture exactly circular and concentric with the cylinder, so as to admit a vertical or nearly vertical sunbeam somewhat less in section than the vessel, and *wholly incident on the surface of the contained liquid.* This cover also projected over the exterior of the cylinder on all sides, so as to prevent any ray from striking on its outside, even when the upper iron plate was removed from the exterior vessel. Lastly, to cut off effectually all lateral radiation from the region of sky near the sun, a paper diaphragm but very little more in aperture than the mouth of the tin cylinder was laid concentrically on the upper iron plate and its diaphragms. Plunged into the liquid, and resting on the bottom when not in use, was a circular plate of mica 3¼ inches in diameter, attached to a light rod of reed 0.1 inch in diameter, for the purpose of completely stirring and mixing the strata of the liquid by one or two up and down movements. When thus prepared, the whole apparatus was placed in the sunshine at noon, or somewhat before, and so adjusted that, on the admission of sunlight, a narrow ring of light surrounded concentrically the aperture in the diaphragm of the tin cylinder beneath, which was carefully watched during the progress of the experiment, and kept unaltered. These arrangements being made, the sun was shaded off, the temperature of the liquid (after stirring by the mica plate) taken by an exceedingly delicate and sensitive thermometer by Crichton, and again after a certain noted number of minutes. The shade being then removed, the sun was allowed to shine into the aperture on the liquid for ten minutes. During this exposure, the liquid was three times stirred by the mica plate, allowing five seconds for each stirring, and shading the aperture during that operation (which, of course, was not counted as part of the ten minutes' exposure). The temperature was now again taken, and, after remaining shaded again a certain noted number of minutes, finally once more. The mean of the minutely change of temperature, deduced from the shade observations, being obtained, was applied as a correction (in all cases a very small one) to the minutely elevation of temperature in the sun exposure; and thus the true effect of the sun was concluded."

The "pyrheliometre" having been described in nearly all recent works on solar energy, and accurately delineated in Pouillet's "Éléments de Physique" (Tome II., Paris, 1856), it will only be necessary to remind the reader that the vessel exposed to the sun, composed of polished silver, contains 100 grammes of water. The diameter is 1 decimetre and the depth 15 millimetres, the top exposed to the sun's rays being coated with lamp-black. The radical defect of Pouillet's instrument is that it cannot be used during winter when the thermometer is below the freezing point, as warm water would have to be used, in which case the loss of heat by radiation and convection would be so great as to render the task futile of accurately measuring the force of solar radiation. This defect of Pouillet's method is the more serious as the heat of the sun is most intense during the winter solstice for given zenith distances, on account of the diminished distance between the sun and the earth, and because the sky is generally clearer on a cold winter's day than during the heat of summer when the air is charged with vapor.

The loss of heat by radiation, in the pyrheliometre; the loss of heat by convection, accelerated by currents of air; the absence of adequate means for circulating the fluid contained within the heater; the rude method of keeping the instrument perpendicular to the sun with the hand, not to mention the disturbing influence of respiration and the radiation from the operator's body, are self-evident defects. Nor can we pass unnoticed the want of any direct means of ascertaining the depth of the atmosphere through which the radiant heat passes at the moment of measuring its energy. I need scarcely point out that computations based on *latitude*, *date*, and *exact time* are too complex and tedious for investigations in which the principal element, the depth of the atmosphere, is continually changing.

It will be well to state that the solar calorimeter, and all my instruments constructed for investigating the mechanical properties of solar heat, are attached to a vibrating table applied within a revolving observatory, supported on horizontal journals and provided with a declination movement and a graduated arc. Consequently, the sun's zenith distance may at all times be ascertained by mere inspection, a very great convenience in an investigation which at every instant is dependent on the changing depth of the atmosphere through which the solar rays pass. As this depth bears a fixed relation to the sun's zenith distance, it may of course be accurately determined by noting the position of the fixed index on the graduated arc; but, as already pointed out, there is no time during investigations of this kind for computations. I have, therefore, constructed a graduated scale provided with a movable radial index, which, by being brought to the division corresponding with the observed zenith distance, shows the depth of atmosphere (see diagram in Chap. III., Plate 9). It is proper to observe that, in constructing this scale, I have assumed the earth to be a perfect sphere of 3,956 miles radius. The error resulting from this assumption is, however, so trifling that the described graphic method of ascertaining the depth of the atmosphere may, without appreciable error, be employed for all latitudes. The *solar calorimeter* consists of a double vessel, cylindrical at the bottom and conical at the top, an 8-in. lens being inserted at the wide end in the manner shown by the illustration. The interior is lined with polished silver, the space between the two vessels being closed at the top and bottom by means of perforated rings, as shown in the transverse section. The object of these perforations is that of distributing equally a current of water to be circulated through the space between the vessels. Nozzles are applied at the top and bottom of the external vessel, of suitable form to admit of small flexible pipes being attached. A stop-cock with coupling-joint is applied at the bottom, communicating with the interior chamber of the calorimeter and connected with an air-pump, for exhausting the same. A cylindrical vessel, with closed ends, composed of polished silver, is secured in the lower part of the interior chamber, and provided with a conical nozzle at the top, through which a thermometer is inserted from without. Within the lower part of this cylindrical vessel a centrifugal paddle-wheel is applied, surrounded by a cylindrical casing divided into two compartments by a circular diaphragm. The lower compartment contains four radial wings, or paddles, the diaphragm being perforated in the centre. The said paddle-wheel revolves on a vertical axle, which passes through a stuffing-box applied at the bottom of the surrounding vessels, the rotary motion being imparted by means of a pulley secured to the lower end of the axle. The operation of this wheel, designed to promote perfect circulation of the fluid within the cylindrical vessel when charged, is quite peculiar. It will be readily understood that the centrifugal action produced by the rotation of the paddles will draw in water downwards through the central perforation of the diaphragm, and force the same into the annular space round the casing of the wheel; thus an upward current will be kept up through this annular space uniform on all sides. The circulating water, after reaching the top of the heater, will then return, first entering the open end of the casing of the wheel, and ultimately the central perforation of the diaphragm. I have been thus particular in describing this system of promoting uniform circulation, because a correct indication of the mean temperature of the water contained within the vessel subjected to the action of the concentrated rays, is the all-important condition on which depends the accuracy of the determination of the number of thermal units developed by the radiant heat. It only remains to be pointed out that the lens, which is so proportioned as to admit a sunbeam of 53.45 sq. ins. of section, is placed at such a distance from the heater that when the concentrated rays reach the upper end (coated with lamp-black) they are confined to an area of 3.35 sq. ins., viz., $\frac{1}{16}$ of the sectional area of the pencil of rays which enters the lens.

It will be obvious that the concentration of the radiant heat on an area of only one-sixteenth of that of the section of the pencil of rays admitted to the instrument removes a very difficult disturbing element from the investigation—namely, the great amount of heat radiated by the blackened surface of the heater, which in the pyrheliometre is 16 times greater for a given amount of radiant heat than in the solar calorimeter. But this is not all; while the extensive blackened surface of the former is exposed to currents of air, the disturbing effect of which can neither be controlled nor computed, error arising from convection is wholly removed from the latter, because the reduced blackened surface of the vessel exposed to the solar rays receives the concentrated radiant heat within a vacuum. The loss of heat at the bottom and sides of Pouillet's instrument, caused by convection and currents of air, is likewise wholly removed in the solar calorimeter by the expedient of operating within a vacuum. It will be seen, therefore, that the loss from these causes has been wholly obviated in this instrument, while the loss occasioned by radiation from the blackened surface which receives the concentrated radiant heat has been reduced to a mere fraction. It may be contended, however, that the loss by radiation of the heater against the interior surface of the calorimeter, although minute, is yet appreciable, and that some heat will be lost by conduction at the points where that vessel joins the surrounding chambers. Even these trifling sources of error, it will be seen presently, have been removed by the new method. A force-pump and a cistern containing water maintained at a constant temperature of 60° F. are arranged near the calorimeter. By means of this pump and the flexible pipes before referred to, a constant current is kept up through the space between the internal and external casings of the instrument; hence the materials composing the latter may quickly be brought to the same temperature as the circulating water. The process of measuring the radiant energy is conducted in the following manner: The thermometer being withdrawn, the cylindrical vessel or heater is charged with distilled water of a temperature of about 45° F., after which the thermometer is again inserted and the instrument exposed to the sun, the paddle-wheel being kept in motion. The indication of the thermometer must then be watched, and the time accurately noted when the mercurial column marks 50° on the scale, the observation continuing until the thermometer marks 70°, at which point the time is again accurately noted. The experiment being then concluded, the lens should be covered. The circulating water being kept at a constant temperature of 60° F., it scarcely needs explanation that, during the elevation of the temperature of the water from 50° to 60°, the instrument radiates *towards the heater;* and that, while the temperature rises from 60° to 70°, the heater radiates *towards the instrument.* In each case the amount of heat radiated and received is almost inappreciable, since the vessel containing the water to be heated and the surrounding vessel are composed of highly polished metal. The amounts of gain and loss of heat by *conduction* at the points where the heater is joined to the external vessel, if appreciable, evidently balance each other in the same manner as the gain and loss by radiation.

The weight of distilled water at 60° contained in the heater, and the weight and specific heat of the materials which compose its parts, being ascertained, the number of thermal units necessary to elevate the temperature of the whole 20° F. may be readily calculated. To this must be added the percentage of calorific energy lost during the passage of the sun's rays through the lens. The sum will represent a permanent coefficient for each particular instrument. Obviously, the indication of the solar calorimeter will not be less reliable during winter in a northern latitude, with the mercury at zero, than during summer within the tropics, when the thermometer marks 100° in the shade. Nor must it be supposed that the same difficulty presents itself in ascertaining the loss of energy of the rays of heat as that involved in a determination of the retardation which rays of light suffer during their passage through a lens. In order to determine the former, we have only to compare the units of heat developed by the *direct* action of a pencil of rays of a given section with the number of units developed by another pencil of equal section, acting during an equal interval and at the *same time*, through the lens the retarding influence of which we desire to ascertain.

The weight of water contained in the heater of the solar calorimeter employed during the investigations referred to in this work is 0.8125 lb. avoirdupois, the weight of the materials composing the heater, paddle-wheel, and other parts being 0.298 lb. As the specific heat of these materials is 0.125, it will be evident that $0.125 \times 0.298 = 0.0372$ lb. should be added to the weight of water contained in the heater. Accordingly, the total weight will amount to $0.8125 + 0.0372 = 0.8497$ lb. The elevation of temperature in the heater being fixed at 20° F., it will be seen that the dynamic energy developed during each experiment will amount to $20 \times 0.8497 = 16.994$ thermal units, besides the energy absorbed by the lens, which, agreeably to actual trial, amounts to very nearly 0.10. Consequently, 0.10 × 16.994 + 16.994 = 18.6934 thermal units represent a permanent coefficient of energy for the particular instrument referred to. Let us clearly understand that, at the conclusion of each experiment, whatever be the time occupied in attaining the stipulated 20° F., the stated amount of energy, viz., 18.6934 thermal units, has been developed. We are, therefore, enabled to determine the amount of mechanical energy developed by solar radiation at the surface of the earth by observing the time occupied in attaining the stipulated temperature, and then dividing the coefficient of energy by the time thus observed. But it will be perceived, on reflection, that, in order to solve the important problem of solar emission, the following conditions must be fulfilled at the time of conducting the experiment: (1) The sun must be perfectly clear. (2) The position of the earth in the orbit must be known in order to enable us to determine the distance of the sun and the consequent dispersion of the rays during the observation. (3) The sun's zenith distance must be known, since the loss of radiant energy by absorption depends on the depth of atmosphere penetrated by the rays. The second and third of these conditions are of course readily met; but the first condition can only be fulfilled by repeating the observations during a series of years whenever the sun is exceptionally clear. The writer feels confident that, by having adopted this system, the problem of solar emission has been satisfactorily solved. An account of the observations successively made being devoid of interest, it will be sufficient to state that the observed maximum solar intensity occurred March 7, 1871, the sun being then so clear that the before-mentioned amount of 18.6934 thermal units was developed in 10 min. 0.5 sec., hence $\frac{18.6934}{10.00833} = 1.8678$ units per minute. The sectional area of the pencil of rays entering the solar calorimeter was, as already stated, 0.37187 square foot. Consequently, if we reduce the foregoing elements to the usual standard—*one square foot of area acted upon by the sun in one minute*—it will be found that, on the occasion referred to, an energy of 5.03 units of heat per minute was developed by a pencil of solar rays of 1 square foot section. The mean zenith distance during the experiment was 46 deg. 5 min., while the position of the earth in the orbit was such that the sun's rays suffered a dispersion of 45,400 to 1. Referring to the table of temperatures for given zenith distances (see page 62), it will be found that the radiant intensity at 46 deg. 5 min. zenith distance is diminished in the ratio of 67°.2 : 59°.85. The energy developed by our calorimeter during the experiment was, of course, reduced in the same proportion. Introducing, then, the necessary correction for the stated loss caused by zenith distance—*i.e.*, atmospheric absorption—the true energy developed by the radiation at the surface of the earth during the experiment was $\frac{67.20 \times 5.03}{59.85} = 5.64$ units per minute. Referring to Chap. III., it will be found that the temperature produced by solar radiation at the boundary of the terrestrial atmosphere is 0.207 greater than that developed near the surface of the earth; in other words, the energy absorbed by the atmosphere is to that transmitted to the earth as 0.207 : 0.793. Consequently, the energy developed by solar radiation at the boundary of the atmosphere, March 7, 1871, was $\frac{5.64}{0.793} = 7.11$ thermal units on one square foot of surface; while the dispersion of the rays on that day was in the ratio of 45,400 to 1. It needs no demonstration to prove that, according to this ratio of dispersion of the rays, the energy emanating from one square foot of the photosphere must heat 45,400 square feet of surface at the boundary of the terrestrial atmosphere. Our investigation having shown that solar radiation develops an energy of 7.11 units to the square foot on entering the terrestrial atmosphere, it follows that solar emission amounts to $45{,}400 \times 7.11 = 322{,}794$ thermal units in one minute for each square foot of the photosphere. In view of the completeness of the means adopted in measuring the energy developed, and the ample time which has been devoted to the determination of maximum intensity, it is not probable that future labors will change the result of our investigation. The continuous shrinking of the sun will produce a perceptible diminution of the radiant energy transmitted to the earth in the course of a few hundred centuries, but the emissive energy for a given area of the sun will remain constant for millions of years, since the intensity developed by the falling mass will increase inversely as the square of its distance from the solar centre, thus balancing the diminution of energy consequent on the reduced fall of the mass.

The illustration shown on Plate 11 represents a vertical section of a portable solar calorimeter, in all essential features similar to the instrument described in the present chapter, the only material difference being that of employing a *self-acting* circulating wheel within the heater. Referring to the illustration, it will be seen that the instrument is placed on an ordinary table, a weight being suspended under the same for actuating the circulating wheel. The cylindrical chamber which contains the heater moves on a hinge secured to a circular bed-plate provided with cogs, turning round a vertical pivot fastened to the top of the table, the inclination being regulated by a tangential screw. A horizontal pinion, geared into the cogged bed-plate referred to, enables the operator to follow the diurnal motion, while the tangential screw enables him to regulate the inclination of the lens with reference to the sun's declination. Appropriate sights are applied to the front side of the cylindrical chamber, showing when its axis points towards the sun's centre, while a graduated quadrant indicates the zenith distance at all times. It will be found, by inspecting the illustration, that the axle of the barrel actuated by the motive weight is connected by a train of cog-wheels to the shaft of the circulating wheel within the heater. The perfect regularity of rotation imparted to this wheel, and the consequent perfectly uniform circulation kept up within the heater, dispenses with the necessity of exhausting the air from the cylindrical chamber, on the following grounds: The heat imparted by the air within the chamber during the first half of the experiment balances the heat absorbed during the second half. There *is* a difference, but too small to cause an appreciable error. It may be mentioned that the portable solar calorimeter thus described was originally constructed for ascertaining the dynamic energy developed by solar radiation on the plains of India and in Australia.

CHAPTER VI.

THERMAL ENERGY TRANSMITTED TO THE EARTH BY RADIATION FROM DIFFERENT PARTS OF THE SOLAR SURFACE.

Père Secchi, in the second edition of "Le Soleil," published at Paris, 1875, calls special attention to the result of his early investigations of the force of radiation emanating from different regions of the sun's surface, reiterating without modification his former opinions regarding the absorption of the radiant heat by the solar atmosphere. It will be well to bear in mind that the plan adopted by the Italian physicist in his original researches, on which his present opinion is based, was that of projecting the sun's image on a screen, and then, by means of thermopiles, measuring the temperature at different points. The serious defects inseparable from this method of measuring the intensity of the radiant heat I need not point out, nor will it be necessary to urge that a correct determination of the energy transmitted calls for direct observation of the temperature produced by the rays projected towards the earth. Accordingly, on taking up that branch of my investigations of radiant heat which relates to the difference of intensity transmitted from different parts of the sun's surface, I adopted the method of *direct* observation. The progress was slow at the beginning, owing to the necessity of constructing an astronomical apparatus of unusual dimensions; but having devised means which rendered the employment of any desirable focal length easy, the work has progressed rapidly. An instrument of 17.7 metres (58 feet) focal length, erected to conduct preliminary experiments, has proved so satisfactory that the construction of one of 30 metres focal length, which I supposed to be necessary, has been dispensed with. Considering that the apparent diameter of the sun at a distance of 17.7 metres from the observer's eye is 162.4 millimetres, even when the earth is in aphelion, the efficacy of the instrument employed might have been anticipated. The nature of the device will be readily comprehended by the following explanation: Suppose a telescopic tube 17.7 metres long, 1 metre in diameter, devoid of object-glass and lenses, and mounted equatorially, to be closed at both ends by metallic plates or diaphragms, at right angles to the telescopic axis; suppose the diaphragm at the upper end to be perforated with two circular apertures 200 millimetres in diameter, situated one above the other in the vertical line, 360 millimetres from centre to centre; and suppose a third circular perforation whose area is one-fifth of the apparent area of the solar disc—viz., 72.6 millimetres diameter—to be made on either side of the vertical line; suppose, lastly, that the diaphragm which closes the lower end of the tube be perforated with three small apertures 6 millimetres in diameter, whose centres correspond exactly with the centres of the three large perforations in the upper diaphragm. The tube being then directed towards the sun, and actinometers applied below the three small apertures in the lower diaphragm, it will be evident that two of these instruments will, after due exposure to a clear sun, indicate maximum solar intensity, say 35° C., while the actinometer applied in line with the perforation whose area is one-fifth of the apparent area of the solar disc will indicate $\frac{35}{5} = 7°$ C., unless the central portion of the solar disc radiates more powerfully towards the earth than the rest, in which case a higher intensity than 7° C. will be indicated by the actinometer referred to. It will be readily understood that the solar rays entering through the perforations at the upper end of the tube converge at the lower end and pass through the small perforations, causing maximum indication of the focal actinometers as stated. Now, suppose that a circular plate, the area of which is exactly four-fifths of the apparent area of the sun—viz., 145.2 millimetres diameter—be inserted concentrically in either of the two large perforations of the diaphragm at the top of the telescopic tube. The apparent diameter of the sun being, as before stated, 162.4 millimetres, it will be perceived that the inserted plate will only partially exclude the solar radiation, and that the rays from a zone 1′ 42″ wide will pass outside the said plate, converging in the form of a hollow cone at the lower end of the tube, and there enter the respective actinometer. The indication of the latter will then show the thermal energy transmitted by radiation from a zone whose mean width extends 49″ from the sun's border. It should be particularly observed that the three focal actinometers employed will be acted upon *simultaneously* by the converged rays, (1) from the entire area of the solar disc, (2) from a *central* region containing one-fifth of the area, and (3) from a *zone* at the border containing also one-fifth of the area of the solar disc. It is scarcely necessary to point out that an accurate comparison of the intensity of the radiant heat emanating from the central part and from the sun's border calls for *simultaneous* observation, in order to avoid the errors resulting from change of zenith distance and variation of atmospheric absorption during the investigation. The great advantage of obtaining also a simultaneous indication of the intensity transmitted by radiation from the entire solar disc is self-evident, since this indication serves as an effectual check on the observed intensities emanating from the *centre* and from the *border*. The latter obviously must be less, while the former must be greater, for a given area, than the indication of the focal actinometer which receives the radiation of the entire solar disc.

The foregoing demonstration, based on hypothesis, having established the possibility of ascertaining by direct observation the temperature produced by the rays projected from certain parts of the solar surface, let us now examine the means actually employed. An observer on the 40th deg. latitude, stationed on the north side of a building 28 metres high, pointing east and west, can just see the sun pass the meridian, during the summer solstice, if he occupies a position about 8 metres from such building. Now, if an opaque screen, perforated by a circular opening 313 millimetres in diameter, be placed on the top of the supposed building, the entire solar disc may be seen through the same, provided it faces the sun at right angles. But if the perforation in the said screen be 140 millimetres in diameter, only one-fifth of the area of the solar disc will be seen. And if the screen be removed and a circular plate 280 millimetres in diameter put in its place, the observer, ranging himself in line with the plate and the sun's centre, can see only a narrow border 1′ 42″ of the solar disc. Obviously the screen placed on the top of the building might be perforated like the upper diaphragm of the supposed telescopic tube, and a plate resembling the lower diaphragm, secured by appropriate means near the ground, might be made to support the focal actinometers in such a manner that their axes pass through the centres of the perforations of the screen above the building. It is hardly necessary to state that the plate supporting the actinometers should be attached to some mechanism capable of imparting to it a parallactic movement, during the observation, corresponding with the sun's declination and the earth's diurnal motion, and that some adequate mechanism should be employed for regulating the position of the perforated screen and adjusting the focal distance in accordance with the change of the subtended angle consequent on the varying distance from the sun. It will be evident that, since the first-named mechanism rests on the ground, while the latter is secured to a massive building, far greater steadiness will be attained by our simple and comparatively inexpensive device than by employing a telescopic tube of the most perfect construction mounted equatorially.

With reference to the influence of diffraction, it should be stated that, before determining the size of the screens intended to shut out certain parts of the solar disc during the investigation, the amount of inflection of the sun's rays was carefully ascertained. Two distinct methods were adopted: (1) measuring the additional amount of heat transmitted to the focal thermometers in consequence of the inflection of the rays; (2) increasing the *theoretical* size of the screens until the effect of inflection was overcome and the luminous rays completely excluded. Regarding the first-named method of ascertaining the diffraction, it is important to mention that the temperature transmitted to the focal actinometers by the inflected radiation which passes outside of the theoretically determined screens is not proportionate to the inflection ascertained by the process of enlargement referred to. This circumstance at first rendered the investigation somewhat complicated, but it soon became evident that the discrepancy was caused by the comparatively small inflection of the *invisible* heat rays. It will be seen presently that the radiant heat which passes outside of the screens in consequence of diffraction is considerably less than that which would be transmitted to the focal actinometers if the calorific rays were subjected to an amount of inflection corresponding with the enlargement of the screens beyond the theoretical dimensions necessary to exclude the luminous rays.

Let us first consider the method of ascertaining the inflection of the rays by measuring the additional amount of heat transmitted to the focal actinometers. Fig. 1 (see Plate 12) represents the solar disc, *a* being the focal actinometer exposed to the converged rays, *a′ a′* representing an imaginary plane situated 17.7 metres from *a*, at which distance the section of the pencil of converging rays will be 162.4 millimetres in diameter, provided the earth is near aphelion. Fig. 2 also represents the solar disc, and *c* the actinometer exposed to the converged rays; but a perforated screen *b′ b′* is interposed, the perforation being of such a size that only the rays projected by the central half of the solar disc (indicated by the circle *b b*) pass through the same and reach the focal actinometer. The screen *b′ b′* being situated 17.7 metres from *c* when the earth is in the position before referred to, the said perforation must be 114.83 millimetres in diameter, in order that the lines *b x′ c* may be straight. Fig. 3 likewise represents the solar disc, its area being divided into two concentric halves by the circle *d d;* but, in place of a perforated screen, an opaque circular screen *d′* is introduced at the same distance from the focal actinometer as in Fig. 2; consequently, the lines *d y′ f* will be straight. Now, if the actinometers *a*, *c*, and *f* be exposed to the converged solar radiation *simultaneously and during an equal interval of time*, *c* and *f* receiving the heat from one half of the solar disc (the former from the central and the latter from the surrounding half), the temperatures of *c* and *f* added together should correspond exactly with the temperature transmitted from the entire solar disc to *a*. Observation, however, shows that the temperature of *c* and *f* together is 0.091 greater than the temperature imparted to *a*. Hence an increase of temperature of nearly one-eleventh is produced by the inflection of the calorific rays, one-half being the result of the bending of the rays within the perforation of the screen *b′ b′*, the other half resulting from the bending outside of the screen *d′*. The increment of temperature being thus known, the degree of inflection may be easily determined by drawing a circle *x x* round the circle *b b*, covering an additional area of $\frac{0.091}{2} = 0.0455$; and by inscribing a circle *y y* within *d d*, covering an area of 0.0455 less than the area of *d d*. It will be perceived, on reflection, that *x x′ b* represents the angle of inflection of the calorific rays within the perforation of the screen *b′ b′*, and that *d y′ y* represents the angle of inflection outside of the screen *d′*. Demonstration shows that the former angle measures 14″.57, while the latter measures 14″.86, the mean being 14″.71. Having thus determined the inflection resulting from invisible radiation, let us now ascertain the inflection of the luminous rays. As before stated, the apparent diameter of the sun at a distance of 17.7 metres from a given point is 162.4 millimetres when the luminary is furthest from the earth. Now, our investigation shows that a screen 167 millimetres in diameter hardly suffices to exclude the luminous rays; hence their inflection amounts to $\frac{167 - 162.4}{2} = 2.3$

millimetres in a length of 17.7 metres. Their angle of inflection will therefore be 26″.81, against 14″.71 for the dark rays. We have thus incidentally established the fact that the inflection of the luminous and calorific rays differs nearly in the same proportion as the calorific energies of the invisible and visible portions of the solar spectrum.

The illustration on Plate 13 represents a top view (see Fig. 15) and a transverse section (see Fig. 17) of the parallactic mechanism employed in the investigation. The leading feature of the device is that of attaching three actinometers, *f*, *h*, and *g*, to a plate which may be set at any desired inclination, and capable of being moved simultaneously at right angles to, and in a direction parallel with, the meridian. The mode of effecting this movement will be readily understood by the following description, reference being had to the illustration: *a* is a screw, the threads of which are formed to a pitch of three-eighths of an inch, placed horizontally and at right angles to the meridian, the ends turning in bearings bolted to a substantial frame *b b*, supported by legs resting on a solid stone foundation. A radial arm *c*, the position of which is regulated by a graduated quadrant *c′*, is fastened to the end of the screw *a;* the latter being by that means prevented from turning round. *d d*, arms connected by a cylindrical socket *d′*, which slides freely back and forwards on the screw. The said socket is prevented from turning round the screw by the application of a square key *a′*, fitted accurately into a rectangular longitudinal groove formed in the side of the screw. *e e*, plate sliding between appropriate guide-rods secured to the upper side of the arms *d d*, motion being imparted to this plate by a micrometric screw *e'*. The actinometers *f*, *g*, and *h* are attached to a plate *k* bolted to the top of *e e*. The sliding socket *d'* is moved along the main screw by a milled nut *l*, held against the end of the said socket by a forked piece *l'* fastened to the arm *d* and acting on a collar formed at the small end of the milled nut. It scarcely needs explanation that, by turning this nut, the sliding socket *d'* may be made to move along the main screw in either direction, thereby imparting motion to the plate *k* which supports the three actinometers. Nor will it be necessary to demonstrate that, by turning the micrometric screw *e'*, the said plate may be moved at right angles to the main screw *a*. Consequently, the mechanism thus described enables us to move the actinometers with great regularity and precision across the meridian, and in a direction parallel with it. By means of a flexible tube *m m*, which connects the surrounding casings of the three actinometers, a stream of water is circulated through the latter during observations. An ordinary force-pump is employed for this purpose, attached to a capacious cistern containing water maintained at a constant temperature. The centres of the actinometers *f* and *g* are 160 centimetres apart, a colored glass *n* being attached to the plate *k* in a direct line with, and equidistant from, the stated centres. An eyepiece is applied to the colored glass *n*, below the plate *k*. The actinometers are provided with conical apertures on the upper side, through which the thermometers are introduced when the instrument is in operation. In the illustration these apertures are closed by conical plugs provided with globular handles. Fig. 16 represents a square bar *r*, to which three circular discs, composed of sheet brass, are attached by means of deep and thin arms, formed as shown by the drawing. The discs *f′* and *g′* are placed 160 centimetres apart, from centre to centre, corresponding exactly with the distance between the axes of the actinometers *f* and *g*; while the centre of the disc *s* corresponds with the centre of the eyepiece below the colored glass *n*. The square bar *r* is held horizontally and at right angles to the meridian by a substantial bracket secured to the top of some building of adequate height; the angular position of the bar being such that it corresponds with the sun's zenith distance. The frame *b b*, which supports the parallactic mechanism, rests on a level stone foundation, its distance from the building referred to depending on the season and the latitude of the place of observation. Assuming that the bar *r*, which supports the discs *f′*, *s*, and *g′*, has been correctly placed, and that the parallactic mechanism occupies a proper position on the ground, it will then be found that, when the sun passes the meridian, the disc *s* will throw a small round shadow covering the colored glass *n*. Obviously, an operator lying on his back under the frame which supports the instrument, with his right hand turning the milled nut *l*, and his left hand turning the micrometric screw *e′*, will be enabled to impart a simultaneous right-angular movement to the actinometers. Now, the diameter of the disc *s* is such that, when brought in line with the sun and the eye-piece below *n*, only the extreme edge of the solar disc is seen through the colored glass. The operator, therefore, by careful manipulation, may readily keep the eye-piece and the disc *s* in line with the solar centre. My original design was that of actuating the parallactic mechanism by clock-work; but, warned by the frequent failures of astronomers to keep the sun accurately in focus even during the short period of an eclipse, I adopted the safer method of operating by hand. The distance between the centres of the discs f' and g' corresponding exactly with the distance between the axes of the actinometers *f* and *g*, both being equidistant from the axis of the eye-piece, it will be evident that the centres of the discs f' and g' will always coincide with the axes of their respective actinometers directed towards the solar centre, provided the operator manipulates the instrument so carefully that the sun is kept accurately in focus; in other words, that no distortion is suffered to take place of the annular face or narrow border of the sun seen through the colored glass. It hardly needs explanation that the actinometer *h* is at all times exposed to the full energy of the converging rays from the sun.

As a detailed account of the result of the investigation would occupy too much space, the leading points only will be presented. The observations have all been made at noon, the duration of the exposure to the sun having been limited to seven minutes, during which period the actinometers are moved, by the parallactic mechanism, through a distance of about 55 centimetres, from west to east. The intensity of the radiant heat imparted to the actinometers has been recorded by the observers at the termination of the fourth, fifth, sixth, and seventh minute, the exact moment for reading off being indicated by a chronograph. The relative intensities transmitted by radiation from the centre and from the border of the solar disc first claim our attention. Fig. 6 represents the solar disc covered by a circular screen 145.25 millimetres in diameter, excluding the rays excepting from a narrow zone, the mean width of which is situated 49″ from the border of the photosphere. Fig. 7 shows a screen excluding the solar rays excepting from the central portion, *the area of which is precisely equal to the area of the narrow zone in* Fig. 6. The following table shows the intensities transmitted to the actinometers

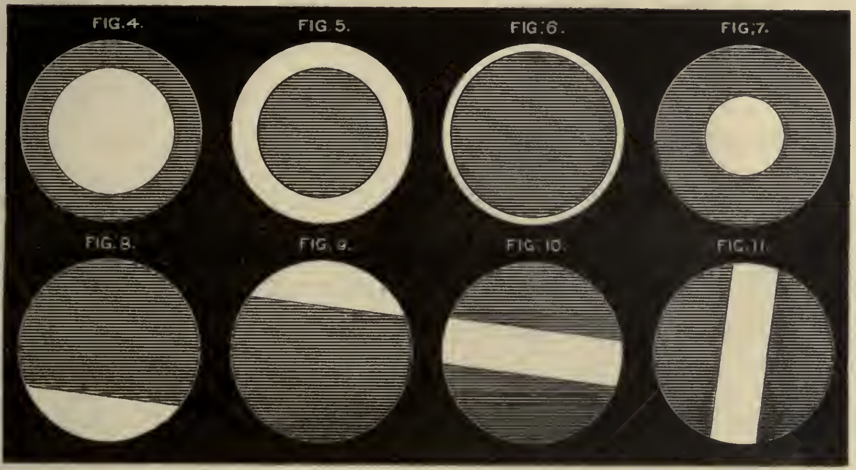


FIG. 4. FIG. 5. FIG. 6. FIG. 7.
FIG. 8. FIG. 9. FIG. 10. FIG. 11.

during an observation, August 25, 1875, the radiation from the solar disc being then excluded in the manner shown in Figs. 6 and 7.

Time.	Central portion. Cent.	Border. Cent.	Rate of difference.
4′	3°.28	2°.19	$\frac{2.19}{3.28} = 0.667$
5′	3°.56	2°.37	$\frac{2.37}{3.56} = 0.665$
6′	3°.73	2°.49	$\frac{2.49}{3.73} = 0.667$
7′	3°.88	2°.60	$\frac{2.60}{3.88} = 0.669$
			Mean = 0.667

It should be particularly observed that this table records the result of four distinct observations; nor should it be overlooked that although the intensities vary greatly for each observation, in consequence of the continued exposure to the sun, yet the rates showing the difference of the intensity of the rays transmitted from the border, inserted in the last column, is practically the same for each observation, the discrepancy between the highest and the lowest rate being only 0.004. It should be mentioned that all my instruments for measuring radiant heat referred to in this work have been graduated to the Fahrenheit scale, which practically is more exact than the Centigrade, owing to its finer divisions. For the benefit of the majority of readers the observed temperatures have been reduced to Centigrade scale before being entered in our tables. Persons practically acquainted with the difficulty of ascertaining the intensity of solar radiation will be surprised at the exactness and consistency of the indications of our instruments. This desirable exactness has been attained by surrounding the actinometers with water-jackets, which communicate with each other by connecting pipes, through which a steady stream of water is circulated. By this expedient the chambers containing the bulbs of the several thermometers are maintained with critical nicety at equal temperature—an inexorable condition when the object is to determine differential temperature with great exactness. Apart from this, the chambers which contain the bulbs of the thermometers are air-tight, the radiant heat being admitted through a small aperture at the top of the chamber, covered by a thin crystal.

Referring to the preceding table, it will be seen that the intensity transmitted by radiation from the sun's border, represented in Fig. 6, is 0.667 of the intensity transmitted from the central region represented in Fig. 7, the area of each being precisely alike. From the stated intensity must be deducted the heat imparted to the actinometer by the inflection of the calorific rays. The circumference of the perforation of the screen shown in Fig. 7 being exactly one-half of the circumference of the screen in Fig. 6, while the central region radiates more powerfully than the border, fully one-half of the inflected radiation from the border will be balanced by the inflected radiation emanating from the central region. Agreeably to the previous demonstration relating to Figs. 2 and 3, it will be seen that the unbalanced inflection amounts to

0.029; hence the radiation transmitted from the border zone will be 0.667 − 0.029 = 0.638 of the intensity of radiation transmitted from the central region. We have thus shown by a reliable method that the intensity of the rays directed towards the earth from the border zone suffers a diminution of 1.000 − 0.638 = 0.362 of the intensity of the radiation emanating from the central region. But the mean depth of the solar atmosphere of the border zone, in the direction of the earth, is 2.551 greater than the vertical depth, while the mean depth over the central region referred to is only 0.036 greater than the vertical depth of the solar atmosphere. It will be evident that if the law of retardation were known, the foregoing figures would enable us to determine the absorptive power of the solar atmosphere. Concerning this law, it should be mentioned that in the first edition of "Le Soleil," page 264, the author assumes that the absorption of the calorific rays by the atmosphere "augments in proportion to the secant of the zenith distance"; in other words, as the depth of the atmosphere penetrated by the rays. Consequently, if this assumption be correct, the absorption by the solar atmosphere cannot exceed $\frac{0.362}{2.551 - 0.036} = 0.144$ of the radiant heat emanating from the photosphere. It will be found, on referring to the revised edition of "Le Soleil," Vol. I., p. 212, that Père Secchi makes the following statements regarding the absorptive power of the solar atmosphere: (1) "At the centre of the disc—that is to say, perpendicularly to the surface of the photosphere—the absorption arrests about $\frac{2}{3}$, or, more exactly, $\frac{62}{100}$, of the total force." (2) "The total action of the absorbing envelope on the hemisphere visible from the sun is so great that it allows only $\frac{12}{100}$ of the total radiation to pass, the remainder, namely, $\frac{88}{100}$, being absorbed." It is unnecessary to criticise these figures presented by the Roman astronomer, as a cursory inspection of our table and diagrams is sufficient to show the fallacy of his computations. Besides determining the absorptive power of the solar atmosphere, another important problem may be solved by accurately measuring the intensity of the radiation emanating from various parts of the disc—namely, that relating to the sun's emissive power in different directions. In order to decide this question, I have adopted the plan of measuring the energy of the radiant heat transmitted from zones crossing the solar disc at right angles, as shown in Figs. 10 and 11. Repeated observations having shown that the actinometers are equally affected by the radiation from these zones, each of which occupies an arc of 30 deg., containing one-third of the area of the disc, the inference is irresistible that the sun emits heat of equal intensity in all directions. It should be borne in mind that, agreeably to our method, the radiations from these zones are observed simultaneously—a fact tending to prove that our conclusions cannot be erroneous. The arrangement exhibited in Figs. 10 and 11 hardly needs explanation. Referring to Fig. 10, it will be seen that two segmental screens are employed excluding the radiant heat, excepting from the zone, which is parallel with the sun's equator. Similar screens are employed (see Fig. 11) for excluding the rays excepting from the zone parallel with the sun's polar axis. The curvatures of the segmental screens, it should be observed, have been struck to a radius of ninety millimetres, in order to cut off effectually the inflected radiation from the sun's border. Obviously diffraction has not called for any correction of our observations relating to this part of the investigation, since the inflected radiation from the equatorial zone exactly balances the inflected radiation from the polar zone. As already stated, repeated observations show that the radiant energies transmitted to the actinometers from the two zones are identical.

The observations relating to the temperature of the polar regions, represented in Figs. 8 and 9, at first led to the supposition that the rays projected from the north pole of the sun transmit a perceptibly greater energy to the actinometers than the rays from the opposite pole. Subsequent observations having positively established the fact that the polar and equatorial zones transmit equal intensities, it became evident that some other cause than difference of temperature within the polar regions influenced the actinometers. The only valid reason that could be assigned in explanation of the anomaly being the considerable angle subtended, and the consequent difference of zenith distance of the opposite poles of the sun, my table of maximum solar intensity for given zenith distances (prepared from data collected during a series of years) was consulted, in order to ascertain the influence of zenith distance. The observations indicating a higher temperature at the north pole, it should be mentioned, had been made while the sun's zenith distance ranged between 32 deg. and 33 deg. at noon. Now, the table referred to shows that there is a difference of radiant intensity of 63°.63 − 63°.40 = 0°.23 F. between the stated zenith distances. The mean angle subtended by the sun being fully thirty-two minutes, it will thus be seen that, owing to the absorptive power of the terrestrial atmosphere, the radiant intensities transmitted from the opposite poles of the luminary differ considerably. The magnitude of this difference, adequate to explain the discrepancy under consideration, need not excite surprise if we consider that thirty-two minutes of zenith distance involves an additional depth of more than half a mile of atmosphere to be penetrated by the rays projected towards the actinometer from the *south* pole of the sun. The foregoing facts show the necessity of taking the difference of zenith distance between the opposite poles into account in making exact observations of the sun's polar temperature, especially at the lower altitudes, where the secant of the zenith distance increases rapidly.

Regarding the calorific energy of the radiation emanating from the border of the sun, the following brief statement presents facts of considerable importance hitherto unknown. Several observations during the early part of the investigation pointed to the fact that increased energy is transmitted to the actinometers by radiation from the sun's border. Again, considerable irregularity was observed in the progressive diminution of the force of radiation towards the circumference of the solar disc. It has already been shown that the radiation from the border zone, 1′ 42″ wide, occupying one-fifth of the area of the solar disc, transmits 0.638 of the intensity transmitted from an equal area at the centre of the disc. Of course it will be supposed that the rate of the diminution of intensity within the zone thus ascertained is much greater near the border of the photosphere than at the middle of the zone. Such, however, is by no means the case, notwithstanding the assumption of physicists that the heat transmitted by radiation from the border is very feeble. In order to test

FIG. 12.

FIG. 13.

the truth of the indications referred to, showing considerable radiant energy at the border of the photosphere, a very careful investigation was made, Sept. 9, 1875, by means of screens excluding the rays from the solar disc, as shown in Figs. 12 and 13. The diameter of the screen represented in Fig. 12, being 154.06 millimetres, covered nine-tenths of the area of the disc; while the screen shown in Fig. 13, being 145.25 millimetres, covered four-fifths of the disc. It will be well to mention that the dimensions of the screens referred to correspond to the angle subtended by the sun when the earth is in aphelion. Accordingly, the distance between the actinometers and the screens was adjusted previous to the observation—that is, shortened—in order to compensate for the increase of the angle subtended by the sun. Agreeably to the stated dimensions of the screens, it will be found that the zone represented in Fig. 13 is 1′ 42″, while the zone in Fig. 12 is 49″.6. The mean width of the latter is consequently situated only 24″.3 from the border of the photosphere.

The following table shows the intensities transmitted to the actinometers from the zones represented in Figs. 12 and 13:

Time.	Zone, Fig. 13. Cent.	Zone, Fig. 12. Cent.	Rate of Difference.
4′	2°.011	1°.333	$\frac{1.333}{2.011} = 0.662$
5′	2°.248	1°.471	$\frac{1.471}{2.248} = 0.654$
6′	2°.425	1°.583	$\frac{1.583}{2.425} = 0.652$
7′	2°.485	1°.666	$\frac{1.666}{2.485} = 0.670$
			Mean = 0.660

The rate of difference inserted in the last column, it will be noticed, is not quite so consistent as in the table recording the observations made Aug. 25. The discrepancy is, however, not material, the difference between the lowest and the mean rate being 0.008. It will be seen, on inspecting the registered intensities, that the border zone represented in Fig. 12, whose area is only one-half of the area of the zone in Fig. 13, transmits 0.660 of the intensity of the latter. This, at first sight, indicates an extremely disproportionate transmission of heat from the narrow border zone; but it should be considered that the inflected radiation imparts relatively more heat to the actinometer exposed to the radiation from the narrow zone than from the wide zone. It will be readily understood that, since the inflection of the calorific rays is $14''.7$, the first-mentioned actinometer receives radiant heat from $14''.7 + 49''.6 = 64''.3$; while the actinometer exposed to the radiation from the wide zone receives heat from $1' \, 42'' + 14''.7 = 116''.7$. Consequently, the radiant heat emanating from the narrow zone will be $\frac{64''.3}{116''.7} = 0.551$ of that transmitted from the wide zone, hence somewhat more than one-half. Our investigation therefore proves that the radiant heat transmitted from the narrow border zone represented in Fig. 12 is $0.660 - 0.551 = 0.109$ more intense than that transmitted from the zone represented in Fig. 13, although the mean distance of the latter is twice as far from the border of the photosphere as the mean distance of the former. The singular fact thus revealed can only be accounted for by supposing that internal radiation is not incompatible with the constitution of the photosphere, and by adopting Lockyer's views expressed in the Senate House at Cambridge, 1871, that "the photosphere must be a something suspended in the solar atmosphere." Let *a b*, Fig. 14, represent a section of the "suspended" photosphere, and *d c*, *g f*, rays projected towards the earth. Agreeably to the conditions mentioned, and in view of the fact that the force of radiation from incandescent gases presenting equal areas varies nearly as their depth, we are warranted in concluding that, since the depth *d d'* is greater than *g g'*, the radiant heat transmitted from the photosphere by the ray *d c* will be greater than that transmitted by the ray *g f*. It should be observed that the energy transmitted towards the earth by *d c* suffers a greater diminution than the energy transmitted by *g f*, in consequence of the greater depth of the solar atmosphere penetrated. Hence the augmented energy established by our investigation does not show the full amount of the increase of radiant heat transmitted from the border of the sun.

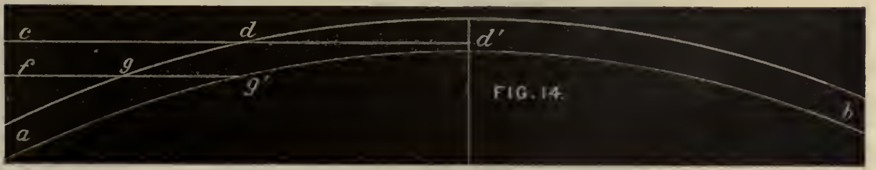


FIG. 14.

Having thus briefly stated the result of my observations, it will be proper to mention that, before undertaking a systematic investigation of the difference of thermal energy transmitted to the earth by radiation from different parts of the solar surface, I examined thoroughly the merits of Laplace's famous demonstration relating to the absorptive power of the sun's atmosphere, proving that only $\frac{1}{12}$ of the energy developed by the sun is transmitted to the earth. The demonstration being based on the assumption that the sun's rays emit energy of equal intensity in all directions, my initiary step was that of testing practically the truth of that proposition. It has been asserted that Laplace did not propound the singular doctrine involved in such a proposition; I therefore feel called upon, before proving its unsoundness, to quote the words employed by the celebrated mathematician (see "Mécanique Céleste," Tom. IV. page 284). Having called attention to the fact that any portion of the solar


FIG. 18

disc, as it approaches the limb, ought to appear *more brilliant* because it is viewed under a *less angle*, Laplace adds: "Car il est naturel de penser que chaque point de la surface du soleil renvoie une lumière égale dans tous les sens." Let *a b c d* in the above diagram, Fig. 18, represent part of the border of the sun, and *b a*, *c d*, small *equal* arcs; *a a′*, *b b′*, *c c′*, *d d′*, being parallel rays projected towards the earth. Laplace's theory asserts that, owing to the concentration of the rays, the radiation emanating from the portion *d c* transmits *greater* intensity towards the earth than *b a*, in the proportion of *c d* to *f c*. The proposition is thus stated in "Mécanique Céleste": "Call θ the arc of a great circle of the sun's surface, included between the luminous point and the centre of the sun's disc, the sun's radius being taken for unity; a very small portion, *a*, of the surface being removed to the distance θ from the centre of the disc, will appear to be reduced to the space a cos. θ; the intensity of its light must therefore be increased in the ratio of unity to cos. θ."

In order to disprove the correctness of the stated demonstration, I have measured the relative thermal energy of rays projected in different directions from an incandescent metallic disc by the method minutely described in Chap. XI. The following brief description will, however, be necessary in this place, reference being had to the illustration adverted to in the said Chapter XI. (see Plate 21). Fig. 2 represents a section of a conical vessel covered by a movable semi-spherical top, the vessel being surrounded by a jacket through which water may be circulated. A revolving disc *a a*, composed of cast iron, the back being semi-spherical and protected by fire-clay, is suspended across the top of the conical vessel, supported by horizontal journals attached at opposite sides. The angular position of the disc is regulated by a radial handle *b*, connected to one of the journals, the exact inclination to the vertical line being ascertained by means of a graduated quadrant *d*. An instrument *c*, capable of indicating the intensity of the radiant heat transmitted by the incandescent disc, is applied at the bottom of the conical vessel. The movable cover and its lining of fire-clay being removed, the cast-iron disc is heated in an air-furnace to a temperature of 1,800° F. It is then removed by appropriate tongs, and suspended over the conical vessel, the lining and cover being quickly replaced. The temperature shown by the instrument at the bottom of the conical vessel, resulting from the action of the radiant heat of the disc, is then recorded for every tenth degree of inclination. The investigation, it may be briefly stated, shows that the temperature imparted by radiation to the recording instrument is exactly as the sines of the angles of inclination of the disc. Hence, at an inclination of 10 deg. to the vertical line, the temperature imparted to the thermometer is scarcely $\frac{1}{6}$ of that imparted when the disc faces the thermometer at right angles; yet in both cases *an equal amount of surface of an equal degree of incandescence* is radiating towards the instrument. Laplace and his followers have evidently overlooked this important and somewhat anomalous fact proving that radiation emanating from heated bodies is incapable of exerting full energy in more than one direction. Our practical experiments with the revolving incandescent disc have thus fully demonstrated the truth of the proposition intended to be established—namely, that the rays emanating from incandescent planes do not transmit heat of equal intensity in all directions, the energy transmitted being, as stated, proportionate to the sines of their angle of inclination to the radiating surface.

The next step in the preliminary investigation was that of measuring the radiant energy transmitted in a given direction by an incandescent solid metallic sphere. For this purpose I employed a double conical vessel similar to the one already described, the incandescent sphere being suspended over the conical vessel in the manner minutely described in Chap. XII. A brief explanation will, however, be necessary here, reference being had to the diagram on Plate 24, representing four spheres, Figs. 3, 4, 5, and 6. Each sphere is divided into four zones, A, B, C, and D, occupying unequal arcs, but containing equal convex areas. Semi-spherical screens, composed of non-conducting substances, were applied below each sphere, provided with annular openings arranged as shown in the diagram. Through these annular openings the radiant heat from the incandescent zones D, C, B, and A was transmitted to the thermometers *f*, *g*, *h*, and *k* respectively. Père Secchi and other followers of Laplace will be surprised to learn that when the suspended sphere was maintained at a temperature of 1,800° F., the radiation from the zone C, Fig. 4, imparted a temperature of 27°.49 F. to the thermometer *g;* while the radiation from the zone A, Fig. 6, imparted only 6°.19 F. to the thermometer *k*. Let us bear in mind that the radiating surface *l m* of the zone A is equal to the radiating surface *p q* of the zone C. The stated great difference of temperature produced by the radiation from zones of equal area furnishes additional proof that Laplace based his remarkable analysis on false premises. "The sun's disc ought to appear more brilliant towards the border because viewed under a less angle," we are told by the great analyst. The instituted practical tests, however, prove positively that the energy of the rays projected from the border of an incandescent sphere is greatly diminished *because viewed under a less angle* from the point occupied by the recording thermometer.

The result of the experiment with the revolving incandescent disc shows that if the small arc *b a*, in Fig. 18, be reduced until the field represented by *b′ a′* becomes equal to the field represented by *c′ d′*, the radiant energy transmitted through each of those fields will be alike; the reason being that the number of rays of diminished intensity passing through *c′ d′* will be as much greater than the number of rays of maximum intensity passing through *b′ a′* as *c d* is greater than the reduced $b\ a = f\ c$. It should be observed that *c d* is so small that we may, without appreciable error, regard it as a straight line, and *f c* as the sine of the angle *c d f*. It follows from this demonstration that if the solar atmosphere exerted no retarding influence, the radiant heat transmitted towards the earth would be alike for equal areas of the solar disc; more correctly, for areas subtending equal angles, since the receding part of the solar surface is at a greater distance from the earth than the central part.

Encouraged by the results of the instituted practical tests showing the actual intensity transmitted by radiant heat emanating from incandescent spheres and inclined discs, I devised the method before described, proving positively that the polar and equatorial regions of the solar disc transmit radiant heat of equal intensity to the earth, and that the sun emits heat of equal energy in all directions. Accepting Secchi's doctrine relating to the retardation suffered by calorific rays in passing through atmospheres—namely, that the diminution of energy is as the depth penetrated by the rays—I have shown, by the easy calculation before presented, that the absorption by the solar atmosphere cannot exceed $\frac{144}{1000}$ of the radiant energy emanating from the photosphere.

Concerning the plan resorted to by the Director of the Roman Observatory and others of investigating the sun's image instead of adopting the method of *direct* observations, I will merely observe, in addition to what has already been stated, that the information contained in the several works of the Roman astronomer furnishes the best possible guide in judging of the efficacy of *image-investigation.* Let us select his account of the investigations conducted between the 19th and 23d of March, 1852. Having pointed out that in these experiments it was impossible to approach within a minute of the edge of the sun, and that during a later observation —date not mentioned—he had approached within a minute, the investigator observes: "But at this extreme limit, even making use of the most accurate means of observation, we find difficulties which it is impossible to overcome completely." In addition to this emphatic expression regarding the difficulties encountered, the author adds: "Moreover, it is impossible to study the edge alone, for the unavoidable motions of the image do not admit of its being retained at exactly the same point of the pile; we have, therefore, been unable to push the exactness as far as we hoped, and we have discontinued the pursuit of these researches, although the results obtained are quite interesting." (See revised edition of "Le Soleil," Vol. I. p. 205.) It is needless to institute a comparison between a system of which its founder speaks so despondingly and one which enables us to push our investigations to the extreme limit of the solar disc, admitting of entire zones being viewed at once, instead of only small, isolated spots.

The foregoing demonstration, showing that the solar atmosphere absorbs 0.144 of the heat radiated, it should be remembered, is based on the assumption that the retardation is as the depth penetrated by the rays. In view of the fact that projectile force diminishes inversely as the square of the depth of the medium penetrated, we are, of course, not compelled to accept the stated assumption. Adopting the dynamical law relating to projectile motion, referred to, it will be found that the retardation, instead of being 0.144, will be $\frac{0.362}{(2.551 - 0.036)^2} = 0.057$. But even this apparently small amount of absorption of the radiant intensity cannot be satisfactorily accounted for, since the mechanical energy developed by the sun is at least 322,000 thermal units per minute upon an area of one square foot. Consequently, $322{,}000 \times 0.057 \times 772 = 14{,}169{,}288$ foot-pounds represent the mechanical equivalent of $\frac{57}{1000}$ of the radiant energy emanating from each square foot of the photosphere. Owing to the high temperature and consequent lightness, no conceivable work performed within the solar atmosphere can satisfactorily account for the disappearance, every minute, of such an amount of energy. It is therefore demonstrable that we have not underrated the absorptive power.

CHAPTER VII.

THE SOURCE OF SOLAR ENERGY.

Sir William Thomson, in his celebrated paper on the Mechanical Energies of the Solar System, read before the Royal Society of Edinburgh, April, 1854, puts the question: "What is the source of mechanical energy, drawn upon by the sun, in emitting heat, to be dissipated in space?" Having very briefly examined the question, he adds: "We see, then, that all theories which have yet been proposed, as well as every conceivable theory, must be one or other, or a combination, of the following three: (1) That the sun is a heated body losing heat. (2) That the heat emitted from the sun is due to chemical action among materials originally belonging to the mass, or that the sun is a great fire. (3) That meteors falling into the sun give rise to the heat which he emits." The second and third of these suppositions having been disposed of by more recent investigations, let us confine our discussion to the *first* hypothesis, that the sun is a heated body losing heat, regarding which the eminent physicist remarks: "In alluding to theories of solar heat in a former communication to the Royal Society I pointed out that the first hypothesis is quite untenable. In fact, it is demonstrable that, unless the sun be of matter inconceivably more conductive for heat, and less volatile, than any terrestrial meteoric matter we know, he would become dark in two or three minutes, or days, or months, or years, at his present rate of emission, if he had no source of energy to draw from but primitive heat. This assertion is founded on the supposition that conduction is the only means by which heat could reach the sun's surface from the interior, and perhaps requires limitation. For it might be supposed that, as the sun is no doubt a melted mass, the brightness of his surface is constantly refreshed by incandescent fluid rushing from below to take the place of matter falling upon the surface after becoming somewhat cooled and consequently denser—a process which might go on for many years without any sensible loss of brightness. If we consider, however, the whole annular emission at the present actual rate, we find, even if the sun's thermal capacity were as great as that of an equal mass of water, that his mean temperature would be lowered by about 3° Cent. in two years." It would appear from this reasoning that Sir William Thomson had overlooked Laplace's important nebular theory which leads to the conclusion that the sun's heat is the result of condensation caused by gravitation. Obviously this condensation is progressing at the present time as fast as the mass cools, the process being the same now as millions of years ago, the heat generated by the condensation becoming gradually intensified in the inverse ratio of the radius of the contracting mass. Let us consider, however, that the matter composing this contracting mass suffers a proportionate reduction of velocity; hence the emission of heat becomes constant for a given area of the solar surface, notwithstanding the augmentation of intensity. But, while the emission from a given area is constant, the bulk of the cooling mass is continually diminishing. The important consequences of this diminution of bulk will be considered presently. Of course it will not be necessary to prove that the sun is continually becoming smaller, since all incandescent bodies shrink rapidly if permitted to radiate freely, the rate being nearly proportional to the degree of incandescence. Our task, therefore, will be confined to a simple demonstration showing that the emission of 322,000 thermal units per minute on each square foot of solar surface, established in Chapter V., is capable of being developed by the contraction of the mass, in accordance with the nebular theory of Laplace. At first sight it would appear that no probable amount of contraction of the solar mass could develop, by gravitation towards the centre, an amount of mechanical energy of 322,000 × 772 = 248,584,000 foot-pounds per *minute* for each square foot of the surface of the sun. Yet so vast is the amount of matter covered by the insignificant area of 144 square inches of the solar surface—in other words, such is the contents of a spherical pyramid the base of which is one square foot, and whose length is equal to the sun's radius—that a very small amount of contraction suffices to develop, by gravitation towards the solar centre, the stated enormous mechanical energy. It will be readily understood that the energy developed by the shrinking of a spherical pyramid whose sides are sectors of the great circle of the sun will represent correctly the relative energy produced by the shrinking of the entire solar mass. Hence, if we can determine the amount of longitudinal contraction of the supposed spherical pyramid requisite to produce, by gravitation towards the centre of the mass, a mechanical energy of 248,584,000 foot-pounds per minute, we need not enter into any further computation, since a corresponding contraction of the sun's radius will develop for every square foot of his surface a like energy.

Let I K S, Fig. 1 (see Plate 14), represent the great circle of the sun, *a m a'* the spherical pyramid referred to, and Fig. 2 the said pyramid drawn to a larger scale, its axis being divided into ten equal parts. It is proposed to ascertain what extent of longitudinal contraction of the spherical pyramid *a m a'* is necessary to produce an amount of dynamic energy corresponding with that developed by the radiation from 1 sq. ft. of the solar surface in a given time. The investigation will be facilitated and more readily comprehended if we compute the amount of energy developed by a definite contraction of the sun's radius, say one foot. Let us, therefore, suppose that the surface *a a'*, the distance of which is $\frac{852,584}{2} \times 5,280 = 2,250,821,760$ ft. from *m*, has fallen through a space of one foot, the intermediate points *b*, *c*, *d*, etc., participating proportionably in the fall. Assuming that the solar mass remains homogeneous during the contraction, it follows from Newton's demonstration ("Principia," Lib. I. Prop. LXXIII.) that, since a particle just within the circumference of the sphere at *a* is ten times further from the centre *m* than a particle at *l*, the former will be attracted towards *m* with ten times greater force than the latter. It will be perceived, on reflection, that, for a given movement towards the centre, the quantity of matter put in motion at *a* will be greater than at *l*, in the ratio of the squares of *a a'*, and *l* 1, or 100 : 1. Hence, in accordance with the demonstration referred to, a given radial depth of the solar mass at *a* will exert a force towards *m* 10 × 100 = 1,000 times greater than an equal radial depth at *l*. But in computing the dynamic energy developed by the shrinking of the sun, it must be borne in mind that a particle at *a* falls through a distance ten times greater than a particle at *l*. The length of the ordinates of the curve *p t*, Fig. 3, representing the ratio of dynamic energy developed at the respective distances from the sun's centre, has been calculated accordingly. A cursory examination of Fig. 2 can scarcely fail to lead to the supposition that the mass composing the smaller sections of the spherical pyramid near the centre of the sphere will be attracted by the larger mass composing the sections near the circumference. Newton has disposed of this question by a geometrical demonstration which, considering the form of the attracting mass, and the extreme complication arising from the varying direction and unequal magnitude of the attracting forces, may be regarded as one of the most elegant of his masterly demonstrations of important propositions and theorems. Unless it can be proved that a particle at P is not attracted by any portion of the mass contained within the external spherical superficies I K S and the interior spherical superficies P *p*, we must assume that the mass composing the sections near the base of the spherical pyramid will exert the disturbing attraction before alluded to. Hence our demonstration of the energy produced by the attraction of the matter within the sun, during shrinking, falls to the ground unless it can be shown that every particle composing the spherical pyramid is in perfect repose as regards the attraction exerted by exterior particles. The great geometer thus establishes that repose: "Let H I K L be a spherical superficies and P a corpuscle placed within. Through P let there be drawn to this superficies the two lines H K, I L, intersecting very small arcs H I, K L; and because the triangles H P I, L P K are homogeneous, those arcs will be proportional to the distances H P, L P, and any particles at H I and K L of the spherical superficies, terminated by right lines passing through P, will be in duplicate ratio of those distances. Therefore the forces of these particles exerted upon the body P are equal between themselves. For the forces are as the particles directly, and the squares of the distances inversely. And these two ratios compose the ratio of equality. The attractions, therefore, being made equally towards contrary parts, destroy each other; and, by a like reasoning, all the attractions through the whole spherical superficies are destroyed by contrary attractions. Therefore the body P will not be any way impelled by those attractions."

Sir Isaac Newton, in his demonstrations relating to spherical bodies, supposed these to be composed of an infinite number of spherical superficies, the thickness of which he thus defines: "By the superficies of which I here imagine the solids composed, I do not mean superficies purely mathematical, but orbs so extremely thin that their thickness is as nothing; that is, the evanescent orbs of which the sphere will at last consist when the number of the orbs is increased, and their thickness diminished without end."

Referring to Fig. 3, it should be particularly observed that the ordinates of the curve *p t* do not indicate the force exerted by mere attraction. As already stated, their length represents the *dynamic energy* developed at the indicated distances from the solar centre. Consequently, the energy actually developed by the shrinking of the mass is represented by the superficies *o p t*, while the rectangle *o p u t* represents the energy that would be called forth if the force exerted at every point of the axis of the spherical pyramid were the same as that exerted at *a a'*. Having already pointed out the manner of determining the length of the ordinates of the curve *p t*, it will suffice to state that their mean length is 0.20015 of *o p;* hence the superficies *o p t* is 0.20015 of the superficies *o p u t*.

Let us now consider whether the want of homogeneity of the solar mass will materially affect the calculated amount of energy developed by the gravitating force during the sun's shrinking. Referring to the diagram Fig. 3, it will be seen that the energy exerted by a given small amount of contraction at a section equidistant between *m* and *a*—viz., at *f* 5—will be, as shown by the length of the ordinates, $\frac{625}{10,000} = \frac{1}{16}$ of that exerted by a like amount of contraction at *a a′;* and that, since *m f* is one-half of *m a*, the energy developed by the contraction of the mass contained within the spherical pyramid *f m* 5 amounts to only $\frac{1}{32}$ of that developed by the contraction of the mass contained in the spherical pyramid *a m a′*. Now, the volume of the spherical pyramid *f m* 5 represents that of a sphere the diameter of which is one-half of the sun, while the spherical pyramid *a m a′* represents the volume of the entire solar mass. The energy resulting from gravitation during the contraction of the central spherical mass P *p* being thus only $\frac{1}{32}$ of the energy resulting from gravitation during the contraction of the spherical mass I K S, it will be perceived that the degree of density of the matter near the sun's centre will not materially affect the result of our calculations founded on perfect homogeneity.

We may now proceed to ascertain the amount of dynamic energy produced by the assumed contraction of one foot of the axis of the spherical pyramid *a m a′*. Having already demonstrated that the said energy will be 0.20015 of that produced by the gravitation of a homogeneous mass, the section of which is one square foot, extending from *a a′* to *m*, it only remains to determine the weight of one cubic foot at the surface of the sun. The weight of the solar mass being 85.6 lbs. per cubic foot, while the sun's attraction is 27.2 times greater than terrestrial attraction, the weight of one cubic foot of the solar surface will be 27.2 × 85.6 = 2,328.3 lbs.; multiplying this weight by the sun's radius, expressed in feet, we have 2,328.3 × 2,250,821,000 = 5,240,586,000,000, which product multiplied by 0.20015 shows that the gravitating energy of the matter contained in the spherical pyramid, exerted during a longitudinal contraction of one foot, amounts to 1,048,900,000,000 foot-pounds. Dividing this latter product by the ascertained solar emission of 248,584,000 foot-pounds per minute, it will be seen that the mechanical energy produced by the shrinking of one foot of the sun's radius is sufficient to make good the power lost by solar emission during a period of 4,219.5 minutes. If we then divide this quotient in the minutes in a year, 525,960, it will be found that a fall of 124.65 feet of the solar surface per annum must take place in order to sustain the present emission of heat. At this rate of shrinking the diameter of the sun will be reduced $\frac{1}{10000}$ in the course of 1,805 years. It has already been observed that the intensity of the radiant heat will not diminish with the diminished size of the sun. On the contrary, for a given area of the solar surface, the dynamic energy produced by a given rate of shrinking will be increased, since the mass remains the same, while the attraction is inversely proportional to the distance from the centre. But the *rate* will diminish with the contraction of the sphere; hence a shrinking of $\frac{1}{10}$th of the sun's diameter, instead of occupying 1,000 × 1,805 = 1,805,000 years, will require somewhat more than 2,000,000 years. At the end of that period the gravitating energy will continue to develop, as at present, an amount of dynamic energy represented by 322,000 thermal units per minute for each superficial foot; but the radiating surface —*i.e.*, the area of the solar disc—will have diminished in the ratio of nearly 10^2 to 9^2.

The present maximum temperature produced by solar radiation on the ecliptic when the earth is in aphelion being 67.2 deg. (see Chap. III.), while the intensity of radiant heat diminishes as the area of the radiating surface, it follows that at the end of 2,000,000 years from the present time the tropical solar intensity will be reduced to $\frac{9^2 \times 67.2}{10^2} = 54.4$ deg. Fahrenheit. The result of the elaborate investigations of solar intensity described in the preceding chapter proves the correctness of the foregoing calculations based on the *area* of the solar disc, and disposes of the opinion held by some physicists that there is no established relation between the diameter of the sun and the transmitted energy. It was found, during the investigation referred to, that, in shutting out the radiation from the external zones of the sun and exposing an actinometer to the rays emanating from a circular area at the centre measuring 380,000 miles in diameter, the intensity of the radiant heat was reduced to one-third of that transmitted to another actinometer exposed to the radiation from the entire solar disc. Can we doubt, then, that the future diminution of the diameter of the sun will cause a corresponding diminution of the transmitted energy? Adopting the same mode of calculating the solar intensity for past ages as the foregoing calculation of future solar intensity, it will be found that the temperature produced by solar radiation 2,000,000 years ago (owing to the greater diameter of the sun at that period) must have been nearly $\frac{11^2 \times 67.2}{10^2} = 81$ deg. Fah. within the tropics. Concerning this great intensity of the radiant heat, and the consequent high atmospheric temperature, we are justified in assuming that increased evaporation of the sea, and corresponding humidity of the atmosphere, mollified the apparently destructive temperature, calling forth the luxuriant flora which geology has made us acquainted with. The computed diminution of solar intensity, 67 deg. − 54 deg. = 13 deg., during the next 2,000,000 years, will be deemed extravagant by those who do not bear in mind that we must base our computation on the assumption that a *continuous* power will be exerted during the stated period capable of developing, as at present, the stupendous energy of 248 millions of foot-pounds in a single minute for each square foot of the surface of a sphere whose diameter exceeds 850,000 miles. Persons speculating on the cause of solar energy will do well to consider that this inconceivable amount of work cannot be performed with a less expenditure than the motive energy developed by the fall of a mass equal to the mass contained in the sun. But a *continuous* development of such an amount of energy is obviously impossible, since the distance is limited through which the mass can fall. Now, the foregoing demonstration enables us to determine the said limit with sufficient exactness to prove that, although the efficiency of the great motor during the past may be measured by hundreds of millions of years, its future efficiency will be of comparatively brief duration.

Statements frequently made relating to the permanency of solar heat, based on the assertion that no diminution has been observed during historic times, have no weight in view of our demonstration showing that a shrinking of $\frac{1}{10}$ of the sun's diameter can only reduce the intensity from 81 deg. to 67.2 deg., difference = 13.8 deg., in the course of two millions of years. This period being 500 times longer than "historic times," it will be seen that the diminution of the temperature produced by solar radiation has not exceeded $\frac{13.8}{500} = 0.027$, or $\frac{1}{37}$ deg. Fah., since the erection of the Pyramids.

It will be proper to notice, before concluding our brief investigation of the source of solar energy, that the development of heat by the shrinking of the sun, however fully demonstrated, leaves the important question unanswered: How is the heat generated by gravitation within the mass transmitted to the surface? If the matter within the sun is a perfect conductor of heat—a very improbable supposition—that fact alone furnishes a satisfactory answer. Imperfect conductivity, on the other hand, calls for other means of transmitting the energy from within to the surface. What those means are presents a problem susceptible of positive demonstration. The application of cold at the surface of any heated gaseous fluid, or the reduction of temperature of such a fluid by radiation upwards, invariably produces a vertical circulation within the heated mass, the particles cooled descending, in virtue of their increased specific gravity. Evidently a number of particles descending one after the other will produce a downward vertical current of greater specific gravity than the rest of the fluid. Now, as this current, composed of comparatively cold and heavy particles, descends, it displaces a corresponding bulk of heated fluid, which, since there is no unoccupied space below, must rise to the surface. Descending and ascending currents of nearly uniform magnitude and velocity will thus be established in the heated fluid mass, provided no disturbing force be applied, causing agitation either at the surface or within. It needs no proof to show that in case disturbing force be applied the regularity of the distribution of descending and ascending currents within the fluid ceases, and that the established vertical circulation, instead of being alike at all points, becomes divided into groups. Nor is it necessary that the disturbing force should be of great magnitude. Obviously a continued uniform distribution of the descending and ascending currents through the heated mass calls for perfect absence of disturbing influences of any kind. Now, within the sun the descending and ascending masses of heated matter are influenced by numerous disturbing causes. (1) The particles composing the descending currents, possessing the *vis viva* due to the angular velocity of the sun's surface, gradually encounter the particles of less angular velocity composing the ascending columns. Conflicting motions will thus be produced, resulting in an increased angular velocity of the interior of the solar mass; while (2) the particles of the ascending currents, which start with a slow angular velocity, will be gradually impelled by the surrounding mass during their ascent; the energy thereby absorbed causing a lagging of the entire solar mass towards the surface. Of course there is an exchange of angular *vis viva* between the descending and ascending currents, but obviously there will be a loss, productive of perceptible lagging at the surface of the rotating mass. (3) The attraction of the planetary masses will seriously disturb the vertical circulation by alternately impelling and retarding one or the other of the descending and ascending columns of heated matter, thus occasioning great irregularity. (4) The periodic change of position of the centre of gravity of the aggregate planetary mass must necessarily produce a periodic maximum and minimum disturbance of the descending and ascending currents within the solar mass. It will be evident that the frequent near approach and consequent powerful attraction of Venus greatly complicates the question of maximum disturbance. (5) The rotation of the sun, it should be particularly observed, tends to mollify the disturbing influence of planetary attraction on the vertical circulation, since, owing to this rotation, the descending and ascending motion of the heated matter within the solar mass is successively relieved from maximum disturbing influence twice in twenty-five days. It may be shown that, but for this frequent check, the power exercised by planetary attraction would augment, and fatally derange the internal circulation indispensable to the regular performance of the functions assigned to the sun. (6) It needs no explanation that a continuous disturbance and consequent cessation of circulation at certain points of the solar surface would produce permanent dark spots. Bearing in mind the enormous amount of the regular emission of heat demonstrated in Chap. V. (322,000 thermal units per minute on a square foot of the solar surface), it becomes evident that any considerable diminution of the supply of energy from within, consequent on deranged circulation, will at once produce a great fall of temperature at the surface of the photosphere, and a corresponding diminution of the temperature of the contiguous solar atmosphere, accompanied by a sudden condensation and down-rush over the regions of obstructed circulation. Considering the increased weight of the condensed matter put in motion by the sun's powerful attraction, we can readily imagine that the photosphere, suspended over the solar mass, as supposed by Lockyer, may be pierced by the descending column, and an opening formed, exposing that part of the solar mass which, for want of circulation and supply of heat from within, has lost intensity and radiant power. It should be observed that, although we have no knowledge of the constitution of the photosphere, we may assert positively that its radiant power is derived from the underlying solar mass, and that, therefore, any diminution of energy of the latter, occasioned by disturbed circulation, will at once diminish the temperature and radiant power of that portion of the photosphere which is situated above the obstruction. (7) The descending and ascending columns of heated matter between the solar centre and the poles, being acted upon almost at right angles by planetary attraction, remain at all times nearly undisturbed; hence only a few dark spots, of small size, form in the polar regions.

Regarding the permanency of solar radiation, the foregoing explanations show that the system of vertical circulation, upon which depends the efficiency of the sun as a motor, may become deranged. The consequence of this precarious feature of the scheme is self-evident, if we consider that the present solar emission is dependent on a given rate of contraction of the solar mass. Should that contraction be checked by interrupted circulation, the development of heat will also be checked, and, consequently, the intensity of solar radiation become inadequate to sustain animal and vegetable life, as now organized, on our planet. History informs us that the luminary has at certain epochs partially failed to perform its functions. Herschel mentions, in his "Outlines of Astronomy," that "in the annals of the year A.D. 536 the sun is said to have suffered a great diminution of light, which continued fourteen months. From October A.D. 626 to the following June a defalcation of light to the extent of one-half is recorded; and in A.D. 1547, during three days, the sun is said to have been so darkened that stars were seen in the day-time." Again, the glacial periods, the ascertained abrupt termination and recurrence of which puzzles the geologist, point to periodical derangement of the solar mechanism in past ages.

CHAPTER VIII.

RADIATING POWER AND DEPTH OF THE SOLAR ATMOSPHERE.

The illustration shown on Plate 15 represents an instrument constructed for the purpose of ascertaining the radiant power of the solar atmosphere, and for measuring its depth, the leading feature of the device being that of shutting out the rays from the photosphere during the investigation. Evidently the expedient of shutting out the photosphere while examining the effect produced by the rays emanating from the solar envelope calls for means by which the sun may be kept accurately in focus during the period required to complete the observations. The main features of the instrument being clearly shown by the illustration, a brief description will be sufficient to explain its detail. A parabolic reflector, applied for the purpose of concentrating the rays of the solar atmosphere, is inserted in the cavity of a conical dish of cast iron, secured to the top of a table suspended on two horizontal journals, and revolving on a vertical axle. The latter, slightly taper, turns in a cast-iron socket, which is bushed with brass and supported by three legs stepped on a triangular base, resting on friction-rollers. The horizontal journals referred to turn in bearings attached to a rigid bar of wrought iron situated under the table, firmly secured to the upper end of the vertical axle. The horizontal angular position of the table is adjusted by a screw operated by the small hand-wheel *a*, the inclination being regulated by another screw turned by the hand-wheel *b*. A graduated quadrant, *e*, is attached to the end of the table in order to afford means of ascertaining the sun's zenith distance at any moment. The index *d*, which marks the degree of inclination, is stationary, being secured to the rigid bar before described. The rays from the photosphere are shut out by a circular disc *f*, composed of sheet metal turned to exact size, and supported by three diagonal rods of steel. These rods are secured to the circumference of the conical dish by screws and adjustable nuts in such a manner that the centre of the disc *f* may readily be brought in a direct line with the axis of the reflector. The mechanism adopted for adjusting the position of the table by the hand-wheels *a* and *b* requires no explanation; but the device which enables the operator to ascertain when the axis of the reflector is pointed exactly towards the centre of the sun demands particular notice. A shallow cylindrical box *g*, provided with a flat lid and open at the bottom, excepting a narrow flange extending round the circumference, is firmly held by two columns secured to the top of the table. A convex lens of 26 ins. focus is inserted in the cylindrical box, the narrow flange mentioned affording necessary support. The lid is perforated by two openings at right angles, 0.05 in. wide, 2.5 ins. long, forming a cross, the lens being so adjusted that its axis passes through the central point of intersection of the cross. The face of the table being turned at right angles to the sun, or nearly so, it will be evident that the rays passing through the perforations and through the lens will produce, at a certain distance, a brilliantly illuminated cross of small size and sharp outline. A piece of ivory, on which parallel lines are drawn intersecting each other at right angles, is attached to the top of the table in such a position that the centre of intersection of the said lines coincides with the axis of the lens. This axis being parallel with the line passing through the centre of the disc *f* and the focus of the reflector, it will be perceived that the operator, in directing the table, has only to bring the illuminated cross within the intersecting parallel lines on the piece of ivory. Ample practice has shown that by this arrangement an attentive person can easily keep the disc *f* accurately in line with the focus of the reflector and the centre of the sun during any desirable length of time. The absence of any perceptible motion of the column of the focal thermometer employed during the experiments furnishes the best evidence that the sun's rays have been effectually shut out by the intervening disc *f*, which, it should be remembered, is only large enough to screen the aperture of the reflector from the rays projected by the photosphere. It is worthy of observation that the lightness of the adopted mechanism renders exact adjustment easy, since screws of small diameter and fine pitch may be employed. It is hardly necessary to point out that the table represented by our illustration is admirably adapted for actinometric observations, since, apart from its perfect parallactic motion, it is provided with a quadrant and index showing the sun's zenith distance.

Fig. 2 (see Plate 16) represents a vertical section of the parabolic reflector before adverted to, inserted in the cast-iron dish attached to the parallactic table. This reflector consists of a solid wrought-iron ring lined with silver on the inside, turned to exact form and highly polished. An annular plate 9.5 ins. internal diameter is secured to the top of the wrought-iron ring, in order to prevent effectually all rays projected by the photosphere from reaching the reflector.

The important question whether the solar envelope possesses an appreciable radiant power, and whether the high temperature of the attenuated matter of which it is composed exercises any marked influence on the sun's radiant energy, may unquestionably be answered practically by means of the instrument thus described. I have accordingly conducted an investigation based on the expedient of concentrating the heat-rays of the solar atmosphere by the parabolic reflector mentioned, in such a manner that only the heat-rays, if such there be, from the chromosphere and exterior solar envelope are reflected, while the rays from the photosphere are effectually shut out. Fig. 1 shows the general arrangement; f' a' represents the exterior of the photosphere, and g' h the boundary of the surrounding solar atmosphere; k l is the circular metallic disc, supported above the parabolic reflector before described, and marked *f* in the illustration on Plate 15. This disc is exactly 10 ins. in diameter, placed 53.76 ins. above the base line *a o;* the latter coinciding with the top of the parabolic reflector. The stated distance between the disc and the top of the reflector obviously varies considerably with the seasons. Assuming that the investigation takes place when the sun subtends an angle of 32 min. 1 sec., and making proper allowance for diffraction, the disc *k l*, if placed 53.76 inches from *a o*, will throw a shadow of fully 9.5 ins. diameter; hence, if *f o* be 9.5 inches, objects in the plane *a o*, placed within *f o*, will be effectually shut out from the rays projected by the photosphere, while they will be fully exposed to the rays *g' g* and *h n*, emanating from the chromosphere and outer strata of the solar envelope. It is evident, therefore, that a parabolic reflector of proper size placed immediately below *f o* will concentrate the radiant heat, if any, transmitted by the rays *f' f* and *g' g*, and the intermediate rays. It has already been stated that an annular plate 9.5 ins. internal diameter is secured to the top of the reflector to prevent effectually any rays projected by the photosphere from reaching the same. The prolongation of the rays *f' f* – *g' g* and *h n* – *a' o* are shown by dotted lines *f*, *g* and *n*, *o* in Fig. 2; also the reflected rays directed towards the bulb of the focal thermometer, marked respectively *f'*, *o'* and *g'*, *n'*.

The following brief account is deemed sufficient to explain the mode of conducting the investigation: Turning the reflector towards the sun, without applying the disc *k l*, it will be found that a narrow zone of dazzling white light is produced on the black bulb of the focal thermometer *p*, the mercurial column commencing to rise the moment the rays strike the reflecting surface. With a perfectly clear sky, the column has been found to reach 320 deg. Fah. in 35 sec. The screen *k l* being applied *after* cooling the thermometer, a zone of feeble gray light appears on the black bulb nearly as deep as the one produced by the rays from the photosphere, but situated somewhat lower. The column of the focal thermometer invariably remains stationary, excepting the oscillation which always takes place when a thermometer is subjected to the influence of the currents of air unavoidable in a place exposed to a powerful sun. It is proper to remark that, owing to the stated oscillation, it cannot be positively asserted that no heating whatever has been produced by the reflection and concentration of the rays which form the zone of gray light adverted to. But the recorded oscillations prove absolutely that the heating does not *exceed* 0.5 deg. Fah.

Assuming that a temperature of 0.5 deg. Fah. has actually been produced by the reflected concentrated heat emanating from the solar envelope, the following calculation will show that the energy thereby established is too insignificant to exercise any appreciable influence on the sun's radiant power. Theoretically, the temperature transmitted to the bulb of the focal thermometer by the reflection of the rays *f* and *o*, Fig. 2, is as the foreshortened illuminated area of the reflector to the area of the zone of light produced on the bulb. Obviously these areas bear nearly the same relation to each other as the squares of f' or o' to the square of the radius of the bulb p. The length of f' being 4.77 ins., while the radius of the bulb is 0.125 in., calculation shows that the temperature transmitted by the ray f would be increased 1,456 times if the reflector did not absorb any heat. Allowing that 0.72 of the heat is reflected, the augmentation of intensity by concentration will amount to $0.72 \times 1{,}456 = 1{,}048$ times the temperature transmitted by the rays f and o. The records of the oscillations of the mercurial column during the experiments show, as stated, that the temperature resulting from concentration cannot exceed 0.5 deg.; hence the temperature transmitted by the rays emanating from the heated matter of the solar envelope will only amount to $\frac{0.5}{1{,}048} = 0.00047$ deg. Fah. The recorded observations having been made when the sun's zenith distance was 32 deg. 15 min., a correction for loss occasioned by atmospheric absorption amounting to 0.26 will, however, be necessary. This correction being made, it will be found that the heat actually transmitted by the rays from the solar envelope during the experiment referred to did not exceed 0.00059 deg. Fah.—a fact which completely disposes of Secchi's remarkable assumption that the high temperature of the photosphere is owing to the "radiation received from all the transparent strata of the solar envelope" (see his letter to *Nature*, published June 1, 1871).

Having thus positively established the fact that no appreciable heat is transmitted to the earth by the radiant power of the solar atmosphere, and thereby disposed of Secchi's erroneous assumptions, and proved the unsoundness of the views entertained by other physicists that "the regions near the sun augment the radiant energy transmitted by the luminary," let us now consider the probable weight and depth of the solar atmosphere. The investigation will be greatly facilitated by instituting a comparison between the sun's envelope and the terrestrial atmosphere, and by adopting as a basis in our calculation the fact, established in Chap. X., that the temperature at the surface of the photosphere, and hence that of the contiguous solar atmosphere, exceeds 4,000,000 deg. Fah. The fallacy of Dulong and Petit's formula relating to the rate of cooling of incandescent matter at high temperatures, and its consequent inapplicability to the question of solar temperature, having been fully demonstrated in Chap. II., while our actinometric observations recorded in Chap. III. have established the intensity of solar radiation at the boundary of the terrestrial atmosphere, we possess, it should be borne in mind, the elements necessary to prove the correctness of the assumed high degree of solar temperature. As before stated, our investigation will be simplified by comparing the solar and terrestrial atmospheres; hence the following mode of solving the important problem: The increase of the volume of atmospheric air, under constant pressure, being directly proportional to the increment of temperature, while the coefficient of expansion is 0.00203 deg. for 1 deg. of Fahrenheit, it will be found by calculation that 3,272,000 deg. Fah. (that being the mean temperature of the solar atmosphere) communicated to the terrestrial atmosphere would reduce its density to $\frac{1}{6643}$ of the existing density. Accordingly, if we assume that the height of our atmosphere is only 42 miles, the elevation of temperature mentioned would cause an expansion increasing its height to $6,643 \times 42 = 279,006$ miles. This calculation, it should be observed, takes no cognizance of the diminution of the earth's attraction at great altitudes, which, if taken into account, would considerably increase the estimated height. Let us now suppose the atmosphere of the sun to be replaced by a medium similar to the terrestrial atmosphere raised to the temperature of 3,272,000 deg. Fah., and containing the same quantity of matter as the terrestrial atmosphere for corresponding area of the solar surface. Evidently the attraction of the sun's mass would, under these conditions, augment the density and weight of the supposed atmosphere nearly in the ratio of 27.9 : 1; hence its height would be reduced to $\frac{279,006}{27.9} = 10,000$ miles. But if the atmosphere thus increased in density by the sun's superior attraction consisted of a compound gas, principally hydrogen, say 1.4 times heavier than pure hydrogen (the specific weight of which is only $\frac{1}{14}$ of that of atmospheric air), the height would be $10 \times 10,000 = 100,000$ miles. The pressure exerted by this supposed atmosphere at the surface of the photosphere would obviously be $14.7 \times 27.9 = 410$ lbs.

per sq. in. nearly. It will be observed that our computations are based on a solar attraction of 27.9, instead of the recent estimate of 27.2. The foregoing calculations prove that, unless the depth greatly exceeds 100,000 miles, and unless it can be shown that the mean temperature is less than 3,272,000 deg. Fah., the important conclusion must be accepted that the solar atmosphere contains an exceedingly small quantity of matter. Now, the assumed mean temperature, 3,272,000 deg. Fah., so far from being too high, will be found to be underrated. It will be seen, on reference to Chap. X., that the temperature at the surface of the photosphere, determined in accordance with well-ascertained elements, somewhat exceeds 4,035,000 deg. Fah. Consequently, as the diminution of intensity caused by the dispersion of the rays is inversely as the convex area of the photosphere and that of the sphere formed by the boundary of the solar envelope—namely, as 1.52 : 1—under the supposition that the depth of the solar atmosphere is 100,000 miles, the temperature at the said boundary will be $\frac{4,035,000}{1.52} = 2,654,000$ deg. The true mean, therefore, will be 3,344,800 deg., instead of 3,272,000 deg. Fah.—a difference which leads irresistibly to the inference that either the sun's atmosphere is more than 100,000 miles in depth, or it contains less matter than the terrestrial atmosphere for corresponding area of the solar surface. The ratio of diminution of the density of the gases composing the solar atmosphere at succeeding altitudes is represented by Fig. 3, in which the length of the ordinates of the curve *a d b* shows the degree of tenuity at definite points above the photosphere. This curve has been constructed agreeably to the theory that the densities at different altitudes, or, what amounts to the same, the weight of the masses incumbent at succeeding points, decreases in geometrical progression as the height above the base increases in arithmetical progression. The vertical line *a c* has been divided into 42 equal parts, in order to facilitate comparisons with the terrestrial atmosphere, supposed to be 42 miles deep, the relative density of which, at corresponding heights, is obviously as correctly represented by our diagram as that of the solar atmosphere. It is true that, owing to the greater height of the latter compared with the attractive force of the sun's mass, the upper strata of the terrestrial atmosphere will be relatively more powerfully attracted than the upper strata of the vastly deeper solar atmosphere. The ordinates of the curve *a d b* will therefore not represent the density quite correctly in both cases. The discrepancy, however, resulting from the relatively inferior attraction of the sun's mass at the boundary of its atmosphere will be very nearly neutralized by the increased density towards that boundary, consequent on the great reduction of temperature—fully 1,380,000 deg. Fah.—caused by the dispersion of the solar rays before entering space. It may be well to state that, in representing the relative height and pressure of the terrestrial atmosphere, *a c* in our diagram indicates 42 miles, while *b c* indicates a pressure of 14.7 lbs. per sq. in.; and that, in representing the solar atmosphere, *a c* indicates 100,000 miles, and *b c*

410 lbs. per sq. in. Bearing in mind the high temperature and the exceedingly small specific gravity of the matter composing the solar atmosphere, the extreme tenuity of the higher regions, indicated by the ordinates shown in the diagram, will be readily comprehended. Calculation shows that towards the assumed boundary the density of the solar atmosphere is so far reduced that it contains only $\frac{1}{152000}$ of the quantity of matter contained in an equal volume of atmosphere at the surface of the earth.

The diminution of intensity consequent on the increased depth of the solar atmosphere through which the calorific rays pass, which are projected towards the earth from the receding surface of the photosphere, having been considered in Chap. VI., it will only be necessary to mention in this place that Fig. 4 represents the sun, and its atmosphere extending $\frac{1}{4}$ of the semi-diameter of the photosphere, *m h*, *c g*, etc., being the rays projected towards the earth. The depth of the solar atmosphere at a distance of $\frac{19}{20}$ of the radius from the centre of the luminary, it will be seen, amounts to only 2.0012 of that of the vertical depth. It is hardly necessary to observe that the radiant energy transmitted by the ray *c d* will be to the energy transmitted by *a b* as the sine of the angle *f c d* to unity.

The foregoing reasoning demonstrates that the solar atmosphere, owing to its enormous temperature, may reach a height of 100,000 miles and yet not contain more matter on a given area of the sun than the terrestrial atmosphere on an equal area. I have endeavored to verify this important conclusion practically, and for that purpose resorted to the expedient of enlarging the disc *f* (see illustration on Plate 15) until the spectrum disappears which is formed on the focal thermometer by the concentration of the rays emanating from the sun's atmosphere. It should be stated that the original object of the instrument illustrated was merely that of ascertaining whether the incandescent matter contained in the solar atmosphere transmits radiant heat of sufficient energy to admit of thermometric measurement. But the appearance of a spectrum on the bulb of the focal thermometer, after shutting out the rays from the photosphere, suggested the expedient of substituting for the thermometer a small cylindrical stem of metal, coated with lamp-black, in order to ascertain with some degree of precision what amount of enlargement of the disc *f* is necessary to exclude the focal spectrum, as by that means the depth of the sun's atmosphere might be measured. The result of the observation proves that while a disc of 10 ins. diameter effectually shuts out the rays from the photosphere, an enlargement of about 0.15 inch of the radius of the disc is necessary to exclude completely the observed spectrum from the focal stem. Now, the distance between the spectrum and the disc being 53.7 ins., it will be found by calculation that the stated enlargement of the disc corresponds with an angular distance of 9′ 45″; hence, assuming the radius of the photosphere to be 426,000 miles, the depth of the measurable part of the solar envelope cannot be less than 255,000 miles.

CHAPTER IX.

THE FEEBLENESS OF SOLAR RADIATION DEMONSTRATED.

It is a remarkable fact that some of the most prominent scientists entertain wholly incorrect views regarding the sun's radiant intensity. Apparently, they are not aware that the temperature produced by *unaided* solar radiation is fully 300 deg. Fahrenheit below the freezing-point of water. Sir John Herschel, in discussing the increase of the intensity of solar radiation consequent on the reduced distance from the sun when the earth is in perihelion, presents the following views: "In estimating the effect of any additional fraction, as *one-fifteenth*, of solar radiation on temperature (this fraction being determined by applying the law of inverse squares to the diminution of the sun's distance when the earth is in perihelion), we have to consider as our unit, not the number of degrees above a purely arbitrary zero-point—such as the freezing-point of water or the zero of Fahrenheit's scale—on which a thermometer stands in a hot summer day, as compared with a cold winter one, but *the thermometric interval between* *the temperature it indicates in the two cases and that which it would indicate did the sun not exist,* which there is good reason to believe would be at least as low as 239° below zero of Fahrenheit. And as a temperature of 100° above zero is no uncommon one in a fair shade exposure under a sun nearly vertical, we have to take one-fifteenth of the sum of these intervals $\left(\frac{239 + 100}{15}\right) = 23°$ Fahrenheit, as the least variation of temperature under such circumstances which can reasonably be attributed to the *actual variation of the sun's distance.*" It will be observed that the foregoing quotation has partially appeared in a preceding chapter, yet it could not be omitted in this place without rendering the demonstration incomplete. Considering that "absolute zero" (ascertained in the meantime) is 460° below the zero of Fahrenheit instead of 239°, as supposed by Herschel, it will be seen that, according to his doctrine, the increase of temperature *resulting from the sun's proximity when the earth is in perihelion* should be $\frac{460 + 100}{15} = 37°$ F. Referring to Chap. IV., it will be found that solar intensity at the atmospheric boundary is 90°.72 F. during the winter solstice, and that the increase of the radiant intensity at that time, *owing to the sun's proximity,* is 4°.66 F., besides the loss of energy, 0.207, caused by atmospheric absorption, together 5°.88 F., instead of 37° F. This extraordinary discrepancy is the result of Sir John Herschel's misapprehension of solar intensity. He supposes, as we have seen, that the energy required to raise the temperature from absolute cold to Fahrenheit's zero, added to the energy necessary to raise the temperature from that zero to the point reached on the Fahrenheit scale, indicates the true intensity of the radiant heat; hence 460°, in addition to the 90°.72 before mentioned, together 550°.72 F., instead of 90°.72 F. Referring again to Chap. IV., it will be found that the intensity of solar radiation when the earth is in aphelion is 84°.84 F.; hence the *mean* will be $\frac{90.72 + 84.84}{2}$ = 87°.78 F. Now, the mean distance of the earth from the sun's centre being 91,430,000 miles, it will be perceived that solar intensity at that distance cannot exceed 87°.78 Fahrenheit. In order to show the practical result of this determination of solar intensity, let us suppose that an air-thermometer, surrounded by some permanent gas maintained at a temperature of 100° F. above absolute zero, be exposed to the sun, and that the side of the bulb exposed to the sun's rays is nearly flat, while the back is semi-spherical and effectually protected by non-conducting substances. It needs no demonstration to prove that the said thermometer will indicate $100 + 87.78 = 187°.78$ F. above absolute zero, or $492 - 187.78 = 304°.22$ F. below the freezing-point of water, although exposed to the full energy of the sun's rays. Persons assigning a high temperature to the surface of the moon will do well to consider the important fact thus established. A moment's reflection will convince them that, but for the accumulation of heat effected by the intervention of the terrestrial atmosphere, water could not exist in a fluid state, and that even the vertical rays of the sun within the tropics would not possess sufficient power to retain mercury in a fluid state.

It has been asserted by physicists that the differential temperature shown by thermometers, however judiciously arranged, does not furnish a reliable indication of solar energy, on the ground that when the supposed maximum intensity has been reached the temperature of the bulb balances that of the solar heat, thus preventing further increment. The radiating power of the heated bulb, it is urged, remains undiminished, while the differential temperature between the same and the surrounding medium is at its maximum; consequently promoting maximum loss of energy by radiation. In order to test practically the merits of this plausible argument, and in order to determine the true intensity of solar radiation, I have constructed the instrument illustrated on Plate 17. The delineation represents a vertical section through the centre line of the instrument. The leading feature of the device is that of applying a hollow revolving sphere (composed of very thin copper) within an exhausted cylindrical vessel. This revolving sphere, coated with lamp-black inside and outside, is exposed to the sun's rays admitted through a thin crystal covering the open end of the exhausted vessel, the diameter of the crystal being equal to that of the sphere. The exhausted cylindrical vessel, it will be seen by inspecting the illustration, is surrounded by an external casing, water of a given temperature being circulated through the intervening space. The sphere is caused to revolve by means of a small hand-wheel attached to a hollow stem connected with the sphere; the said stem turning in an air-tight stuffing-box applied on the upper side of the exhausted vessel. A thermometer is inserted through the hollow stem, the bulb, coated with lamp-black, occupying a central position within the sphere. Obviously the thermometer participates in the rotary motion of the sphere when turned by the hand-wheel. The instrument is supported on columns secured to a table provided with parallactic movement for the purpose of pointing the axis of the exhausted cylindrical vessel towards the solar centre. The water circulated through the external casing of the instrument is maintained at a constant temperature of 60° F., a vacuum being kept up within the internal vessel. As the thermometer does not fit air-tight in the hollow stem, it will be evident that the pressure of the air within the revolving sphere will at all times balance the external atmospheric pressure. Let us now institute a comparison between the instrument described and the ordinary thermometer.

The convex area of the revolving sphere being four times greater than the area of its great circle, the latter being equal to the area of the pencil of rays admitted through the crystal, it will be evident that the refrigerating surface of the sphere is *four* times greater than the sectional area of the solar rays which supply the radiant heat. Accordingly, if the surrounding cylindrical vessel be permitted to radiate freely towards the centre, the temperature retained by the revolving sphere thus exposed to cold radiation from all points will be only one-fourth of the temperature capable of being imparted by the pencil of rays to the face of a flat disc composed of some non-conducting substance. It may be stated, in further explanation of the foregoing demonstration, that, since the surrounding exhausted vessel is maintained at a constant temperature of 60° F., it will radiate heat of that energy towards the sphere. An exchange will consequently take place which will prevent maximum temperature being attained by the sphere unless the radiant energy transmitted by the solar rays entering the instrument be *four* times greater for equal area than the radiant energy of the heat-rays projected by the sphere towards the cold enclosure. It follows from this important proposition that the temperature acquired by the revolving sphere represents only one-fourth of the intensity of the radiant energy actually passing through the crystal of the exhausted cylindrical vessel. It will be readily perceived that the temperature of the air within the revolving sphere correctly represents the temperature of the metal composing the same; also, that the metal itself, owing to its almost perfect conductivity, will become uniformly heated all over. The inserted thermometer, therefore, will show the temperature of the revolving sphere sufficiently near for the object in view. As already demonstrated, only one-fourth of the radiant heat entering through the crystal is retained by the sphere; hence the thermometer will indicate only one-fourth of the actual intensity of the sun's rays. Accordingly, if we multiply the indication of the thermometer within the revolving sphere by 4, we ascertain the true solar intensity, less the heat absorbed by the crystal covering the exhausted vessel. The result of careful observation has proved the soundness of the foregoing reasoning and demonstration. The concluding investigation, instituted when the zenith distance was 30 deg. 50 min., established the fact that while the standard actinometer indicated a solar intensity of 54°.57 F., the thermometer within the revolving sphere indicated a differential temperature of 13°.3 F. According to our theory, it should have indicated $\frac{54.57}{4} = 13°.64$ F., thus showing a deficiency of 0°.34. If, however, a correction be introduced adding the proportion of heat absorbed by the crystal—viz., 0.066—the stated deficiency of temperature will be more than balanced. This apparent inaccuracy is occasioned by the radiation of the crystal towards the sphere, and by the diminution of the radiating surface of the surrounding vessel at the point where the crystal is inserted. The last-mentioned source of error may be easily ascertained, as it depends on the solid angle formed by straight lines drawn from the circumference of the crystal to the centre of the sphere. The deficiency of radiating surface ascertained by that process amounts to 0.012. Proper allowance having been made on account of these sources of error, it was found during the concluding investigation referred to that the temperature retained by the sphere exposed to the solar heat is exactly *one-fourth* of the temperature imparted and retained by the bulb of an actinometer simultaneously exposed to the sun. It is important to observe that the difference between the intensity of the radiant heat of the sun and the temperature of the metal composing the sphere was 54°.57 – 13°.64 = 40°.93 F. during the investigation; while the temperature of the bulb of the actinometer exposed to the sun, at the same time, balanced the intensity of the solar heat. This fact completely refutes the assertions of certain physicists before referred to. Regarding the *actual intensity* of solar radiation, no further demonstration is needed to show that the temperature indicated by the thermometer within the revolving sphere, multiplied by 4, determines the true energy of the sun's radiant heat at the surface of the earth; not, however, including the energy lost by atmospheric absorption. The close agreement between the indication furnished by the instrument thus examined and the indications of the actinometer described in Chap. III. proves, it is satisfactory to observe, the reliable character of the tables of solar temperature contained in that chapter constructed in accordance with our actinometric observations. It remains to be noticed that, before the conception of a dry revolving bulb, I constructed an instrument for determining solar intensity, in which a large stationary bulb, filled with water and provided with an internal rotating paddle-wheel, was employed. The illustration on Plate 18 represents a section through the vertical plane of that instrument. Before giving a description of the same, it will be well to present an outline of the reasoning which led to its construction.

Suppose a small spherical body of perfect conductivity and radiating power to be suspended within a large enclosure provided with a perforation in the direction of the sun, of sufficient size to admit a pencil of rays of the same diameter as the spherical body. Suppose, also, that the temperature of the said body is 64° F. higher than the temperature of the enclosure and the air contained within the same. The convex area of a sphere being four times greater than the area of its great circle, while the area of the great circle of the sphere which we have imagined corresponds exactly with the sectional area of the pencil of rays entering through the perforation of the enclosure, it will be evident that the supposed excess of temperature, 64°, cannot be maintained unless the radiant energy of the sun's rays be *four* times greater for corresponding area than the radiating energy of the sphere. It will also be evident that, if the assumed excess of temperature of the sphere gradually falls while exposed to the sun's rays, until it is reduced to 16° above the temperature of the enclosure, then the intensity of the sun's rays cannot be more than $4 \times 16 = 64°$. Bearing in mind that the section of the pencil of rays which transmits the energy is only 0.25 of the convex area of the radiating sphere which receives the heat and, in turn, radiates that heat towards the enclosure, we cannot question the correctness of the deduction that, assuming the rays to be parallel, the intensity of the radiant energy which enters through the perforation of the enclosure is four times greater than the radiant energy which the sphere parts with. Again, the intensity of the radiant heat emanating from solid bodies being a correct index of dynamic energy, it will be perceived that the energy transmitted to the enclosure by the radiating sphere at a differential temperature of 16° will be exactly balanced by the energy transmitted by the pencil of rays at 64° entering through the perforation of the enclosure, the area of which is 0.25 of the convex area of the sphere.

The demonstration thus presented, it will be admitted, establishes the important fact that the temperature produced by solar radiation is four times higher than the differential temperature of a black sphere, composed of materials of perfect conductivity, exposed to the sun, and permitted to radiate freely towards an enclosure of a uniform temperature.

Let us now examine the instrument before referred to, shown by our illustration, which represents a section through the central vertical plane: *k p* is a spherical vessel composed of copper, charged with water and coated with lamp-black on the outside, suspended within a spherical enclosure *o*. The latter is provided with a circular opening *a b*, to which a cylindrical trunk *a g* is attached, the spherical enclosure as well as the trunk being coated with lamp-black on the inside, as shown by the black tint in the illustration. A thermometer provided with a cylindrical bulb is inserted into the spherical vessel, and also a rotating paddle-wheel, operated by an axle passing through a water-tight stuffing-box. A cylindrical vessel *r r*, filled with water, surrounds the spherical enclosure and trunk, nozzles being applied at the top and bottom, to which flexible tubes are attached for circulating a current of cold water through the vessel. The instrument is mounted within a revolving observatory, and attached to a table turning on horizontal journals, and provided with appropriate mechanism, by means of which it may be directed at right angles to the sun. It will be evident that, if the axis of the cylindrical trunk *a g* be pointed accurately towards the centre of the sun, the sphere *k p* will receive the whole radiant energy of the rays within the tangential lines *k f* and *p g*, the sectional area of the pencil of rays, as before stated, being 0.25 of the convex area of the sphere. It will be evident also that, owing to the opening *a b* of the spherical enclosure, the sphere *k p* will not be acted upon by the full amount of refrigeration that would be produced by the radiation of a continuous enclosure. Agreeably to the theory of exchanges, the deficiency will, however, not be great, since the side *f a* of the trunk *a g* will radiate as powerfully towards the sphere as a portion of the spherical enclosure corresponding with the angular distance determined by the radial lines *a c* and *f c*. But the convex surface of the segment *e d*, depending on the angle subtended by *f c* and *g c*, will obviously be subjected to far less refrigeration than an equal surface on the opposite side of the sphere. Regarding the exact amount of deficient refrigeration consequent on the opening in the enclosure at *a b* referred to, it will be perceived, on reflection, that the radiation of the enclosure towards the semi-spherical surface presented to the sun will be reduced in the exact proportion which the area *e d* bears to the entire convex area of the semi-sphere. It will be seen, therefore, that although the condition coupled with our proposition has not been fully complied with—

namely, that the enclosure should be of great extent compared with the size of the radiating sphere—yet the enclosure of our instrument and the comparatively large opening at *a b* will not materially affect the refrigerating influence to which the sphere is subjected. Besides, the known solid angle subtended by the radial lines *f c* and *g c* enable us to calculate the amount of deficient radiating surface presented by the enclosure.

Several experiments have been made simultaneously with this instrument and a standard actinometer, in order to ascertain the precise relation between the temperature transmitted by the sun's rays to the radiating sphere and to the actinometer. Both instruments have invariably been attached to the same parallactic table during the investigation; consequently the energy of the radiant heat transmitted to each has been precisely alike. Respecting the instituted tests, it will suffice to record the result of an experiment conducted at noon, October 20, 1871, the solar radiation on that day being of nearly average intensity, while the sun's zenith distance, 51 deg. 40 min., was also near an average. Observations made at equal intervals of 5 min., from 11 hours 55 min. A.M. to 12 hours 30 min., showed that the radiating sphere of the instrument, the contents of which was effectually agitated by the internal paddle-wheel, attained a temperature of precisely 75°, while the enclosure was maintained at a constant temperature of 61°.3. Accordingly, an increase of temperature of 13°.7 above that of the enclosure was produced by the solar radiation acting freely on the sphere, the actinometer, at the same time, indicating a temperature of 51°.36. Now, agreeably to our theory, the temperature of the sphere ought to have been only $\frac{51.36}{4} = 12°.84$, thus showing a discrepancy of $13.7 - 12.84 = 0°.86$ F. It has already been explained that the sphere does not receive a full amount of refrigeration, in consequence of the opening in the enclosure necessary to admit the cylindrical trunk; hence the temperature of the sphere ought to exceed that which our theory has established. The observed difference, 0°.86, is, however, greater than it should be in accordance with the relative magnitude of the convex surface *e d* and the area of the sphere. But, referring to the illustration, it will be seen that, at the point where the thermometer is inserted, a considerable area of the sphere is not subjected to any radiation from the enclosure, nor at the point where the axle of the paddle-wheel enters. Adding these areas to that of *e d*, calculation shows that the amount of cold radiation prevented from acting on the sphere accounts very nearly for the discrepancy of 0°.86 F. before referred to. We are, therefore, warranted in stating that the temperature indicated by the actinometer during the experiments has proved to be exactly *four* times higher than that indicated by the thermometer inserted in the sphere exposed to the radiant power of the sun's rays and to the refrigerating influence of the enclosure. The soundness of our theory has thus been fully proved, and, consequently, additional evidence furnished of the correctness of the determination of solar intensity by means of the *actinometer* described in Chap. III. No further proof is needed in support of the demonstration already presented, showing that the temperature produced by solar radiation, instead of being, as Sir John Herschel supposed, equal to the maximum shade temperature within the tropics added to the temperature of the Fahrenheit zero above absolute zero—viz., $100 + 460 = 560°$ F.—scarcely reaches 88° F. at a distance of 91,430,000 miles from the solar centre.

Concerning the radiant heat which reaches the distant planets of the solar system, the stated discrepancy is of vital importance. Were it true that the intensity of the sun's radiant heat is 560° F. at the distance mentioned, the rays on reaching Jupiter's atmosphere would be capable of developing a temperature of $\frac{560}{5.2^2} = 20°.7$ F. We can readily imagine that the atmosphere of the giant planet might, by some system of accumulation, raise this temperature to such a degree that organisms like those of the earth might be sustained. But can the insignificant temperature of $\frac{88}{5^2} = 3°.2$ F. transmitted to Jupiter's atmosphere be sufficiently elevated by the process of accumulation to sustain animate and vegetable organizations resembling those of our planet? The stated low temperature need excite no surprise if we reflect on the fact that the sun, as seen from the boundary of the atmosphere of Jupiter, is no larger than an orange viewed at a distance of one hundred feet. As seen from Saturn, the size of the sun is that of a musket-ball at a distance of fifty feet from the observer's eye; while the transmitted solar heat scarcely develops a temperature of 1° F. where it enters Saturn's atmosphere. Speculations regarding the habitability of the distant planets are futile, in view of the insufficient radiant intensity of solar emission established by the actinometric observations recorded in this work, and by the adopted tests proving their reliability.

CHAPTER X.

TEMPERATURE OF THE SOLAR SURFACE.

The illustration on Plate 19 represents an instrument for ascertaining the temperature of the surface of the sun. At first sight it will appear futile to undertake the construction of an instrument capable of indicating temperature at a distance exceeding 90,000,000 miles; but in view of the fact that the sun has been weighed by an instrument consisting principally of four leaden balls less than one foot in diameter, the attempt cannot justly be deemed absurd. The reader will remember that in the celebrated Cavendish experiments, afterwards repeated by Baily and others, the weight of the earth—on which the weight of the sun is based—was ascertained by measuring the attraction exerted by spheres of lead weighing 174 lbs. The delicate nature of the experiment may be inferred from the fact that the ascertained attractive force was found to be only $\frac{1}{4300}$ of a grain. The illustrated instrument, the *solar pyrometer*, by means of which the temperature of the sun has been measured, involves no such nicety.

Before entering on a description of the solar pyrometer, it will be necessary to call attention to the demonstration in Chap. I., showing that the law relating to radiating spheres is also applicable to concave spherical radiators, if the substances exposed to their radiant heat be placed in their *foci.* The demonstration referred to also proves that the temperature produced by the radiant heat transmitted by concave radiators of equal temperatures and curvature, at equal distances, is *directly as their areas.* Melloni and Leslie's experiments, conducted in the presence of the disturbing influences of atmospheric air, not being sufficiently accurate to warrant their being cited in support of the correctness of the stated relation between areas and temperatures, the construction of the pyrometer has been so modified as to enable us to prove, independently of the demonstrations in the preceding chapter referred to, that, under the stated conditions, the temperatures correspond exactly with the areas.

Our illustration represents a longitudinal section through the vertical plane, and a photographic perspective view of the pyrometer. It will be seen, by inspecting the longitudinal section, that the instrument is composed of four principal parts: (1) A heater consisting of a cylindrical vessel with spherical bottom and open top, supported by an ordinary stove, the fire-chamber of which it partially enters. Enlargements resembling truncated cones with concave spherical ends are formed near the middle of the heater. The latter is partially filled with water, as shown in the illustration. (2) A conical vessel, surrounded by a double casing, secured to the base of the large conical enlargement of the heater. (3) A cylindrical vessel secured to the small end of the enlargement, likewise surrounded by a double casing. (4) An ordinary stove, into which the lower end of the heater is inserted. The curvature of the spherical concavity at the base of the large conical enlargement of the heater is struck to a radius of 18 inches, its diameter being 10 inches, hence presenting an area of 78.84 square inches. The opposite spherical concavity, the radius of which is 9 ins. (its diameter being 5 ins.) presents an area of $\frac{78.84}{4} = 19.51$ square inches. Thermometers are applied at the *foci* of the spherical concavities, their stems being placed as shown in the illustration, in order that the bulbs may present unobstructed semispheres towards the radiators. It is hardly necessary to observe that thermometers intended to measure the intensity of radiant heat should be protected so that those parts of their bulbs which are not acted upon by the heat-rays emanating from the radiators may not lose their heat by radiation or convection. The cylindrical as well as the conical chamber of the pyrometer containing the thermometers are connected by suitable tubes with an air-pump, by which the air is withdrawn; a current of water being circulated through the double casings when the instrument is in operation. With reference to the heater, it should be observed that, being open at the top, the water it contains will always be maintained at a constant temperature when the furnace is in action.

It may be briefly stated that the principle of the pyrometer is that of ascertaining solar intensity by comparing the temperature transmitted by a concave spherical radiator of 10 ins. diameter to a thermometer placed at a distance of 18 ins. from its face, with the temperature produced by the radiant heat emanating from an incandescent sphere of 832,584 miles in diameter, at a distance of 91,430,000 miles. The radiant heat in both cases is transmitted through ether; in the former to the surface of the bulb of the enclosed thermometer; in the latter to the boundary of the earth's atmosphere. The law which governs the transmission of radiant heat through space is as absolute as the law of gravitation, whatever be the distance; hence it is indisputable that the solar pyrometer in which the radiant heat acts at a distance of 18 inches is as competent to determine the temperature of the sun as the Cavendish leaden spheres acting at a distance of 8.85 inches to determine his weight. The chances, however, of an exact determination are greatly in favor of the pyrometer. In the first place, while the area of the concave radiator of the pyrometer is to the area of the great circle of the sun as $1 : 2{,}871 \times 10^{16}$, the weight of the leaden ball employed in the Cavendish experiments is to the weight of the sun as $1 : 2{,}367 \times 10^{25}$; thus showing a difference of 1 : 824,500,000 in favor of the pyrometer. Besides, the element of distance through which the radiant and the gravitating forces act is in favor of the pyrometer, in the ratio of 18 to 8.85. But these considerations, however important on account of the greater difference of the magnitudes involved, may be considered unimportant in comparison with the directness of the means by which the solar pyrometer solves the problem, contrasted with the indirectness, exceeding complication, and nicety involved in the Cavendish experiments. In the solar pyrometer we only require a correct indication of the temperature of the radiating concave spherical surface, and of the temperature transmitted to its focus; together with an accurate measurement of the distance of that focus, and of the area of the radiating surface. These points being readily determined, while the relative distance and diameter of the sun and the temperature produced by solar radiation at the boundary of the terrestrial atmosphere are known, we may enter upon and carry out our computation without introducing a single correction. How different the Cavendish experiment, with its numerous disturbing elements depending on barometric and thermometric conditions and changes, influencing a gravitating force amounting to only $\frac{1}{4300}$ of a grain! An account of the almost insuperable difficulties which were surmounted in those remarkable experiments, which for ingenuity, care, and perseverance stand unequalled in the annals of physics, would be out of place here; yet the foregoing brief allusion to experiments which satisfactorily determined the weight of the earth, and thereby the weight of the sun, has been deemed appropriate as a contrast. The directness, facility, and certainty of measuring solar temperature by the means we are now considering would scarcely be appreciated without calling to mind the method adopted for ascertaining the sun's weight.

Referring to the construction of the solar pyrometer and its apparently ponderous character, it will be well to bear in mind that the indispensable condition in this instrument of maintaining a constant temperature of the comparatively large concave spherical radiator is not easily fulfilled. Nothing short of an *open* heater containing a fluid which readily evaporates, and the application of an excess of heating power, will effectually accomplish the object in view. Evidently the loss occasioned by radiation cannot be exactly made good by the most delicate mechanical contrivance; but by applying an excess of heat in the furnace, the fluid which regulates the temperature of the radiator will be prevented from falling below the boiling point; and since the heater is open, the steam formed will carry off superfluous heat, and thus maintain the fluid at the desired uniform temperature. The exhausted chambers which contain the thermometers must of course be maintained at a constant temperature, the least fluctuation being fatal to accurate indication of the intensity of the heat transmitted by the radiators. In order, therefore, to keep up the necessary constant temperature during the investigation, a current of water has been circulated through the double casings which surround the exhausted chambers. By this expedient, in connection with the perfectly uniform temperature maintained in the heater, it has been easy to ascertain with critical nicety the temperature produced by the radiant heat transmitted from the spherical radiator to its focus. Regarding the area and curvature of the radiators, accurate workmanship alone will insure what is requisite; but the position of the thermometer, the placing the bulb at the proper distance with reference to the focus, demands some consideration. Obviously it would not be correct to place the centre of the bulb in the focus of the radiator, as that would bring the face of a bulb of ½ in. diameter ¼ in. in advance of said focus; nor would it be proper to carry the bulb so far back that its face would intersect the focus. The focal distance being 18 ins., it will be found that placing the bulb half way between these two positions will cause an error of fully 0.007. Conflicting indication, it should be observed, is unavoidable, since every part of the exposed half of the convex surface of the bulb cannot be equidistant from the face of the concave radiator; but this notwithstanding, there *is* a distance at which the indication of the thermometer will be precisely the same as if its entire contents were concentrated in the focus of the radiators. This position has been practically determined.

The hitherto accepted doctrine, that the intensity of radiant heat is directly as the area of the radiators, for equal distances, has been shown, in a previous chapter, to be fallacious, because the radiant heat transmitted from the boundaries of plane radiators becomes enfeebled by distance and the consequent dispersion of the heat-rays, in the ratio of the squares of the distance between the radiator and the recipient of the radiant heat. The solar pyrometer having been constructed before I had satisfactorily demonstrated that the intensity of the radiant heat transmitted from concave spherical surfaces is directly as the areas of such radiators, it was deemed necessary to establish the correctness of that assumption; hence the solar pyrometer has been modified as before mentioned. The lesser radiator attached to the conical enlargement of the heater, and the cylindrical chamber enclosing the same, were accordingly added to the instrument. It has already been stated that the area of the spherical radiator within the conical chamber is exactly four times greater than that of the opposite radiator, and that the radius of the curvature of the latter is one-half of the radius of the former. The demonstration contained in Chap. I., before referred to, has established the fact that in concave spherical radiators presenting equal areas the radiant heat transmitted is in the inverse ratio of the square of the distances if the substance exposed to the radiant heat be placed in the focus of the radiator. It follows from this demonstration that, for equal area, the intensity of the radiant heat transmitted to the focus of the lesser radiator will be four times greater than the intensity of the radiant heat transmitted to the focus of the large radiator. But the area of the latter is exactly four times greater than the area of the former, while the thermometers in both chambers are exposed to the radiation of surfaces heated by the same medium, and therefore of precisely equal temperatures. At the same time these thermometers radiate against surfaces maintained at a constant temperature, by the reliable expedient of employing a powerful continuous current of water. Consequently, the enclosed thermometers, although exposed to radiators of different area, should indicate precisely equal temperature. Actual trial having shown that such is the case, the correctness of the foregoing assumption must be accepted as fully established.

I will now briefly advert to the result of an experiment made with the solar pyrometer while the atmospheric pressure balanced 29.91 inches column of mercury, the temperature of the water in the heater being then precisely 212°. Apart from having thus insured a definite indication of heat applied to the concave radiator, the temperature of the current of cold water circulated through the casing surrounding the exhausted chambers did not fluctuate in the least during the experiment, the thermometer inserted in the exit-pipe of the casings continuing to indicate steadily 48°.1 F. The circulation of cold water having been kept up fully half an hour previous to the experiment, it is hardly necessary to state that, before the fire was applied in the furnace, the enclosed thermometer, the surrounding chamber, the water contained in the heater, and the radiator all indicated 48°.1. The fuel in the furnace having been ignited, and the water in the heater brought to boiling-point, the temperature of the spherical radiator was observed to increase from 48°.1 to 212°, difference = 163°.9; the temperature of the focal thermometer at the same time rising from 48°.1 to 60°.3, difference = 12°.2.

It results, from previous demonstrations (see Chap. I.), that the temperature of spherical radiators transmitting equal intensities to their *foci* are inversely as the square of the sines of half of the angles which they subtend—that is, the angles formed by the axis of the radiator and the heat-rays projected from the circumference to the *focus*. Consequently, as the spherical radiator of the solar pyrometer, the differential temperature of which is 163°.9, transmits to its focus an intensity of 12°.2, we are enabled to calculate what temperature the sun must possess in order to transmit an intensity of 12°.2 to the boundary of our atmosphere. The mean angle subtended by the sun being 32 min. 1 sec. during the experiment, while that subtended by the radiator of the pyrometer was 32 deg. 15 min., it follows that the ratio of the square of the sines of half these angles will be 1 : 3,567.7. Accordingly, the sun, in order to produce by its radiant heat a temperature of 12°.2 at the boundary of the atmosphere of the earth, must possess a temperature 3,567.7 times greater than that of the spherical radiator of the pyrometer. This latter temperature being 163°.9, that of the sun cannot be less than $3{,}567.7 \times 163.9 = 584{,}746°$ in order to transmit an intensity corresponding with a thermometric interval of 12°.2 on the Fahrenheit scale. But solar intensity at the boundary of our atmosphere, as shown by our actinometric observations (see Chap. III.), is 84°.84; hence $\frac{84.84}{12.2} = 6.95$ times greater than that transmitted by the radiator of the pyrometer to its focus. The temperature of the sun, therefore, cannot be less than $6.95 \times 584{,}746 = 4{,}063{,}984$ deg. Fah.

It will be recollected that the demonstration in a preceding chapter established with as much certainty as any proposition in the "Principia" that the temperature produced by the radiant heat transmitted by a sphere of uniform temperature at the surface is to the temperature of the sphere itself inversely as the square of the radius to the square of the distance from the centre to the point exposed to the radiant heat. The distance between the earth and the sun, at the summer solstice, being such that the angle subtended by the latter is 31 min. 32 secs., the ratio of distance and radius will be 218.1 : 1; hence the ratio of the squares, 47,567 : 1. Consequently, the temperature of the sun must be 47,567 times greater than the temperature produced by solar radiation at the boundary of the earth's atmosphere. That temperature being, as before stated, 84°.84, the sun's temperature cannot be less than 47,567 × 84°.84 = 4,035,584 deg. Fah. Thus the previously demonstrated temperature of 4,063,984 deg. Fah., based on the indications of the solar pyrometer and the angles subtended by its radiator, differs only 0.007 from the computations just presented. The methods by means of which these results have been reached differing entirely, both being based on sound physical and mathematical principles, we cannot doubt the correctness of the determination. Nor can it be questioned that the actual temperature of the surface of the sun, at the point of maximum intensity, is still higher, since the rays in passing through the solar atmosphere suffer considerable loss of energy, as shown in Chap. VI.

Let us now consider briefly the extraordinary diversity of views entertained by scientists regarding the temperature of the sun. In view of the fact that all practical data necessary to solve the problem are known, it is surprising that any difference of opinion should exist on the subject. Zöllner apparently rejects the positive evidence of high solar temperature furnished by the fact that the sun's rays, after having suffered dispersion in the ratio of 46,000 to 1, and penetrated the terrestrial atmosphere, are capable of developing a temperature of nearly 70° F. on the ecliptic. It will be remembered that he published, some time ago, an elaborate demonstration, founded on the height of the solar prominences, showing that the sun's temperature does not exceed 70,000° C. Secchi, on the other hand, asserted, in his original work on the sun, that, owing to the accession of energy received by radiation from the outer layers of the solar atmosphere, the temperature of the surface of the photosphere is fully 140 times greater than the temperature announced by Zöllner. Let us first notice the investigations of the Italian astronomer. In his work "Le Soleil," published at Paris, 1870, he presents calculations showing that the temperature of the solar surface is at least 10,000,000° C. Prof. Newcomb, in a review of the work referred to, published in *Nature*, showed that, if the temperature reached ten million degrees of Centigrade, as asserted by the author of "Le Soleil," the earth would speedily be converted into vapor. In answer to this objection, Père Secchi urged, "that a body may have a very high temperature and yet radiate very little," contending "that a thermometer dipped inside the solar envelope in contact with the photosphere" would indicate the temperature mentioned. "This high temperature," he observes, "is really a virtual temperature, as it is the amount of radiation received from all the transparent strata of the solar envelope, and this body at the outer shell must certainly be at a lower temperature." What information is intended to be conveyed by the statement that 10,000,000° C. "is really a virtual temperature," on the ground that it is "the amount of radiation received from all the transparent strata outside of the photosphere," we can only conjecture.

Our demonstrations, based on the indication of the solar pyrometer, have shown that the supposed thermometer, if brought in contact with the photosphere, cannot possibly indicate the enormous temperature of 10,000,000° C. assumed by the Italian physicist. The assertion that "a body may have a very high temperature and yet radiate but very little," were it correct with reference to the photosphere, does not affect the question. It is of no consequence whether the photosphere belongs to the class of active or sluggish incandescent radiators imagined by the distinguished *savant;* the temperature of the radiant surface, not its capacity to radiate more or less copiously, is the problem to be solved.

Very recently Père Secchi, much to the surprise of those who had accepted his estimate of solar temperature published in "Le Soleil," has changed his views completely. In an elaborate essay presented to the Academy of Sciences at Paris he underrates the intensity of solar energy more than he formerly overestimated it. Apprehensive that a synopsis would fail to give a correct idea of the remarkable demonstration by which the author of "Le Soleil" now reverses all his previous notions on the subject, and in order to furnish a complete exposition of the untenable character of the hypothesis tending to discredit the result of my labors, I will present without abridgment the essential points of his communication to the French Academy, published in "Comptes Rendus," Tome LXXVIII., No. 11: "During last summer (1873) I made some experiments in order to determine the relation of the radiation of the sun to that of the electric light, in the hope of solving the question of solar temperature. This source of light was selected, because its intensity differs the least from that of the sun. Hence I expect to harmonize the conflicting opinions regarding the law of radiation existing among the followers of Newton and those of Dulong and Petit. In estimating the two radiations I have used the thermoheliometre, the same apparatus described in my work 'Le Soleil.' This instrument, in spite of the objections made to it [by the writer of this work], seems to me appropriate, particularly for determining mere differences, as in this case. Let I_s and I_c be the absolute intensities of the radiations of the sun and of the charcoal points; θ_s and θ_c the excess of temperature of the black thermometer above that of the surrounding medium, in the cases of the solar and the electric radiations; α and δ the apparent diameters of the radiating surfaces, viewed from the centre of the black thermometer, and we have $\frac{\theta_s}{\theta_c} = \frac{I_s \text{ tang.}^2\, \delta}{I_c \text{ tang.}^2\, \alpha}$ whence $I_s = I_c \frac{\theta_s \text{ tang.}^2\, \alpha}{\theta_c \text{ tang.}^2\, \delta}$. It is very difficult to determine practically the radiating surface of the charcoal points. The point is generally very brilliant, but beyond this the incandescence decreases very rapidly; besides, the arc between them has a very different radiation. We have tried to determine the surface of the radiating parts of the charcoal points by comparing their dimensions with those of glass tubes placed in their immediate vicinity, and estimating the distance at which a thin wire of platinum commenced to melt without touching them. We have thus obtained an almost rectangular surface, equal to that of a circle of 1 centimetre in diameter; besides, the radiation from the parts outside of this limit was intercepted by diaphragms. The pile consisted of 50 elements (Bunsen) immersed in fresh nitric acid. The diameter of the elements was $0^{m}.12$ and their height $0^{m}.20$. The electrodes were short and very thick; the current was so intense that the insulating plates of an apparatus of Foucault were fused almost immediately, and an iron wire of 1 millimetre in diameter and $2^{m}.50$ of length was constantly kept at white-heat." The author having explained that these data are vague, proceeds: "Having placed the thermoheliometre at a level with the charcoal points and the black thermometer at a distance of $0^{m}.395$, I found after half an hour a difference of 3°.63 between the temperature of the surrounding medium and the black thermometer. During several days of July, about noon, I determined, with the same instrument, the temperature produced by solar radiation. I found a difference of 17°.37, allowing for zenith distance. By substituting these amounts in the previous formula and calculating the diameters α and δ according to the dimensions and distances of the radiating atmosphere, we have $I_s = I_c \times 36.468$, making the intensity of solar radiation 36½ times greater than that of the charcoal points. This estimate, however, falls short of the actual temperature; for we know that the correction for atmospheric absorption is too small. Mr. Soret has found on the Mont Blanc 21°.13; at the upper limit of our atmosphere that amount would probably be about 27°. These two amounts would give respectively: For 21°.13: $I_s = I_c \times 44.36$; for 27°.00: $I_s = I_c \times 56.66$.

These results differ materially from those obtained by other observers. Apprehending that some unknown cause in my electric light might produce an excessive error, I compared it with the light from a stearin candle. I found that it equalled 1,450 common candles, showing the intensity of an ordinary good pile. In another series of experiments, instituted when the pile had worked for some time, I found $I_s = I_c \times 47.5$, which result differs very little from that obtained by adopting the temperature of 21°.13 observed by Mr. Soret. Thus, if we accept this temperature of 21°.13, which is incontestably below the real one, and supposing the temperature of the radiating surface of the charcoal points to be 3,000°—an amount by no means exaggerated, since that part of the platinum exposed to the heat was fused—and if we estimate radiation as proportional to temperature, we obtain 133,780° as the potential temperature of the sun. This amount may be raised even to 169,980°, by adopting the temperature of 27° produced by solar radiation."

The result, then, of Père Secchi's latest researches shows that the potential temperature of the sun is 133,780° C., which he thinks may be raised even to 169,980° C. Accordingly, his former computation of solar intensity was $\frac{10,000,000° \text{ C.}}{169,980° \text{ C.}}$ = 59 times higher than his present. Referring to Chap. XIII., it will be found that Pouillet, whose estimate of solar intensity at the boundary of the terrestrial atmosphere is nearly identical with that which my actinometric observations have established, but who bases his computations on Dulong and Petit's erroneous formula, arrives at the conclusion that the temperature of the sun is from 1,461° to 1,761° C. (mean = 1,611° C.) M. Vicaire, adopting, like Pouillet, Dulong's law, states, in his paper presented to the French Academy, that the temperature deduced from that law is between 1,400° and 1,500° C. Sainte-Claire-Deville concludes his essay on solar temperature by the announcement that "solar temperature will not be found far removed from 2,500° to 2,800° C." It is very important to observe that no difference of opinion exists regarding the *dynamic energy* developed by the sun. All physicists accept Pouillet's computation showing that each square foot of the solar surface develops about 300,000 thermal units per minute. It will be asked how Pouillet could reconcile such an enormous development of energy with the insignificant intensity represented by 1,611° C. A satisfactory answer will be found in Chap. II. An examination of Mr. Boxe's table of temperatures in Chap. XIII. will also suggest a satisfactory answer. This table shows that, agreeably to Dulong's formula, the radiant energy of a body raised to a temperature of 2,520° F. is 4,600 times greater than the radiant energy developed by a body raised to a temperature of 60° F. above that of the atmosphere. It is needless to enter into any further discussion showing that the low solar temperature, 1,611° C., assumed by Pouillet, results from the adoption of the enormous emissive power of radiators announced by Dulong and Petit. It should be borne in mind that no peculiar property has been attributed to solar radiation, by Pouillet or other scientists, distinguishing it from the radiation of such metallic substances as those on which Dulong and Petit experimented. Consequently, if we can show by practical test that the radiation of fluid metals raised to a temperature of 1,611° C. develops only a small fraction of the energy assigned by Dulong's formula to that temperature, we prove conclusively that the method is fallacious which Pouillet and others have adopted in determining the temperature of the solar surface. Now, the result of the calorimetric measurement of the radiant energy of fused and overheated iron, recorded in Chap. XIII., has established in the most positive manner that the emissive power at a temperature of 3,000° − 60 = 2,940° F. (1,633° C.) above that of the atmosphere amounts to only 1,013 thermal units per minute upon an area of one square foot. Pouillet's notions of solar emission being based on the assumption that a temperature of 1,611° C. is capable of developing 300,000 thermal units, while actual trial shows that only 1,013 units are developed by the radiation of fused metal at even a higher temperature, we are compelled to reject his estimate of solar temperature as wholly erroneous.

It should be observed that our precise determination of solar energy by means of the calorimeter described in Chap. V. shows that 322,000 thermal units are developed in one minute by each square foot of the solar surface. Notwithstanding this enormous development of dynamic energy, the emissive power of the sun is relatively less than that of fused cast iron; a fact which tends to prove that the sun's radiant heat emanates from incandescent gases. A brief analysis of this important matter will be appropriate in this place. The radiant energy or emissive power developed by the sun being 322,000 thermal units per minute upon each square foot of surface, while boiling iron at a temperature of 2,940° F. develops 1,013 units upon one square foot, during one minute, it follows that the *emissive power* of the sun is only $\frac{322,000}{1,013} = 318$ times greater than that of iron at the stated temperature. But the temperature of the solar surface being at least 4,036,000°, its *intensity* is $\frac{4,036,000}{2,940} = 1,373$ times greater than that of *boiling* iron. Sir Isaac Newton supposed it to be 2,000 times greater than that of *red-hot* iron; a remarkable agreement. The emissive power of fused iron is consequently $\frac{1,373}{318} = 4.3$ times greater than that of the solar surface at equal temperature. Now, there is no terrestrial incandescent substance, whether solid or liquid, whose emissive power is not more than one-fourth of that of iron at corresponding temperatures; hence it is reasonable to infer that solar radiation emanates from incandescent gases.

The question of relative radiant power of solids and gases having presented itself at the beginning of my investigations of radiant heat, I constructed the apparatus illustrated on Plate 20, in order to ascertain the temperature produced by the radiation of incandescent gases. The illustration represents two vertical sections of the apparatus (see Figs. 2 and 3) and a perspective view (see Fig. 1). Before entering on a description, it will be proper to state that the device resorted to was intended to produce a column of incandescent gas of uniform density supplied with oxygen at every point within the burning mass. This condition, it was supposed, could only be fulfilled by employing a centrifugal blower forcing a current of atmospheric air vertically upwards through a mass of easily-ignited combustibles, divided into small pieces, placed on a horizontal grate. Fig. 1 represents a conical furnace, provided with a grate applied at the contracted lower portion, admitting of a free passage of the air between the bars at every point. A capacious chamber is formed under the grate, into which air is forced by an ordinary centrifugal blower. The internal portion of the furnace is contracted towards the top, as shown at *h* in Fig. 2, terminating with a square opening, over which is placed a square trunk *a*, corresponding exactly with the said opening. The furnace being charged with combustibles which readily ignite, it will be evident that a moderate speed of the blower will, soon after ignition, fill the square trunk with a dense flame of perfectly uniform temperature throughout, contact with the exterior atmosphere being wholly prevented, while the air which supports the combustion is subdivided almost infinitely, and uniformly dispersed, through the mass of burning fuel. A chimney, the section of which is equal to that of the contracted part of the furnace, being applied above the square trunk, any tendency to pressure and accumulation in the same will be effectually prevented. A dense flame of uniform temperature having thus been obtained, its radiant power has been ascertained by the following device: A conical vessel *b*, open at the large end, surrounded with a water-jacket of cylindrical form, shown in Fig. 2, is secured to the square trunk, a circular opening *c*, shown in Fig. 3, being formed in the side of the latter, corresponding with the open end of the conical vessel. Referring to Fig. 2, it will be seen that a perforated diaphragm *d* (composed of polished silver) is introduced near the small end of the conical vessel. A thermometer is applied near the circular perforation of the diaphragm, the bulb being placed exactly in the centre line of the vessel. An opening *f*, surrounded by a short conical tube, covered with a piece of mica, affords a view of the interior of the conical vessel. The water-jacket was supplied from the street-main, a constant stream being kept up during experiments. The application of a chimney of large diameter above the square flame-trunk, and the covering of the short conical tube with mica, as stated, in order to prevent currents of heated air or gas from circulating through the conical vessel, have contributed to secure the desired result—viz., a disc of flame of uniform brightness, the color varying with the speed of the blower. It might be supposed that the high temperature of the flame would at once destroy the square trunk. Such, however, is not the case, the trunk being made of plate-iron only $\frac{1}{16}$ in. thick, the radiation of which is so rapid that the gases composing the flame cannot communicate the heat as fast as it is carried off by external radiation. The top of the furnace at the point where the flame is concentrated and conducted into the square trunk, being exposed to intense heat, is lined with fire-clay. It should be borne in mind that the apparatus is exposed to a high temperature only while the blower is in operation, the motion being stopped as soon as the internal thermometer reaches maximum indication.

It will be noticed by those who have paid attention to the demonstration in Chap I. that, unless the radiant surface forms a spherical concavity, the focus of which coincides with the centre of the bulb of the recording thermometer, the indication will not be exact. The flame-disc being *circular*, this objection may be overcome by removing the thermometer from the flame to such a distance that the mean length of the heat-rays directed to the bulb corresponds with the radius of a concave radiator of the same diameter as the flame-disc. For the sake of ready comparison, the diameter of this disc and the focal distance of the recording thermometer have the same relative proportions as in our solar pyrometer.

The result of the initiary experiments with the apparatus thus described proved that the temperature transmitted to the focal thermometer by the radiation of the flame-disc was relatively the same as in the solar pyrometer. It was inferred from this fact that the radiant power of a dense flame with active combustion kept up through its entire mass is the same, for equal temperatures, as the radiant power of metallic substances. Further investigation, however, disclosed the fact that this unexpected result was owing to the circumstance that the steam emanating from the burning fuel during the experiment had entered the conical vessel, and, reaching the bulb of the recording thermometer, elevated the temperature very considerably. The presence of steam had not been overlooked, but it was supposed that the rapid circulation of cold water through the jacket surrounding the conical chamber would produce instant condensation. It is much to be regretted that before the disturbing influence of the presence of steam in the chamber containing the focal thermometer had been discovered, the results of the initiary experiments had been published in several mechanical journals. The main feature of the apparatus is, however, not without merit, as probably no better method could be devised for producing a dense flame within which active combustion is being kept up at every point. In combination with the thermo-electric pile, should a reliable mode of calibration hereafter be devised, there is reason to suppose that the illustrated machine may prove very useful. In the meantime, I have instituted numerous experiments to ascertain the radiant power of flames as compared with that of metallic substances. The result in every instance proves the feebleness of the radiation of incandescent gases compared with incandescent solid substances of equal temperature; but until the conclusion of the investigation, definite statements must be deferred.

Regarding the constitution of the solar surface, the temperature of which we are now considering, the relative feebleness of its emissive power compared with that of fused iron, shown by our investigations, leads irresistibly to the conclusion that we are dealing with an incandescent gas. The constitution of the solar surface, however, has nothing to do with its temperature. But, obviously, our endeavor to ascertain the constitution of the sun will prove futile until the temperature at its surface be first established. This will be readily admitted. Suppose that the temperature of the sun's surface is only 1,600° C., as Pouillet tells us, and that the solar atmosphere extends to the moderate height of 100,000 miles above the photosphere. It may be shown, by an easy calculation, that the specific gravity of the gases near the solar surface would under these conditions, owing to the low temperature, the depth of the superincumbent mass, and the great attraction of the sun's mass, *exceed that of fused iron*. It will be evident, therefore, that, until the temperature of the surface shall have been established, investigations relating to the constitution of the interior mass and the surrounding atmosphere cannot lead to any safe conclusions.

I now propose to show, by a demonstration which cannot be objected to, that the high temperature established by the indications of the solar pyrometer really exists on the solar surface. Astronomers, while admitting their inability to compute the degree of temperature imparted to the surface of the planets of our solar system, owing to the unknown properties of their atmospheres in retaining the heat received from the sun, have no hesitation in assigning the exact degree of solar intensity transmitted to the atmospheric boundary of each planet, compared with that transmitted to the boundary of our atmosphere. Sir John Herschel, in treating of the planet Mercury, does not admit that any doubt exists as to the relative degree of solar intensity to which its atmosphere is subjected. The mean radius of the orbit of this planet being to that of the earth as 38 : 100, he tells us that the temperature produced by the sun's rays on reaching the atmosphere of Mercury is nearly seven times greater than the temperature produced by solar radiation at the boundary of the terrestrial atmosphere. The following extract from the "Outlines of Astronomy" shows the confidence which Sir John Herschel places in the application of the law of inverse squares to the determination of solar energy at given distances: "The intensity of solar radiation is nearly seven times greater on Mercury than on Earth, and on Neptune 900 times less; the proportion of the two extremes being that of upwards of 5,600 : 1. Let any one figure to himself the condition of our globe were the sun to be septupled, to say nothing of the greater ratio! or were it diminished to a seventh, or to a 900th! It is true that, owing to the remarkable difference between the properties of radiant heat as emitted from bodies of very exalted temperature as the sun, and as from such as we commonly term *warm*, it is very possible that a dense atmosphere surrounding a planet, while allowing the excess of solar heat to its surface, may oppose a powerful obstacle to its escape, and that thus the feeble sunshine on a remote planet may be retained and accumulated on its surface."

No doubt Pouillet would have felt as little hesitation as Herschel in determining by the application of the law of inverse squares the temperature produced by solar radiation on Mercury. Chapter I. contains an elaborate demonstration, proving the correctness of this law with reference to radiating spheres uniformly heated at the surface.

The above diagram represents the orbits of the Earth, Venus, and Mercury, their relative mean distance from the sun being correctly drawn. The orbit of an imaginary body I, revolving at a distance of 10,000,000 miles from the solar centre, has also been introduced in the diagram, for the purpose of demonstrating that a body revolving round the sun at that distance would be exposed to a temperature greatly exceeding that which Pouillet assigns to the solar surface. Astronomers agreeing that the law of inverse squares holds for all distances, whether it be that of Neptune, which is 30 times further from the sun than the earth, or that of Mercury, whose distance from the luminary is less than $\frac{1}{80}$ of that of Neptune, we are warranted in applying that law to the body I, shown in our diagram, supposed to revolve at a distance of ten millions of miles from the centre of the sun. Let us then calculate what degree of solar intensity this imaginary body will be subjected to. Our calculations, obviously, must be based on the temperature produced by solar radiation at the boundary of the earth's atmosphere; hence it will be necessary first to establish that temperature. Assuming that it will prove more satisfactory to persons having obtained their knowledge from standard physical works, I will leave out of sight the result of my own actinometric observations, and adopt those of Pouillet, the difference, besides, being quite unimportant. In his "Éléments de Physique," published at Paris, 1856, second volume, this *savant* states, with reference to the amount of heat given out by the sun: "In the vertical passage the atmosphere absorbs at least 0.21 of the incidental heat, and at most 0.27, beyond which the sky ceases to be serene; I should add, however, that the 28th of June, on which day the absorption was 0.27, a light white veil was perceptible in the sky." The observed and commonly accepted maximum solar intensity on the ecliptic being 68° F., it will be found, by adding the loss of heat caused by atmospheric absorption—viz., 0.21, assumed by Pouillet—that the mean temperature produced by solar radiation at the boundary of the atmosphere is fully 86° F. The mean distance of the earth being in round numbers 92 millions of miles, while that of the imaginary body I is 10 millions of miles, from the sun, the solar intensity to which the latter would be exposed is to that transmitted to the boundary of the terrestrial atmosphere as $10^2 : 92^2 = 1 : 84.6$. Pouillet's calculations, and common observations, having, as before stated, established the intensity of the sun's rays on entering our atmosphere to be nearly 86° F., the foregoing analogy proves that the supposed body I will be subjected to a radiant intensity of $86° \times 84.6 = 7{,}275°$ F. We have thus shown by a method the correctness of which cannot be disproved that the radiant heat emanating from the sun (a body the temperature of which, Pouillet informs us, is under 3,000° F.) develops an intensity of 7,275° Fahrenheit at a distance of *ten millions* of miles. Well-informed persons will not dispute the correctness of the foregoing demonstration, nor ask further evidence of the erroneous character of Secchi's recent speculations or the fallacy of Zöllner's and Pouillet's computations assigning a low temperature to the solar surface.

CHAPTER XI.

RADIATION FROM INCANDESCENT PLANES.

Some eminent scientists have supposed that the surface of an incandescent body projects rays of equal energy in all directions. Laplace, having full confidence in the correctness of this assumption, founded upon it the demonstration adverted to in a previous chapter, proving that the radiant energy which emanates from the receding surface of the sun possesses greater intensity than that emanating from the central regions of the luminary. But actual observation having shown that the radiant energy from the sun's border, so far from being more intense, is considerably less than from its centre, the persistent mathematician was driven to the alternative of proving that the retardation produced by the greater depth of the sun's atmosphere towards the limb neutralizes the assumed increase of intensity of the radiant heat. How satisfactorily the dexterous analyst proves the startling proposition will be found on referring to "Mécanique Céleste," Tome IV. pp. 284–288: the result of his demonstration leading to the monstrous assumption that the solar atmosphere absorbs $\frac{11}{12}$ of the entire energy emanating from the radiant surface. Evidently Laplace did not regard solar radiation as molecular action capable of being converted into mechanical energy, or he would have perceived the impossibility of $\frac{11}{12}$ being absorbed by the solar atmosphere. It is not intended to enter on a criticism of the famous demonstration, but the question is so intimately connected with the subject under consideration that a reference to the main points is called for, showing on what grounds the conclusion was based that, but for the retardation produced by the solar atmosphere, the radiant energy of the luminary would be increased towards the border. If we admit the correctness of Laplace's assumption that the intensity of radiation increases with the obliquity of the radiant surface and the increased number of rays contained in a given section, we must also admit that the radiant energy from the regions near the sun's border will be greatly enhanced. And since it has been found, by actual observation, that no increase of intensity takes place, the inference cannot be resisted that the retardation produced by the solar atmosphere actually neutralizes the increased intensity occasioned by obliquity. Accordingly, the retardation may be determined by calculating the increase of intensity corresponding with the obliquity and consequent crowding of the rays. But this calculation, it is evident, will not show the full extent of retardation, since not only is there no increase, but a considerable *diminution* of intensity towards the sun's border. Hence, the amount of retardation determined agreeably to the doctrine that the radiant intensity is increased by the obliquity of the rays will be still further augmented. The reader will perceive, from this exposition, on what erroneous grounds Laplace's enunciation is based, that "if the sun were stripped of its atmosphere, it would appear twelve times as luminous."

The foregoing reference to doctrines promulgated nearly a century ago, when solar radiation was but imperfectly understood, will be deemed inappropriate by those who do not bear in mind that the highest authorities of the present time advocate similar doctrines. Referring to Chapter VI., it will be seen that Père Secchi, who has devoted more time to the investigation of the subject than any one else, presents calculations intended to prove that the retardation offered by the solar atmosphere to the passage of the rays is so great that only a fraction of the radiant heat enters space. He sums up his investigation by the following positive statement: "1st. At the centre of the disc, perpendicularly to the surface of the photosphere, the absorption arrests about $\frac{2}{3}$, more exactly $\frac{63}{100}$, of the total energy. 2d. The total action of the absorbing envelope of the visible hemisphere of the sun is so great that it allows only $\frac{12}{100}$ of the entire radiation to pass, the remainder—that is to say, $\frac{88}{100}$—being absorbed." Persons accustomed to compare mechanical equivalents, especially those who possess practical knowledge of the amount of mechanical power developed by the radiant heat emitted by incandescent bodies at definite temperatures, positively reject all assumptions involving any considerable loss of radiant energy by absorption in a medium perpetually exposed to the radiator. Nor will the assertion that the radiant heat is converted into molecular motion within the solar envelope be accepted by any person comprehending that the mechanical energy capable of being developed by the heat-rays projected from the photosphere must enter space less only the amount of actual *work* performed during the passage through that envelope. The investigations conducted by means of the solar calorimeter described in Chap. V. have shown that the dynamic energy developed by the sun's radiant heat on entering the earth's atmosphere amounts to 7.11 thermal units per minute upon an area of one square foot, while the dispersion of the rays is in the ratio of 1 : 45,400; hence, each square foot of the photosphere emits, as shown in the chapter referred to, 322,000 thermal units per minute. Secchi says that only $\frac{1}{8}$ of the heat emitted passes through the sun's atmosphere. Accordingly, $7 \times 322{,}000 = 2{,}254{,}000$ thermal units per minute are absorbed. Now, the development of one horse-power requires $\frac{33{,}000}{772} = 42.7$ units per minute; hence the energy supposed to be absorbed represents a mechanical force, *continually acting*, amounting to $\frac{2{,}254{,}000}{42.7} = 52{,}700$ horse-power for each square foot of the surface of the photosphere. Considering that the sun is surrounded by highly attenuated gases, containing a very small quantity of matter, Secchi's assumption that the stated enormous amount of energy is absorbed by the sun's atmosphere is utterly at variance with the laws of mechanics. The foregoing discussion has been deemed appropriate in this place, in order to call attention to the importance of ascertaining the true energy of heat-rays projected from incandescent surfaces at acute angles. If we can prove by positive practical means that the assumption is false which asserts that radiators emit rays of equal energy in all directions, we destroy the foundation on which the theory rests which has led to the conclusion that only $\frac{1}{8}$ of the energy developed by the sun penetrates its atmosphere.

The illustration on Plate 21, referred to in Chapter VI., represents a vertical section and top view of an inverted conical vessel, the bottom of which is concave, the top being open and provided with a wide flange. A revolving semi-spherical disc of cast iron, flat on the under side, is suspended on two transverse axles above the open end of the conical vessel, the axles turning in appropriate bearings resting on the top of the wide flange before mentioned. A lever handle is secured to one of the transverse axles, for the purpose of placing the disc at any desired angle, the degree of inclination being indicated by a graduated quadrant applied as shown in the illustration. The conical vessel is surrounded by a jacket, a stream of water being circulated through the intervening space during experiments. The incandescent revolving disc is protected against loss of heat on the top by a non-conducting covering composed of fire-clay, so arranged that it may be quickly applied and removed. A semi-spherical water-jacket is applied above the revolving disc, to protect the same from the disturbing influence of currents of air. It will be found, on examining the illustration, that the water-jacket referred to is placed on the top flange of the conical vessel, without fastening; hence it may be taken away and replaced in a few seconds. The jacket surrounding the conical vessel being maintained at a constant temperature by a current of water, the air in the lower part will also be maintained at a constant temperature. Obviously, the heated air at the top cannot descend to the bottom; consequently, the bulb of the recording thermometer will be influenced only by the radiation of the surrounding vessel, and by the radiant heat which the incandescent disc transmits. It is hardly necessary to mention that the lower half of the bulb is protected by a non-conducting covering. In view of the foregoing explanation, it will be evident that the measurement of the intensity of the radiant heat projected from the incandescent disc towards the bulb of the thermometer, at different angles of inclination, will be as reliable as if the air were exhausted from the conical vessel. In either case, the temperature of the surrounding vessel which radiates towards the thermometer, being deducted from the temperature indicated by the same, shows the intensity of the radiant heat transmitted to the bulb. It may be contended that the upper part of the latter loses a small amount of heat by convection attending the presence of air within the vessel. Assuming that the loss of heat from that cause *is* appreciable, this loss will be proportionate to the intensity of the heat transmitted during each experiment; hence it cannot affect the relative difference of intensity for different degrees of inclination of the incandescent disc.

During experiments, the apparatus is placed near an air-furnace, hose being attached to the nozzles of the external casing for circulating a constant stream of water through the intervening space. The furnace having been charged with combustibles capable of producing a steady fire, and heated to the requisite degree, the disc is inserted. Having remained in the furnace until the color of the metal approaches bright orange, the disc is quickly withdrawn and placed over the open conical vessel, supported by the axles shown in the top view of the illustration.

Agreeably to the theory, the correctness of which we are going to disprove, the incandescent disc, placed at the inclination shown in the illustration, will transmit a higher temperature to the thermometer than if it were placed at a greater angle to the vertical line; the reasons assigned for this assumption being that the same number of radiating points are presented by the disc, and the same number of rays of equal energy emitted in either position, while in the former they are more concentrated than in the latter. The stated assumption involves the proposition that parallel rays projected at an acute angle, from a given number of radiating points, transmit *greater* intensity than an equal number of parallel rays projected at a less acute angle to the radiant surface. That this proposition, although untenable, is very plausible, will be seen by reference to Fig. 1 (see diagram

Plate 22). Let *a b* represent the inclined radiant surface, and *a c b* the several radiating points projecting heat-rays towards the spaces *d f* and *k g*. The number of radiating points and the number of heat-rays projected being alike in each case, while the space represented by *k g* is only one-third of that represented by *d f*, it must be admitted, if we assume all rays to possess equal energy, that the concentration of heat within *k g* is three times greater than within *d f*. In other words, that a given area within *k g* receives three times more heat than an equal area within *d f*. This apparently correct view of the question, and its application to spheres, led Laplace astray in his demonstration concerning solar intensity. In the next chapter, which, as already stated, will be devoted to the consideration of radiant heat transmitted from incandescent spheres, the influence of the spherical form on radiant intensity will be fully considered. In the meantime, we must admit that the demonstration contained in Fig. 1 is unanswerable under the stipulated condition that all heat-rays emitted by a radiator possess equal energy. Our task, therefore, will be to show, *practically*, that the stated condition is based upon false assumptions. Having already made ourselves acquainted with the apparatus constructed for this purpose, we may at once proceed to consider the results of the experiments which have been instituted. It will be evident that, owing to the high temperature of the revolving disc, it will cool very rapidly after being removed from the furnace and placed in position over the conical vessel, and that the recording thermometer, however sensitive, will require so long a time before reaching maximum indication that only one inclination of the disc can be experimented on at a time, thus rendering reheating indispensable for each change of angle. The number of changes of inclination during the investigation have, therefore, been limited to ten, beginning with 90 deg. and ending with 10 deg. inclination to the vertical line. It will be evident that the high temperature renders it practically impossible to impart exactly the same degree of incandescence at each operation. I have, therefore, resorted to the expedient of maintaining the furnace at a uniform temperature, and to expose the disc to the action of the heat during an equal interval of time for each operation. This method, though not precise, has conclusively established the fact that the temperature transmitted to the thermometer by the radiant heat varies in the exact ratio of the sines of the mean of the angles formed by the face of the disc and a line drawn from its centre through the centre of the bulb. The result of an experiment made with great care will be found recorded by the diagram Fig. 5, in which the ordinates of the curve *a b* represent the sines of the angles formed by the disc and the lines mentioned, the ordinates of the irregular line *c d e* representing the temperature transmitted to the recording thermometer. The figures inserted below the base line *f g* show the number of degrees of inclination corresponding with the sine represented by each ordinate, while the figures above the curve *a b* show the discrepancy between the calculated and the actual temperature transmitted to the thermometer. It will be found on inspection that the mean difference of the actual and the calculated temperature *above* the curve is 1.94°, that *below* the same being 1.08°; hence the mean discrepancy is only 0.86° Fah. Considering the difficulty of imparting an equal temperature at each operation during the experiments, this discrepancy between the calculated and the actual temperature transmitted by the radiation of the incandescent disc is unimportant. We are warranted, therefore, in adopting the conclusion that the temperatures vary exactly as the sines of the angles of inclination of the radiant surface. It has been deemed proper, in view of the great importance of this conclusion, and in order to render the subject clearly understood, to introduce Figs. 4 and 5 combined, showing the several angular positions of the incandescent disc during the investigation. Dotted lines, it will be seen, have been introduced, connecting these angular positions with the corresponding ordinates of the curve *a b*. A mere glance at the geometrical representation contained in Figs. 4 and 5 will show that the temperatures indicated by the ordinates of the curve *a b* correspond exactly with the sines of the angles of inclination of the disc. Bearing in mind the facts thus established, let us again refer to Fig. 1, in which the space *k g* is one-third of the space *d f*. We are now enabled to demonstrate that the heat transmitted to a given area within the former is only one-third of the heat transmitted to an equal area within the latter. Laplace and his followers, assuming the reverse to be the case—viz., that the temperature within *k g* will be three times higher than within *d f*—their estimate of the radiant intensity of inclined surfaces will obviously be too high in the inverse ratio of the sines of angles of inclination. The consequence of this grave mistake, with reference to the radiant power of incandescent spherical bodies, will be demonstrated in the next chapter, containing a record of the temperatures developed by the heat-rays projected in a given direction from different zones of a metallic sphere raised to a high degree of incandescence.

CHAPTER XII.

RADIATION FROM INCANDESCENT SPHERES.

The question whether equal areas at different points of the solar surface transmit equal energy towards the earth has engaged the attention of several eminent scientists. It was mentioned in the previous chapter, on radiation from inclined incandescent planes, that the author of "Mécanique Céleste," finding by observation that equal areas of the sun do not transmit equal energies (the central portion transmitting, in opposition to his reasoning, much greater intensity than those near the border), explains the matter by showing that the solar atmosphere retards the passage of the rays, causing a great diminution of the energy of the radiant heat projected from the border of the sun towards the earth. It but seldom happens that questions of a cosmical nature admit of being decided by actual experiment, the present being one of the rare instances in which experimental tests may be resorted to. Evidently, if the great retardation of energy towards the border, demonstrated by Laplace, is caused solely by the obstruction encountered during the passage of the rays through the atmosphere surrounding the sun, the receding surface of an incandescent spherical body *not* surrounded by a retarding medium will transmit the supposed intensified radiant heat undiminished. The illustration on Plate 23 represents an apparatus by means of which it has been clearly demonstrated that, notwithstanding the absence of a retarding medium round an incandescent sphere, the supposed increase of radiant energy resulting from the obliquity of the heat-rays projected by the receding surface does not take place. The said illustration shows a vertical section and top view of a conical vessel surrounded by a water-jacket, and in other respects constructed as the apparatus described in the preceding chapter. The top flange of the conical vessel now under consideration is, however, provided with a groove, the bottom of which supports a solid sphere of cast iron, in the manner shown in the illustration. Below the sphere are inserted two semi-cylindrical screens of different diameter, each composed of two thin plates of iron, the intervening space between these plates being filled with a fire-proof non-conducting substance. It will be seen, on carefully inspecting the illustration, that the external screen is annular as well as semi-spherical, while the central screen consists of a concave disc; hence an annular opening is formed between each pair of screens. Supposing the cast-iron sphere to be heated before being placed in the position represented, it will be evident that the thermometer at the bottom of the conical vessel will only receive the radiant heat transmitted by the heat-rays projected towards the bulb through the annular opening formed between the two screens. It will be readily understood that, by employing screens of different proportions, zones containing *equal* convex areas, but occupying different positions, may be made to radiate towards the thermometer, and that by this means the radiant intensity transmitted from any portion of the spherical surface may be ascertained. Consequently, we are enabled to test practically the truth of the assertion that, but for the intervention of the sun's atmosphere, the receding solar surface would, owing to the increased number of rays contained within a given section, transmit an increased radiant intensity towards the earth. It may be urged against our device that atmospheric air intervenes between the incandescent sphere and the recording thermometer. A moment's consideration, however, will show that the consequent retardation is practically inappreciable. It has been established in preceding chapters that the retardation sustained by the sun's rays in passing through our atmosphere amounts to 0.207 on the ecliptic, while solar intensity at the boundary of the terrestrial atmosphere is very nearly 85° F. Consequently, the loss of radiant heat hardly reaches 18° F. in passing through 28,800 feet of atmospheric air of maximum density. The radiant heat of our experimental apparatus being transmitted through a depth of only 2 feet, the retarding influence of the air intervening between the radiating sphere and the bulb of the recording thermometer will be only $\frac{2 \times 18^\circ}{28{,}800} = 0.0012^\circ$ F. We may, therefore, without appreciable error, assume that no retarding medium surrounds the experimental incandescent sphere. The principal features of our apparatus having thus been explained, and the method of solving the problem under consideration pointed out, we may now proceed to consider the result of the experiments which have been instituted. In order to facilitate comparison, the lower half of the sphere visible from the centre of the bulb of the recording thermometer (see Fig. 6 in the diagram Plate 24) has been divided into four zones, A, B, C, and D, containing *equal* areas. It will be seen, on inspecting the arrangement of screens shown in the diagram, that no part of the surface of the sphere excepting that contained within the parallel lines defining each zone is capable of radiating towards the thermometer, all the rest being shut out by the screens. Obviously, the latter can be so proportioned that the radiant heat from any part of the lower half of the sphere may be projected towards the bulb. Figs. 3, 4, 5, and 6 in the diagram show the arrangement of screens adopted in our experiments, by means of which the transmitted radiant power of each of the zones has been ascertained. The dimensions of the several screens have been determined by drawing radial lines from the centre of the bulb of the thermometer to the points where the termination of the zones intersect the circumference of the sphere. The subject will be most readily understood by referring to Fig. 4, which exhibits zone C. The screens being made to terminate where they meet the radial lines p, g and q, g, it will be seen that an annular opening p q is formed, permitting all heat-rays to pass which are projected from the zone C in the direction of the bulb of the thermometer. A similar arrangement permits the radiant heat from zone B, in Fig. 5, to act on the thermometer. Referring to Fig. 3, it will be found that only one screen, perforated in the centre, is required to shut out the radiant heat from the three upper zones, C, B, and A; while in Fig. 6 the radiation from the three lower zones, D, C, and B, is shut out by a single central screen, the circumference of which is defined by the radial lines *m*, *k*. It should be borne in mind that, although the several screens are represented by single lines in the diagram, they are, as already explained, composed of double plates, a fire-proof non-conducting substance being inserted between the two, the object of which is self-evident.

Referring to the demonstration contained in the previous chapter relating to the diminution of energy of heat-rays projected at an acute angle to the radiant surface, it will be seen, on mere inspection, that the upper zones represented in our diagram, though containing an equal area with the lower zones, cannot possibly transmit the same temperature as the latter. The advocates of the views expressed in "Mécanique Céleste" will learn with surprise that, notwithstanding the absence of an intervening retarding medium, so great is the difference of energy communicated that, while the zone D, of the experimental incandescent sphere, transmits a temperature of 42°.5 to the thermometer, the zone A transmits only 4°.7. The latter zone being further from the thermometer than the former, a correction is, however, necessary on account of the increased dispersion of the heat-rays before reaching the bulb. This correction being made, the true ratio of temperature transmitted by the zones D and A will be 42°.50 : 6°.19. Consequently, the heat-rays projected from the lower zone of the incandescent sphere towards the bulb of the thermometer transmit nearly seven times higher temperature than the heat-rays from the upper zone. The amount of radiant surface being alike in each zone, while the temperature of the sphere is uniform throughout, it will be admitted that our practical test has clearly demonstrated the feebleness of the heat-rays projected from the border of an incandescent sphere towards a given point. It is hardly necessary to add that each zone has called for a separate experiment, rendering reheating of the sphere indispensable for each. The same expedient has, therefore, been resorted to, in order to insure an equal degree of temperature during each experiment, as in the case of the incandescent inclined disc described in the previous chapter. Of course, it has been found impracticable to impart an equal temperature to the sphere at each operation; but this difficulty has been satisfactorily overcome by establishing a mean, as in determining the intensity of the radiant heat transmitted by the inclined disc referred to. Besides, the result has been checked by computing the degree of temperature capable of being transmitted to the recording thermometer by each zone, in accordance with the relation which the intensities bear to the angles formed by the radiating surface and the heat-rays projected towards the centre of the bulb. Before giving an account of our experiments, let us demonstrate theoretically what temperature each zone ought to communicate to the thermometer, in conformity with the fact established by the experiment recorded in the preceding chapter, that the intensity of the radiant heat transmitted by an incandescent disc is directly proportional to the sines of the angles formed by the projected heat-rays and the radiating surface. In order to simplify the demonstration, the several zones have been divided into halves by dotted lines (see Fig. 7); radial lines being drawn to the thermometer at z from the points of intersection of the dotted lines referred to and the circumference of the sphere. Tangential lines, $d\,t$, $c\,u$, $b\,x$, and $a\,y$, have also been drawn from the said points of intersection. It will be evident, on considering the properties of spherical zones, that the radial lines $d\,z$, $c\,z$, $b\,z$, and $a\,z$ represent the mean direction of the heat-rays projected by each zone respectively towards z. Hence the sines of the angles $t\,d\,z$, $u\,c\,z$, $x\,b\,z$, and $y\,a\,z$ will determine the amount of radiant heat transmitted towards z by each of the zones D, C, B, and A. Calculation shows that if the sine of the angle $t\,d\,z$ be represented by unity, the sines of the other angles, in the order presented, will be 0.671, 0.384, and 0.121, while the experiments which have been made show that the zone D transmits a temperature of 42°.50 to the recording thermometer. Consequently, the zones C, B, and A ought to transmit respectively 28 .50, 16°.31, and 5°.16 to the thermometer at z. The accompanying table shows to what extent the actual temperatures transmitted by the incandescent sphere differ from the stated computed temperatures. It should be observed that no direct comparison can be based upon the temperatures entered in the fourth column, since the heat-rays projected by the several zones are subjected to different degrees of dispersion, owing to the unequal distance from the thermometer. Due allowance being made for the dispersion of the rays, in conformity with the elements furnished in Fig. 7, the consequent augmentation of temperature has been added, and the corrected values entered in the fifth column of the table. The

1	2	3	4	5	6
Zone.	Mean angle of projection.	Comparative sine.	Observed temperature.	Corrected temperature.	Computed temperature.
	Deg. Min.	*Proportion.*	° *Fah.*	° *Fah.*	° *Fah.*
D	58 0	1.000	42.5	42.50	42.50
C	34 40	0.671	24.2	27.49	28.50
B	19 0	0.384	10.1	12.82	16.31
A	5 55	0.121	4.7	6.19	5.16

computed temperatures will be found in the sixth column. It will be imagined, at first sight, that the figures entered in the table indicate a serious discrepancy between the observed and the computed temperature. That such is not the case will be found on referring to Fig. 8, in which the ordinates of the regular curve *a b* represent the computed temperatures, while the ordinates of the irregular curve *a d c* represent the observed temperatures. Obviously, the computed and the observed energies transmitted by the radiation of the incandescent sphere are truly represented by the superficies contained between the base *f g* and the curves *a b* and *a d c* respectively. Calculation shows that these superficies are as 1.000 to 0.945. Considering the small amount of this discrepancy, in connection with the difficulty of bringing the heated sphere to an equal degree of incandescence during each experiment, we are warranted in asserting that the instituted test has proved conclusive, and that the inaccuracy of the doctrine promulgated in "Mécanique Céleste," regarding the radiant energy transmitted by the rays projected from the receding surface of an incandescent sphere, has been fully demonstrated.

CHAPTER XIII.

RADIATION FROM FUSED IRON.

THE illustration on Plate 25 represents a calorimeter originally constructed to demonstrate practically the fallacy of the statements contained in certain papers read before the Academy of Sciences at Paris by Messrs. Sainte-Claire-Deville and M. E. Vicaire. These physicists assert that the temperature of the solar surface does not exceed that produced by the combustion of organic substances. Their reasoning being based on the law of radiant heat established by Dulong and Petit, I instituted, soon after the publication of the papers referred to, a series of experiments on a very large scale, in order to test thoroughly the correctness of that law with reference to radiation at high temperatures. The nature of these experiments will be seen by the following brief description: An iron vessel, lined with fire-clay on the inside, was filled with fused cast-iron obtained from a cupola furnace in which the metal had been raised to a temperature exceeding 3,000° F. by the process of overheating. On the surface of this fused mass, the weight of which exceeded 7,000 pounds, the calorimeter represented in the illustration was floated while registering the dynamic energy developed by the radiant heat of the metal. Sir Isaac Newton, whose sagacity perceived that radiation with reference to mechanics is simply transmission of energy, assumed that the quantity of heat lost or gained by a body in a given time is proportional to the difference between its temperature and that of the surrounding medium. Some eminent scientists, however, accepting the conclusions and formula of Dulong and Petit (see Chap. II.), assert positively that the stated assumption is incorrect. The important fact appears to have been overlooked that the investigations instituted by those experimentalists have in reality established only the degree of conductivity of the radiators employed, under certain conditions, but by no means their true radiant energy at high temperatures. Sainte-Claire-Deville and M. E. Vicaire, therefore, commit a serious mistake in assuming that the quantity of heat transmitted by the radiation of incandescent bodies, at very high temperatures, has been determined by their celebrated countrymen. The fact may properly be adverted to in this place that the relation between the time of cooling and the *quantity* of heat transmitted by radiation which Dulong and Petit established, misled Pouillet regarding the temperature of the solar surface, which he computed at 1,461° C., or at most 1,761° C. It will be well to bear in mind that Pouillet had himself ascertained with considerable accuracy the temperature produced by solar radiation on the surface of the earth, and also the retardation suffered during the passage of the rays through the terrestrial atmosphere. He was, therefore, able to demonstrate that the dynamic energy developed by solar heat amounts to nearly 300,000 thermal units per minute for each square foot of the surface of the sun. Considering the imperfect means employed by Pouillet, his "pyrheliometer," the near approach to exactness of his determination of solar energy is remarkable.

Temperature being a true index of molecular and mechanical energy, conclusively established by the exact relation between the degree of heat and the expansive force of permanent gases under constant volume, it is surprising that Pouillet did not perceive that an intensity of 1,461° C. or 1,761° C. could not possibly develop on a single square foot of surface the enormous energy represented by 300,000 thermal units per minute. M. Vicaire, adopting, like Pouillet, Dulong's formula, states in the paper presented to the French Academy that "an increase of 600° is sufficient to increase the radiation a hundredfold," and that Pouillet has verified Dulong's law to more than 1,000°. "Supposing," he observes, "that beyond this temperature the law ceases to be true, it cannot be absolutely remote from the truth for the temperatures of from 1,400° to 1,500°, which we deduce by adopting the law." Sainte-Claire-Deville concludes his essay on solar temperature thus: "In accordance with my first estimate, I believe that this temperature will not be found far removed from 2,500° to 2,800°, the numbers which result from the experiments of M. Bunsen and those published long ago by

M. Debray and myself." The French scientists then agree that the temperature of the surface of the sun does not exceed the intensity produced by the combustion of organic substances, their grounds for this assumption being, as we have seen, Dulong's formula relating to the velocity of cooling at high temperatures. But Dulong and Petit, apart from the imperfections of the means which they adopted, did not carry their investigations practically beyond the temperature of boiling mercury. It will be seen, on reference to Chap. II., that their formula relating to high temperatures is mere theory, the unsoundness of which the investigation now under consideration has established in the most conclusive manner by the insignificance of the radiant power developed by a mass of fused metal presenting an area of 900 superficial inches, 30 inches deep, raised to a temperature of 3,000° F.

Before describing the instrument employed in determining the radiant energy developed by the stated unprecedentedly large mass, I deem it important to point out briefly the condition of the fluid metal during the experiments. In the first place, the temperature was sufficiently high to produce an intense white light, luminous rays of great brilliancy being emitted by the radiant surface during the trial; (2) the bulk of the fused mass being adequate, the intensity of radiation was sustained without appreciable diminution during the time required for observation. The temperature being higher than that which the French investigators assign to the surface of the sun, while the bulk, as stated, was sufficient to maintain the temperature of the fused mass, it may reasonably be asked why an area of one square foot of our experimental luminous radiator should not emit as much heat in a given time as an equal area of the solar surface, if the temperature of the latter be that assumed by Pouillet? It is hardly necessary to observe that an increase of the dimensions of the radiating mass of metal to any extent whatever could not augment the intensity or add to the dynamic energy developed by a given area. It has been shown in previous chapters that, agreeably to Dulong's erroneous formula, the emissive power of a *metallic radiator* raised to a temperature of 3,000° F. considerably exceeds Pouillet's estimate of solar emission.

Let us now briefly examine the illustrated calorimeter, constructed for ascertaining the mechanical energy developed by the radiation of a fused mass of cast-iron raised to the temperature of 3,000° F. Fig. 1 represents a vertical section, and Fig. 2 a perspective view; *a* is a cylindrical boiler, having a flat bottom, composed of thin sheet-iron 0.012 in. thick, coated with lamp-black. The vertical part of this boiler is surrounded by a concentric casing *b*, the intervening space being filled with a fire-proof non-conducting substance. A horizontal wheel revolving on a vertical axle *d*, and provided with six radial paddles attached to a perforated disc *c c*, is applied within the boiler. An open cylindrical trunk *g* is secured to the perforated disc which supports the paddles. The vertical axle passes through the top of the boiler, a conical pinion being secured to its upper termination. By means of a cog-wheel *h*, attached to the horizontal axle *k*, and geared into the conical pinion, rotary motion is communicated to the paddles. The centrifugal action of the latter will obviously cause a rapid and uniform circulation of the water contained in the boiler—indispensable to prevent the intense radiant heat of the fused metal from burning the bottom. The boiler and mechanism thus described are secured to a raft *l l*, composed of fire-bricks floating on the top of the fluid metal. By this means it has been found practicable to keep the bottom of the boiler at a given distance, very near the surface of the fused mass, while, by moving the raft from point to point during the observation, irregular heating, resulting from the reduction of temperature of the surface of the metal under the bottom of the calorimeter, has been prevented. The radiant heat emanating from such a large body of fused metal being too intense to admit of the axle *k* being turned directly by hand, an intervening shaft of considerable length, provided with a crank-handle at the outer end, has been employed for keeping up the rotation of the paddle-wheel during the trial. It is scarcely necessary to mention that the intervening shaft should be coupled to the gear-work by means of a "universal joint," to admit of the necessary movement of the raft from point to point on the surface of the liquid metal. The experiment, repeated several times, has been conducted in accordance with the following programme: The boiler being charged with pure water, the paddle-wheel should be turned at a moderate speed while observing the temperature of the fluid, the thermometer employed for this purpose being introduced through an opening *m* at the top of the boiler. The temperature being ascertained, the calorimeter should be placed on the raft as quickly as possible, and the time noted. As soon as vapor is observed to escape through the opening at *m*, the instrument must be instantly removed, the time again noted, and the temperature of the water in the boiler ascertained. It will be well to keep the paddle-wheel in motion until the last observation has been concluded.

The temperature of the fused metal having been as high during our experiments as that of the solar surface, according to the computation of Pouillet and his followers, while the thin substance composing the bottom of the calorimeter has been brought almost in contact with, and consequently received the whole energy transmitted by, the radiant surface, the reader will be anxious to learn what amount of dynamic energy has been developed by the radiation of the metal in a given time on a certain area. The desired information is contained in the following brief statement: Allowance being made for heat absorbed by the materials composing the paddle-wheel, etc., the instituted test shows that the temperature of a quantity of water weighing 10 lbs. avoirdupois has been elevated 121° F. in 164 seconds (2.73 min.), the area exposed to the radiant heat being 63 sq. in. Hence a dynamic energy $\frac{10 \times 121}{2.73} \times \frac{144}{63} = 1{,}013$ thermal units per min. has been developed by the radiation from 1 sq. ft. of the surface of the fused metal maintained at 3,000° F., against 300,000 units developed by the radiation of 1 sq. ft. of the solar surface, the temperature of which, agreeably to the calculations of the French physicists, is less than that of our experimental radiator. Comment is unnecessary.

Some advocates of Dulong and Petit's theory explain the enormous discrepancy which our investigation of the radiant power of fused metal discloses, by showing that their law relates to the velocity of cooling, and not to the amount of dynamic energy parted with. That Pouillet regards the law as referring to dynamic energy is evident, or he would not have attempted to establish by computations based upon it that an energy represented by 300,000 thermal units could be developed in one minute upon an area of one square foot by a body whose temperature is under 1,700° C. Before concluding our discussion, let us consider how Dulong and Petit's law is regarded by practical engineers, who are more interested in its infallibility than students of natural philosophy. Mr. Box, in his "Practical Treatise on Heat," published 1868, says, with reference to Dulong and Petit's investigations, in which he evidently places full confidence: "Dulong has given rules which agree well with experiments up to a difference of temperature of 468° F. This rule is a very difficult one to apply, but it may be put in such a form as to give a *ratio* by which calculation by the simple rule may be easily corrected. The rule thus becomes: $\frac{124.72 \times 1.0077^t \times (1.0077^t - 1)}{T} = R''$, in which t = the temperature of the absorbent, or recipient of radiant heat; T = the *excess* of temperature of the radiating body in degrees

Centigrade; and R″ = the ratio of loss of heat under the given temperatures." The author of the "Practical Treatise on Heat" then proceeds to construct a table of temperature and ratio of loss by cooling; but before presenting the same to his readers he prefixes the following observation: "This table shows that with a radiant body at a clear red-heat of 1,860° the loss is about 300! times the amount due by the simple formula, and at a bright white-heat of 2,580 it rises

MR. BOX'S TABLE OF THE RATIO OF LOSS OF HEAT AT VERY HIGH TEMPERATURES, BY THE FORMULA OF DULONG.

Temperature of the heated body.	Temperature of the surrounding air.	Temperature of the body above that of the air.	Ratio of heat at different temperatures. Radiation.	Ratio of heat at different temperatures. Contact of air.
° *Fah.*	° *Fah.*	° *Fah.*	*Ratio.*	*Ratio.*
490	60	450	3.10	1.980
600	60	540	4.19	2.085
780	60	720	7.17	2.230
900 Red, just visible	60	840	12.68	2.378
1140 " "	60	1080	23.01	2.450
1320 Dull red	60	1260	42.70	2.540
1500 Dull cherry red	60	1440	80.67	2.620
1680 Cherry red	60	1620	154.5	2.693
1860 Clear red	60	1800	299.7	2.760
2220 Clear orange	60	2160	1159.0	2.880
2580 White, bright	60	2520	4604.0	2.985

to 4,604 ! ! times that amount." If any doubt existed on the subject, the author's emphatic exclamations furnish unquestionable evidence that he is not aware of the fact that he is propagating a mischievous doctrine, and that he regards the stated extraordinary ratios as true measures of the amount of dynamic energy parted with at high temperatures.

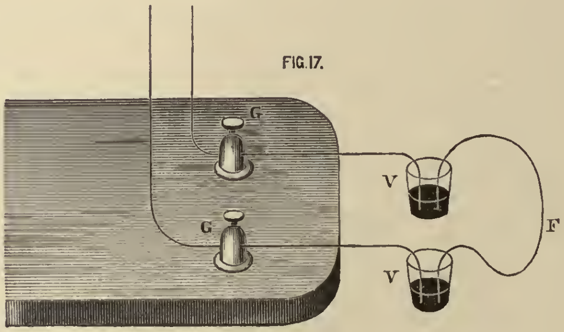
The fallacy of Dulong and Petit's formula relating to high temperatures having been conclusively demonstrated in Chap. II., I have deemed it unnecessary to examine the calculations based on that formula contained in the papers presented by Messrs. Sainte-Claire-Deville and M. E. Vicaire to the Academy of Sciences at Paris, referred to at the commencement of this chapter.

CHAPTER XIV.

RADIANT HEAT MEASURED BY THE THERMO-ELECTRIC METHOD.

Melloni asserts, in "La Thermochrose," that the calorific energies imparted to a thermopile are as the arcs through which the needle of the galvanometer sweeps, until the deflection exceeds 13 degrees. This assumption being at variance with the principles of dynamics, its correctness calls for a thorough investigation before it can be accepted. Intending originally to employ the thermo-electric method for ascertaining the difference of the radiant energy transmitted by the sun's rays from different portions of the solar disc, I carefully investigated the subject, and found, by experimental test, that Melloni's law is not correct. Theoretical demonstration pointed to the fact that, for deflections not exceeding 15 deg., the calorific energy imparted to the pile by radiant heat is very nearly as the square root of the versed sine of the angle of deflection from zero. It may be briefly stated that, having previously resorted to various expedients for testing roughly the reliability of the assumption that the energy is as the arc up to thirteen deg. deflection—the result of the test in each instance proving decidedly unfavorable to Melloni's doctrine—I undertook the construction of a special apparatus for calibrating the galvanometer applied to my thermopile. By means of this apparatus the energy developed for different deflections of the needle from zero to 35 deg. has been accurately determined. Before describing the new device, it will be proper to examine

FIG. 17.



Melloni's method of calibrating galvanometers, described in the work referred to; especially since its supposed correctness has induced several eminent physicists to accept the assumption that the energies are as the arcs swept by the needle from zero to 13 deg. deflection. "Two vessels V V (see Fig. 17) are half filled with quicksilver, and connected by two short wires, separately, with the terminations G G of the galvanometer. The vessels and wires, arranged as shown, will not change the action of the instrument; the thermo-electric current between the pile and the galvanometer being freely kept up as before. But if we establish a communication between the two vessels by means of the wire F, a portion of the current will pass through this wire and then return to the pile. The quantity of circulating electricity in the galvanometer will then be diminished, while the deflection of the needle will be reduced. Suppose that by this expedient we have diminished the galvanometric deviation to one-fourth or one-fifth—viz., that the needle indicating 10 or 12 degrees, by the power of a constant source of heat located at a given distance from the pile, recedes 2 or 3 degrees when part of the current is diverted by the outside wire. If we then cause the source of heat to act at various distances, and observe in each case the maximum deflection and the least deflection, we obtain the necessary data for determining the ratio between the deflection of the needle and the energy causing that deflection. To make the matter better understood, and to give at the same time an example of the manner of operating, let us take the numbers bearing on the application of the method to one of the thermo-multipliers. Let the outside circuit be interrupted, and the source of heat located at an adequate distance from the pile to deflect the needle not more than 5 degrees. The wire being then passed from V to V, the needle falls to 1.5; the connection between the vessels being again interrupted, and the source of heat placed near enough to produce the following deflections in succession: 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°. Applying the same wire between V and V after each deflection, we obtain the following energies: 1°.5, 3°, 4°.5, 6°.3, 8°.4, 11°.2, 15°.3, 22°.7, 29°.7. Supposing the energy equal to unity which is necessary to cause the needle to describe arcs corresponding with each of the first degrees of the galvanometer, we then have the number 5 as an expression of the energy corresponding to the initial observation. The other energies are readily ascertained by the relations: $1.5 : 5 = x = \frac{5}{15} a = 3.333$, where a indicates the deflection when the outside circuit is closed. Obviously, any diminished current is to the total current to which it corresponds as any other diminished current to its corresponding total current. Hence, 5, 10, 15.2, 21, 28, and 37.3 are the energies corresponding to the deflections 5°, 10°, 15°, 20°, 25°, and 30°. In this presentation it will be seen that the energies are nearly proportional to the arcs up to about 15 degrees; but beyond this deflection the proportionability is at an end, the discrepancy augmenting with the arcs." The energies at intermediate degrees, it is stated, are readily ascertained by calculation or by the graphic method, the latter being assumed to be sufficiently precise for the purpose. The accompanying table exhibits the corresponding deflections and energies determined by Melloni in accordance with the foregoing demonstration:

The constructor of the table observes that no notice has been taken of deflections under 13 deg., since the energies within that deflection are, as he supposes, correctly represented by the arcs swept by the needle. It is hardly necessary to call attention to the unsatisfactory nature of the foregoing method of returning part of the electric current by the wire F, for the purpose of ascertaining the calorific energies imparted to the pile by the radiant heat emanating from the radiator. Unless we adopt some positive means of measuring the intensity of the heat to which the face of the pile is subjected at the instant of observing the deflection of the needle of the galvanometer, the relation of deflection and calorific energy cannot be accurately determined. Now, the demonstration contained in Chap. I. proves that the intensity of radiant heat transmitted through a given space by a circular radiator of known diameter and temperature may be determined with positive accuracy. Accordingly, the method of calibrating galvanometers, which I am going to lay before the reader, is based on the stated demonstration proving that a correct knowledge of form, distance, and temperature of

MELLONI'S TABLE, SHOWING THE RELATION BETWEEN DEFLECTION AND ENERGY.

Deflection of needle.	Energy exerted.	Deflection of needle.	Energy exerted.	Deflection of needle.	Energy exerted.
13.0	13.0	19.0	19.8	25.0	28.0
14.0	14.1	20.0	21.0	26.0	29.7
15.0	15.2	21.0	22.3	27.0	31.5
16.0	16.3	22.0	23.5	28.0	33.4
17.0	17.4	23.0	24.9	29.0	35.3
18.0	18.6	24.0	26.4	30.0	37.3

the radiator enables us to ascertain, with absolute precision, the degree of calorific energy imparted to the thermo-electric pile during the investigation. The following brief description of the apparatus represented by our illustration (see Pl. 26) will suffice to give a clear idea of the same: *t*, table having a longitudinal parallel groove, 6 ins. wide, 2 ins. deep, formed on the top. *b*, sliding wooden block, 12 ins. square, 1½ ins. thick, provided with a parallel projection below corresponding with the groove in the table, and admitting of the block sliding freely from end to end. A vertical plate *s*, 20 ins. high, 12 ins. wide, is secured to the sliding block. *p* represents a thermo-electric pile placed on the top of the table. The vertical plate *s* is perforated in the centre, for the purpose of supporting a cylindrical boiler *r*, 4 ins. in diameter, provided with an open trunk on the top, through which a thermometer is inserted. The end of this boiler pointing towards the pile is concave, while the opposite end is flat; a spirit-lamp being applied under the same, supported by the sliding block *b*. A scale, divided into 100 parts of one inch each, is attached to the side of the table, the zero of this scale coinciding with a perpendicular line drawn from the face of the thermo-electric pile *p*. The extreme point of the concavity of the boiler *r* being in line with the front side of the plate *s*, while the zero of the scale, as stated, is in line with the face of the pile, it will be seen that the distance through which the radiant heat acts may be regulated by simply moving the sliding block to any desired division on the scale. A metallic screen *s′*, 20 ins. high, 12 ins. wide, plated with polished silver, is attached to the vertical plate *s*, in order to prevent the radiant heat of the latter from acting on the thermo-electric pile. The metallic screen is provided with a central perforation, 4 ins. in diameter, the centre of which coincides with the prolongation of the axis of the cylindrical boiler. Regarding the temperature of the latter, it will be seen that, by applying the spirit-lamp, as already stated, the water may be kept constantly at the boiling point, since any excess of heat above that point will be carried off by the steam allowed to escape through the open trunk which contains the thermometer. Accordingly, the thermo-electric pile *p* will at all times be subjected to a definite radiant intensity depending on its distance from the radiator *r*; while the graduated scale attached to the side of the table *t* enables the experimenter to regulate that distance rapidly and accurately. In accordance with the law governing the transmission of heat, before referred to, the temperature imparted to the thermo-electric pile *p* will bear the same relation to the differential temperature of the boiler as the square of the radius of the semi-spherical end of the latter bears to the square of the distance of the same from the face of the pile. Consequently, when the boiler is placed as shown in the illustration, the temperature transmitted by radiation may be ascertained by the following calculation: Assuming that the thermometer inserted through the open trunk at the top of the boiler indicates 212° F., and that the tepmerature of the surrounding air is 70° F., the intensity of the radiant heat emanating

from the boiler will be 212 − 70 = 142° F. Now, as the position of the block *b* is such that the concavity *r* coincides with the 50th division on the scale, the distance between the face of the pile and the radiating surface will be 50 inches, while the radius of the concavity is 2 inches. The temperature imparted by the radiation emanating from the boiler will, therefore, amount to $\frac{2^2 \times 142}{50^2} = 0°.227$ F. The calorific energy transmitted by the radiator at all other distances may of course be determined by a similar process of computation. Having theoretically determined the intensity of the radiant heat for each division on the scale, the existing relation between the deflection and the computed energy will be ascertained simply by observing the corresponding position of the needle of the galvanometer. Our task, however, is that of ascertaining the calorific energy corresponding with arcs not of varying length swept by the needle of the galvanometer, but arcs each measuring $\frac{1}{360}$ of a circle commencing at the galvanometric zero. Evidently, *arcs* and energies are not directly comparable; hence, we must ascertain, experimentally, what calorific energy corresponds with the first degree, or the first half degree, of deflection of the needle from zero. It has already been stated that the radiant energy emanating from the concave face of the boiler is 142° F. when the temperature of the surrounding air is 70° F. Hence, agreeably to the foregoing process of calculation, the temperature imparted to the pile when the boiler is placed at the extreme end of the scale—viz., 100 inches from the face of the pile

—will be $\frac{2^2 \times 142}{100^2}$ = 0°.057 F. Now, such are the proportions of the illustrated apparatus that, when the differential temperature of the boiler is 142° F. and the concave face of the boiler coincides with the 100th division of the scale, the deflection of the needle is 30′ from zero. The foregoing demonstrations and reasoning being deemed sufficiently explanatory, we may now consider the diagram attached to the illustration, Plate 26. The length of the ordinates of the curves *b f* and *b d* represent the relation between the energies imparted to the pile and the arcs swept by the needle; the figures marked on the vertical base-line *a c* denoting *the degrees of deflection from zero.* In other words, the ordinates of the curve *b d* show the observed deflections for each degree from zero, while the ordinates of the curve *b f* show the developed energy. It will be seen, therefore, that the portions of the ordinates which are contained between the two curves represent the excess of developed energy above that of the observed deflection. Considering that the length of the ordinates of the curve *b f* have been determined in accordance with the well-established laws governing the transmission of radiant heat, while the length of the ordinates of the curve *b d* is the result of actual observation, the correctness of the ascertained relation cannot be questioned. Consequently, a mere inspection of the diagram suffices to show the fallacy of Melloni's assumption that, within a deflection of 13 degrees, the arc swept by the needle and the energy imparted to the pile correspond exactly. Obviously, by comparing the inter-

Table A, showing the Relation between Energy and Deflection at Definite Distances.

Distance of pile from the heater.	Temperature imparted to the pile.	Energy exerted.	Observed deflection of the needle.	Distance of pile from the heater.	Temperature imparted to the pile.	Energy exerted.	Observed deflection of the needle.
Inches.	*° Fah.*	*Relative.*	*Deg.*	*Inches.*	*° Fah.*	*Relative.*	*Deg.*
100	0.057	0.50	0.50	34	0.491	4.31	3.80
95	0.063	0.55	0.60	33	0.521	4.58	4.00
90	0.070	0.61	0.70	32	0.555	4.87	4.30
85	0.078	0.68	0.80	31	0.591	5.19	4.50
80	0.088	0.77	0.90	30	0.631	5.54	4.90
75	0.101	0.88	1.00	29	0.675	5.92	5.30
70	0.116	1.01	1.10	28	0.724	6.36	5.60
65	0.134	1.17	1.20	27	0.779	6.84	6.00
60	0.158	1.38	1.40	26	0.840	7.37	6.40
55	0.188	1.64	1.60	25	0.909	7.98	6.90
50	0.227	1.99	1.80	24	0.986	8.65	7.30
49	0.236	2.07	1.90	23	1.073	9.42	8.00
48	0.246	2.16	2.00	22	1.173	10.30	8.90
47	0.257	2.26	2.10	21	1.288	11.30	9.90
46	0.268	2.35	2.20	20	1.420	12.46	10.90
45	0.280	2.46	2.30	19	1.573	13.80	12.00
44	0.293	2.57	2.40	18	1.753	15.38	13.10
43	0.307	2.69	2.50	17	1.965	17.24	14.40
42	0.322	2.82	2.60	16	2.219	19.46	16.30
41	0.338	2.96	2.70	15	2.525	22.14	18.50
40	0.355	3.11	2.90	14	2.898	25.42	20.40
39	0.373	3.27	3.00	13	3.361	29.48	23.00
38	0.393	3.45	3.00	12	3.944	34.59	25.90
37	0.415	3.64	3.10	11	4.694	41.18	29.00
36	0.439	3.85	3.30	10	5.680	49.82	32.00
35	0.464	4.07	3.50	9	7.012	61.51	35.00

vening space between the curves *b d* and *b f* on the 13th ordinate, and the length of that ordinate between the base-line *a c* and curve *b d*, we obtain a definite idea of the magnitude of the error involved in Melloni's doctrine that deflection and energy correspond until the position of the needle marks thirteen degrees from zero. It is important to observe that a scale, corresponding with the scale of inches marked on the side of the table represented in the illustration, has been introduced parallel with the vertical base-line *a c* in the diagram. This expedient enables us to make a direct comparison between the position of the concave radiator and the deflection of the needle of the galvanometer, marked on the vertical base-line *a c*. It will be seen, for instance, that, when the deflection of the needle is 35 degrees, the radiator is placed 9 inches from the face of the pile.

Let us now consider briefly the manner of conducting the experiments which have enabled us to construct the diagram referred to and the accompanying table A. The deflections of the needle of the galvanometer and the energies imparted by radiation to the pile beyond the 50th division being very small, the observations between that division and the termination of the scale have been confined to spaces of 5 inches each, as will be seen on reference to the table mentioned. But from the 50th to the 9th division the observations have been made for each inch. Accordingly, 41 distinct experiments were instituted while advancing the boiler from the fiftieth to the ninth division of the scale attached to the side of the table. It is important to mention that, in order to allow the pile to cool effectually, the sliding block *b*, together with the boiler and screens *s* and *s′*, were removed into an adjoining room, and the needle of the galvanometer brought to perfect rest at zero, for each observation. It may be mentioned that the final investigation was carried out under very favorable conditions, the temperature of the surrounding air fluctuating so slightly that the differential temperature of the boiler did not vary one degree during the experiment. The mode of constructing Table A, which exhibits the relation between energy and deflection at definite distances, will be readily understood. The distance between the concave radiator and the face of the pile, it will be seen, has been entered in the first column, while the temperature transmitted to the pile by radiation has been entered in the second column. The determination of the temperature referred to is effected by the following simple arithmetical process: Multiply the square of the radius of the concave surface *r* by the differential temperature of the boiler, and divide the product by the square of the distance between the radiator and the pile; the quotient—entered in the second column of the table—expresses the intensity transmitted to the pile by the heat emanating from the radiator. For example, the intensity of the transmitted radiant heat, at a distance of 19 inches, will be $\frac{2^2 \times 142}{19^2} = 1^\circ.573$ F. Referring to the table, it will be found that the temperature thus ascertained is recorded in the second column, opposite the distance 19 entered in the first column. The mode of ascertaining the temperature transmitted by the radiator to the thermo-electric pile at each point of the scale being thus fully explained, let us now consider the relative amount of energy represented by the temperature entered in the second column of our table. It has already been pointed out that the temperature imparted to the pile by the radiant heat, and definite arcs—say *degrees*—swept by the needle of the galvanometer, are not comparable quantities; hence cannot be determined by calculation. We must therefore, as already pointed out, have recourse to the experimental process in ascertaining the relation of the temperature transmitted and the deflection of the needle when the radiator is at maximum distance from the thermo-electric pile. Repeated trials have shown that, when the radiator is placed at a distance of 100 inches from the face of the pile, the ratio between the deflection of the needle—measured by arcs containing $\frac{1}{360}$ of a circle; and the temperature transmitted to the pile—measured by degrees of Fahrenheit, is as 0.50 to 0.57. The energies inserted in the third column of the table have been determined in accordance with the stated relation of temperature and deflection of the needle of the galvanometer, while the deflections of the needle entered in the fourth column have been determined by observation. It will be seen, by inspecting the latter, that the *energy* exceeds that indicated by the deflection of the needle, for all distances between the 55th division on the scale and the pile; the energy at that point being 1.64, while the *deflection* is only 1.60. Between the 100th and 60th divisions of the scale the observed deflections, it will be noticed, are irregular, slightly exceeding the energies. This irregularity is occasioned by the sensitiveness of the instrument when the radiator is far from the pile. It only remains to call attention to Table B, exhibiting the final result of our elaborate investigation of the thermo-electric method of measuring radiant heat. It will be seen, on carefully examining this table, that the deflection of the needle of the galvanometer at the termination of the first degree *exceeds* the energy transmitted by the radiator towards the thermo-electric pile in the ratio of 100 to 89, difference = 0.11 ;

TABLE B, SHOWING THE RELATION BETWEEN DEFLECTION AND ENERGY.

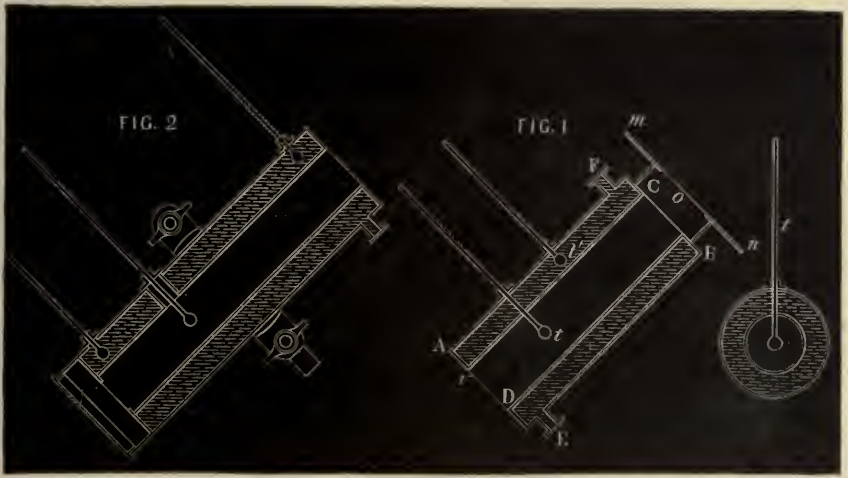
Deflection of needle.	Energy exerted.	Deflection of needle.	Energy exerted.	Deflection of needle.	Energy exerted.
Deg.	*Relative.*	*Deg.*	*Relative.*	*Deg.*	*Relative.*
1	0.89	13	15.28	25	33.07
2	2.17	14	16.58	26	35.00
3	3.38	15	17.90	27	37.05
4	4.59	16	19.24	28	39.24
5	5.77	17	20.60	29	41.58
6	6.86	18	21.98	30	44.20
7	8.00	19	23.39	31	47.00
8	9.15	20	24.84	32	50.00
9	10.33	21	26.34	33	53.30
10	11.53	22	27.90	34	57.00
11	12.75	23	29.53	35	61.23
12	14.00	24	31.25		

an unimportant irregularity already adverted to. Beyond 90′ from zero the energy becomes greater than the deflection in a constantly increasing ratio as the arcs swept by the needle augment. Accordingly, when the needle has moved through an arc of 13 degrees, the energy is greater than the deflection in the ratio of 15.28 to 13.00, instead of being exactly balanced, as stated by Melloni.

CHAPTER XV.

THE THERMOHELIOMETER.

THE calculations presented by Père Secchi in his work "Le Soleil," relative to the intensity of solar radiation and the temperature of the sun, being based on the indications of his thermoheliometer, I have carefully examined the properties of this unique device, delineated on page 267 of the work referred to. The accompanying illustration (see Fig. 1) represents a longitudinal section of the same through the vertical plane. A B and C D are two concentric cylinders soldered one to the other; they form a kind of boiler, the annular space being filled with water or oil at any temperature. A thermometer *t* passes through a tube, across the annular space, to the axis of the cylinder; it receives the solar rays introduced through a diaphragm *m n*, the opening *o* of which is very little larger than the bulb of the thermometer. A thick glass *v* closes the back part of the instrument, and admits of ascertaining whether the thermometer is placed in a direct line with the pencil of rays. The interior cylinder and the thermometer t are coated with lamp-black. A second thermometer t' shows the temperature of the annular space, and consequently that of the enclosure. The whole apparatus is mounted on a support having a parallactic movement, to facilitate following the diurnal motion of the sun. The apparatus being exposed to the sun, it will be found, on observing the two thermometers, that their difference of temperature increases gradually, and that in a short time it ends by being constant.



Before pointing out the peculiarities of the contrivance thus described by Père Secchi, it will be instructive to examine his "solar intensity apparatus," manufactured by Casella, represented in Fig. 2. The manufacturer publishes the following statement regarding this instrument: "Two thermometers are here kept immersed in a fluid at any temperature, and a third surrounded by the same conditions, but not immersed, is exposed to the rays of the sun. The increase of temperature thus obtained is found to be the same, irrespective of the temperature of the fluid which surrounds it." No one acquainted with the principles which govern the transmission of heat within circulating fluids can fail to observe that the thermometers applied above the central tube will not furnish a reliable indication of the temperature of the fluid below the same, nor of any portion of the contents of the annular space towards the bottom. Apart from this defect, it will be perceived that an upward current of atmospheric air will sweep the under side of the external cylinder, causing a reduction of temperature of the fluid confined in the lower half of the annular space. Again, the heat radiated by the bulb of the thermometer exposed to the sun will elevate the temperature of the air within the central tube, and consequently produce an internal circulation tending to heat the upper part of the fluid contained in the annular space. The effect of the irregular heating and cooling thus adverted to will be considered after an examination of the result of some observations recorded in Tables A and B, which I conducted at different times during the month of September, 1871. In order to insure an accurate position, the instrument during these observations was mounted in a revolving observatory upon a table turning on declination axes provided with appropriate mechanism and declination circle. An actinometer being attached to the same table, the true intensity of the radiant heat, as well as the sun's zenith distance, were recorded simultaneously with the indications of the Secchi instrument furnished

TABLE A, SHOWING THE RESULT OF OBSERVATIONS MADE WITH SECCHI'S THERMOHELIOMETER, MANUFACTURED BY CASELLA.

SEPTEMBER 2.

Thermometer exposed to the sun.	External casing.			Differential temperature.	Zenith distance.
	Upper thermometer.	Lower thermometer.	Mean.		
° Fah.	*° Fah.*	*° Fah.*	*° Fah.*	*° Fah.*	*Deg.*
83.5	76.0	70.0	73.0	10.5	33.0
84.2	77.0	71.5	74.2	10.0	
85.5	79.0	74.2	76.6	8.8	32.50
86.0	83.5	74.5	79.0	7.0	
89.0	84.0	75.5	79.7	9.2	33.0
90.5	85.0	76.5	80.7	9.7	
92.0	85.5	78.0	81.7	10.2	33.10
93.0	86.5	79.0	82.7	10.2	
94.0	87.8	80.0	83.9	10.1	33.21
94.5	89.0	81.5	85.2	9.2	
95.5	90.0	82.5	86.2	9.2	33.32
96.5	90.5	83.5	87.0	9.5	
98.0	91.5	84.5	88.0	10.0	33.44
99.0	92.0	85.0	88.5	10.5	
100.0	93.0	86.0	89.5	10.5	33.56
101.0	93.5	86.5	90.0	11.0	
101.5	94.0	87.0	90.5	11.0	34.8
93.1	86.9	79.7	83.3	9.80	33.24

TABLE B, SHOWING THE RESULT OF OBSERVATIONS MADE WITH SECCHI'S THERMOHELIOMETER, MANUFACTURED BY CASELLA.

Thermometer exposed to the sun.	External casing.			Differential temperature.	Zenith distance.
	Upper thermometer.	Lower thermometer.	Mean.		
° *Fah.*	° *Fah.*	° *Fah.*	° *Fah.*	° *Fah.*	*Deg.*
		SEPTEMBER 6.			
94.5	88.0	81.5	84.7	9.7	35.56
95.5	88.5	83.0	85.7	9.7	
96.5	89.5	84.5	87.0	9.5	35.41
97.5	90.0	85.0	87.5	10.0	
98.0	90.0	85.0	87.5	10.5	35.26
98.5	90.5	85.5	88.0	10.5	
99.0	90.5	85.7	88.1	10.9	35.11
100.0	91.0	86.5	88.7	11.2	
100.3	91.0	87.0	89.0	11.3	34.56
100.3	91.2	87.5	89.3	11.0	
100.5	91.5	88.0	89.7	10.8	34.41
98.2	90.1	85.3	87.7	10.45	35.33
		SEPTEMBER 27.			
78.5	64.0	64.0	64.0	14.5	44.0
79.0	65.0	64.0	64.5	14.5	
79.5	65.0	64.5	64.7	14.7	44.55
79.5	63.0	65.0	64.0	15.5	
79.5	64.0	65.0	64.5	15.0	45.51
79.0	64.5	65.0	64.7	14.2	
79.0	64.5	65.5	65.0	14.0	46.48
79.0	64.5	65.5	65.0	14.0	
79.0	65.0	65.5	65.2	13.8	47.46
79.1	64.4	64.9	64.65	14.45	45.16

by Casella. Let us first consider the tabulated observations of September 2, recorded at equal intervals of three minutes. The indication of the two thermometers immersed in the fluid contained in the annular space first claims our attention, since the temperature of this fluid is the principal element in Père Secchi's original computations of solar temperature. It will be seen, on referring to the second and third columns of the table, that, while the upper thermometer indicates a mean temperature of 86°.9, the lower one shows only 79°.5, difference = 7°.4. This great discrepancy of temperature at different points of the upper portions of the annular space at which, owing to the inclined position of the concentric tubes, something like uniformity ought to exist, suggests a still greater discrepancy of temperature at the under side towards the lower termination of the tubes. In addition, therefore, to the observed irregularity of temperature at the upper part, shown by the table, no indication whatever is furnished of the temperature of the fluid in the annular space below the central tube, nor towards the termination at either side. Obviously, then, no accurate computation can be made of the degree of refrigeration to which the central thermometer is exposed by the radiation from the cold blackened surface of the internal tube, every part of which, as we have seen, possesses a different temperature compared with the rest, consequently transmitting radiant energy of different intensity. It will be found practically impossible, therefore, to determine the true differential temperature of the contents of the bulb exposed to the sun's rays and the fluid contained in the annular space. Hence, the differential temperature entered in the table, the result of comparing the indications of the thermometers, is manifestly incorrect. It will be found, also, by reference to Table A, that, while the mean temperature imparted to the central thermometer by the sun's rays is 93°.1, the mean temperature of the fluid in the annular space is 83°.3. Consequently, the intensity of solar radiation established by the instrument is only $93°.1 - 83°.3 = 9°.80$ F. Now, the sun during the recorded experiment of September 2 was exceptionally clear, the mean indication of the actinometer while the experiment lasted being 60°.05, thus showing that the energy developed was only $\frac{9.80}{60.05} = 0.16$ of the true radiant intensity. The mean zenith distance, it may be mentioned, was only 33 deg. 24 min. during the experiment. Agreeably to the table of temperatures (see Chap. III.), the maximum solar intensity for the stated zenith distance is 63°.35; thus we find that the sun, as stated, was exceptionally clear while the trial took place, which resulted in developing the trifling intensity of 9°.80 F. The result of the experiments conducted September 6, recorded in Table B, it will be seen, was nearly the same as that just referred to, the mean temperature indicated by the thermometer exposed to the sun being 98°.2, while the mean of the two thermometers immersed in the fluid was 87°.7; hence the differential temperature $98°.2 - 87°.7 = 10°.45$. The mean temperature of solar radiation during the experiment, ascertained by the actinometer, was 59°.75, the zenith distance being 35 deg. 33 min. Consequently, the intensity indicated September 6 was only $\frac{10.45}{59.75} = 0.17$ of the true energy of the sun's radiant heat, against 0.16 during the previous experiment. It will be observed that the fluctuation of the differential temperature was much greater September 2 than during the succeeding experiment, owing, no doubt, to the influence of currents of air produced by a strong breeze on the first occasion, the revolving observatory being partially open on the side presented to the sun during observations.

With reference to the small differential temperature indicated by the Secchi instrument manufactured by Casella, it may be urged that it is not intended to show the true intensity of solar radiation on the earth's surface, but simply a means of determining solar temperature. Granted that such is the object, yet the extreme irregularity of the temperature of the fluid within the annular space shows that the instrument is unreliable—a fact established beyond contradiction by an experiment instituted September 27, on which occasion water of a uniform temperature was circulated through the annular space. This was effected by gradually charging the intervening space from the top, and carrying off the waste at the bottom, holes having been drilled in the external casing for that purpose. The result of this conclusive experiment is recorded at the foot of Table B. It will be found, on reference to the figures, that the mean difference of the two thermometers immersed in the fluid was only 64°.9 −

64°.4 = 0.5°, while the mean differential temperature was augmented to 79°.1 − 64°.65 = 14°.45, against 9°.80 on the 2nd of September, although the zenith distance was greater, and the solar intensity less; circumstances which ought to have *diminished* the indicated intensity. It is needless to enter into any further discussion of the demerits of the instrument represented in Fig. 2. We may now return to the consideration of the device delineated in Fig. 1, copied from "Le Soleil." It will be seen that the material difference of construction is that of applying only one thermometer for ascertaining the temperature of the fluid in the annular space. Possibly this single thermometer may indicate approximately the mean temperature of the upper and lower portions of the fluid above the central tube; but it furnishes no indication of the temperature below, nor at either extremity of the annular space. The inadequacy of the means adopted for ascertaining the temperature of the internal surface which radiates towards the bulb of the central thermometer having thus been pointed out, it will be well to consider whether the expedient of passing a stream of water of nearly uniform temperature through the annular space will insure trustworthy indication. In order to determine this question, I have constructed two instruments, in strict accordance with the delineation in Fig. 1, excepting that in one of these the concentric cylinders are considerably enlarged, the annular space, however, remaining unchanged. Experiments with the two instruments prove that the enlargement does not materially influence the indications, provided water of a uniform temperature be circulated through the annular space. But these experiments have demonstrated that the *size* of the bulb of the thermometer exposed to the sun cannot be changed without influencing the differential temperature most materially. This will be seen by reference to Table C, which records the result of experiments

TABLE C, SHOWING THE RESULT OF EMPLOYING DIFFERENT THERMOMETERS, THE BULBS OF WHICH ARE OF UNEQUAL DIAMETER.

Diameter of Bulb, 0.30 *Inch.*							
1¼-inch tube.			Zenith distance.	3-inch tube.			Zenith distance.
Sun.	Fluid.	Diff.		Sun.	Fluid.	Diff.	
° Fah.	*° Fah.*	*° Fah.*	*Deg.*	*° Fah.*	*° Fah.*	*° Fah.*	*Deg.*
74.0	60.0	14.0	50.32	77.5	62.1	15.4	49.54
74.5	60.3	14.2	50.24	78.5	62.3	16.2	50.30
75.0	60.7	14.3	50.16	79.0	62.5	16.5	50.12
75.5	61.0	14.4	50.08	79.0	63.0	16.0	50.21
76.0	61.0	15.0	50.01	79.0	63.0	16.0	50.30
75.0	60.6	14.4	50.16	78.6	62.6	16.0	50.12
Diameter of Bulb, 0.58 *Inch.*							
83.6	62.6	21.0	49.54	79.2	60.1	19.1	50.32
85.5	63.0	22.5	50.30	81.0	60.3	20.7	50.24
86.4	63.4	23.0	50.12	82.5	60.7	21.8	50.16
86.7	63.5	23.2	50.21	82.7	60.7	22.0	50.08
87.7	63.7	23.0	50.30	83.0	61.0	22.0	50.01
85.9	63.2	22.5	50.12	81.7	60.6	21.1	50.16

with different thermometers, and tubes of different diameters, conducted October 17. As on previous occasions, the instruments, in order to insure accurate position, were attached to the declination table arranged within the revolving observatory. The bulbs of the thermometers employed were very nearly spherical, their diameters being respectively 0.30 and 0.58 inch. The upper division of Table C, which records the experiment with the *small* bulb exposed to the sun, establishes, it will be seen, a differential temperature of 14°.4 for the instrument having the 1¼-in. central tube, and 16° for the one having the 3-in. central tube. Referring to the lower division of the same table, it will be seen that, when the thermometer with the *large* bulb is exposed to the sun, the differential temperature reaches 22°.5 in the instrument containing the 1¼-in central tube, and 21°.1 in the one having the 3-in. tube. We thus find that, by doubling the diameter of the bulb of the thermometer exposed to the sun, all other things remaining unchanged, an augmentation of the differential temperature amounting to nearly one-third takes place. This fact proves the existence of inherent defects fatal to the device delineated in Fig. 1, rendering the same wholly unreliable.

Agreeably to the doctrine of exchanges, the diameter of the bulb is an element of no moment, since the internal radiation towards the same—*provided its temperature be uniform*—depends solely on the temperature and angular distances of the radiating points of the enclosure. Infallibility of the thermoheliometer has evidently been taken for granted on the strength of the soundness of this doctrine, as we find no allusion to the size of the bulb in M. Soret's account of his observations of solar intensity on Mont Blanc; nor does Mr. Waterston, who employed a similar instrument during his observations in India, advert to the dimensions of the bulb of the thermometer exposed to the sun. These physicists apparently overlook the fact that, while the entire convex area of the bulb is exposed to what may be considered the cold radiation from the enclosure, only one-half receives radiant heat from the sun. This circumstance would be unimportant if the heat thus received were instantly transmitted to every part; but the bulb and its contents are slow conductors, while the conducting power diminishes nearly in the inverse ratio of the square of the depth. Consequently, by increasing the diameter, the parts of the bulb opposite to the sun will receive considerably less heat relatively in a given time than if the diameter be diminished.

CHAPTER XVI.

BAROMETRIC ACTINOMETER.

The bulb of the thermometer is charged with air; the intensity of the radiant heat determined by the pressure in the bulb; the height of the mercurial column indicates the pressure; a fixed graduated arc and movable index show the sun's zenith distance; the graduation of the scale of temperature effected without exposing the bulb to heat or cold; the sun's zenith distance and the intensity of the radiant heat observed simultaneously; the bulb, being placed within a vacuum, is not exposed to the disturbing influence of atmospheric currents; the vessel surrounding the bulb maintained at a constant temperature; the atmospheric temperature does not affect the indication of radiant intensity; the quantity of matter contained in the bulb is exceedingly small compared with the convex area exposed to the solar rays; suitable mechanism, operated by two small hand-wheels, enables the observer to follow the diurnal motion and sun's declination; the instrument is portable.

An accurate determination of the intensity of solar heat calls for a thermometer capable of indicating the temperature produced by radiation after a very brief exposure to the radiant heat. It has been pointed out in previous chapters that the sluggish action of an ordinary thermometer renders it wholly unfit to measure the temperature produced by solar radiation at any given zenith distance, since the diurnal motion is so rapid that before an equilibrium can be established between the heat received by the bulb and the heat radiated by the same, the zenith distance is materially changed. Consequently, the temperatures indicated by common thermometers before noon are too low, while in the afternoon the indication is too high, for the zenith distance at any given instant of time. In order to ascertain to what extent the ordinary thermometer is defective as a means of measuring the sun's radiant heat, consequent on the slow expansion of the contents of the bulb, I have conducted a series of experiments which show that a thermometer surrounded by a vessel kept at a constant temperature and exposed to the radiation of a steady gas-flame, requires from 20 to 25 minutes before the mercurial column becomes stationary. Consequently, the rapid change of the sun's zenith distance, especially early in the morning and late in the afternoon, presents a difficulty which renders ordinary thermometers useless for measuring the intensity of solar heat at given zenith distances. But a far greater defect inseparable from the ordinary form of thermometer remains to be noticed, namely: the section of the pencil of rays which imparts the radiant heat is less than the convex area of the bulb exposed to the sun. This circumstance presents a serious difficulty, calling for delicate counteracting expedients (see Chap. III.), since although that half of the bulb which is turned away from the sun may be protected by a non-conducting substance, the other half on which the sun acts exposes a radiating surface twice as great as the sectional area of the acting pencil of rays, because the convex area of the bulb is four times greater than the area of its greatest section. It should be observed, however, that by employing a long bulb of cylindrical form, the inherent defect of the common thermometer thus pointed out may be mitigated in the ratio of about 4 to 3, since the plane which passes through the axis of a cylinder bears a greater proportion to its convex area than the area of the great circle of a sphere to its convex area. Some scientists contend that, agreeably to the law of exchanges, no actual loss of heat is sustained by the excess of radiating surface of the bulb over the sectional area of the pencil of rays which imparts the radiant heat. A moment's consideration will dispose of this unsound doctrine. Admitting that by means of non-conducting substances the half of the bulb opposite to the sun may be effectually protected against loss of heat by radiation, the other half which is turned towards the luminary will constitute a refrigerator as well as a heater. Now, the efficiency of refrigerators and heaters is as their areas, all other things being alike; hence a spherical bulb of 0.8 in. diameter (the convex area of which is 2 square inches) presents a radiating surface exactly 1 square inch towards the sun, while the section of the pencil of solar rays which the bulb intercepts contains only 0.5 square inch. The rays being thus distributed over an area twice as great as their section, the mean intensity of the radiant heat imparted to the bulb will be diminished one-half. But, while the hemispherical surface of the bulb turned towards the sun is thus rendered inefficient by the dispersion of the rays, its efficiency as a *refrigerator*, remaining unimpaired, carries off the heat with full energy towards the surrounding cold medium. As our demonstration relates only to the defect consequent on the sectional area of the pencil of rays being less than the area which receives the solar heat, I have not noticed the serious loss caused by cold currents of air circulating round the exposed half of the bulb. The self-evident character of the foregoing explanation renders theoretical deductions, from the law of exchanges, unnecessary to establish the fact that ordinary thermometers cannot furnish correct indications of the temperature produced by solar radiation.

Before entering on a detailed description of the instrument illustrated on Plate 27, it will be instructive to consider what proportion of the indicated temperature results from *unaided solar heat* when a substance surrounded by the atmosphere is exposed to the sun's rays; and whether the observed increment of temperature above that of the surrounding air occupies a fixed position on the thermometric scale, or whether it rises and falls with the increase and diminution of the atmospheric temperature. Suppose that we place a circular disc, composed of some black non-conducting substance, at the bottom of a very deep cylindrical vessel, kept at a uniform temperature, whose axis points towards the sun, and which is provided with an opening opposite the disc—the diameter of the disc and opening being alike. Suppose also that, by some adequate device, a perfect vacuum is kept up in the said vessel, and that the axis of the black circular disc is directed towards the solar centre. I maintain that the temperature acquired by the surface of the supposed disc—less the temperature of the surrounding vessel—furnishes an accurate indication of the real intensity of the sun's radiant heat. It will be perceived, on due reflection, that the differential temperature thus ascertained, which furnishes a true measure of the radiant intensity of solar heat, cannot occupy a fixed position on the thermometric scale. It rises and falls by increase and diminution of the temperature of the supposed surrounding vessel. The investigations and observations referred to in Chap. III., conducted during a series of years, it should be borne in mind, have established the fact that during the summer solstice the differential temperature produced by solar radiation, indicated by my actinometer, is fully 66° F. in the latitude of New York, when the sky is perfectly clear and the zenith distance 18 degrees. The question will be asked: Is there any limit to the rise and fall of the thermometric interval of 66°, consequent on changes of the temperature of the surrounding medium? As the leading points connected with this question have been fully discussed in Chap. IX., I will merely observe that the result of numerous observations, and the trial of various expedients resorted to in order to determine the limit, show that the movement is not limited. The extent of the fall, as far as ascertained, is so considerable that we must infer that, but for the intervention of our atmosphere and the accumulation of heat resulting from that intervention, the sun's unaided radiant heat would not be sufficient to prevent the surface of the earth from falling several hundred degrees below the freezing point of water. No reliable experiments have yet been instituted to ascertain the extent of the upward movement of the thermometric interval under discussion, when the solar rays are admitted into an incandescent enclosure.

The following general description will enable the reader to form a correct idea of the nature of the barometric actinometer. The leading feature of the instrument is that of employing a bulb (see Plate 27, Fig. 1) composed of very thin, hard plate-metal, charged with dry atmospheric air, in place of a bulb containing some liquid substance. The lower part of this air-bulb is hemispherical, while the upper part, exposed to the sun, consists of a circular plate with a slight upward curvature, the extreme diameter being 2.75 inches. The hemispherical part of the bulb is plated with nickel on both sides, highly polished and thoroughly protected by a non-conducting external covering, while the top plate, exposed to the radiant heat, is coated with lampblack on the outside, the inside presenting a rough surface. It will be evident from this description that the form of the bulb of the barometric actinometer fulfils the condition inseparable from devices intended to furnish accurate indication of the intensity of solar radiation—namely, that the area of the face which receives the radiant heat should not exceed the area of the section of the pencil of rays admitted to the instrument. The air-bulb, as already stated, is placed near the bottom of an exhausted cylindrical vessel, 8 inches long, 3 inches diameter, surrounded by a double casing through which water, kept at a constant temperature, is circulated. An ordinary force-pump is employed for this purpose, receiving its supply from a small portable cistern; the water thus circulated through the double casing being returned to the cistern by the action of the pump. The upper end of the cylindrical vessel is closed by a plate of glass 0.12 inch thick, forming an air-tight joint. The aperture in the ring which secures the glass to the cylinder is 2.75 ins. in diameter, corresponding exactly with that of the bulb. The exhausted vessel is held in position by a transverse axle secured to its bottom (see Fig. 2), turning in appropriate bearings supported by columns resting on the circular bed-plate of the instrument. The transverse axle mentioned is provided with a central perforation which, by means of minute passages, communicates with the interior of the bulb, communicating also with a close mercurial cistern *f* formed at the lower end of the barometric tube, as represented in the illustration. The height of the column in this barometric tube, it is scarcely necessary to observe, furnishes an exact index of the expansive force of the air within the bulb, and hence the intensity of the radiant heat to which it is subjected. It is important to observe, regarding the graduation of the scale of temperature, that the height of the mercurial column alone will not determine the length of the degrees. Certain obvious corrections must be made, especially on account of the loss of energy of the sun's radiant heat in passing through the crystal which covers the exhausted tube. This loss may be readily ascertained by employing an apparatus by means of which the absorptive property of the crystal is tested before the scale of temperature is graduated. Referring to the mechanism represented in the illustration, it will be seen that the inclination of the exhausted cylinder is regulated by a tangential screw *a*, while the adjustment called for by the earth's diurnal motion is effected by a small pinion *b* actuating the cogged base-plate which supports the instrument. The mechanism thus described, together with a perforated sight *c* and an index-plate *d*, enables the operator to direct the tube accurately towards the sun. The centre line of the index *g* attached to the upper end of the exhausted chamber shows the zenith distance on the graduated quadrant at all times by mere inspection. It should be mentioned that, when the barometric actinometer is arranged within a revolving observatory provided with a declination table, the mechanism just described for obtaining a parallactic movement is wholly dispensed with. Meteorologists will do well to adopt such an instrument in all important observations, since its simultaneous indication of solar intensity and zenith distance enables them to determine the relative amount of vapor present in the atmosphere with a degree of precision probably unattainable by any other means. The sensitive nature of the instrument will be readily comprehended if we consider that while the surface of the bulb, 2.75 ins. diameter, amounts to 5.93 square ins. (the section of the pencil of rays which imparts the radiant heat contains also 5.93 superficial inches), the quantity of matter to be heated is only a small fraction of that contained in an ordinary thermometer whose bulb is only 0.6 in. diameter. Besides, the latter bulb receives heat from a pencil of rays of only 0.28 square in. section. Apart from this important difference in favor of the barometric actinometer, the radiating surface of *spherical* bulbs exposed to solar radiation, as already stated, is twice as great as the section of the pencil of rays which imparts heat to the same.

CHAPTER XVII.

CONDUCTIVITY OF MERCURY.

It was shown in Chapter XV. that the radiant intensity of the sun cannot be accurately ascertained by the thermo-heliometer employed by Père Secchi, owing, among other causes, to the imperfect conductivity of the mercury in the bulb exposed to the sun. Meteorologists are not generally aware of the fact that the conducting power of mercury is so imperfect as to affect materially the correctness of the indication of mercurial thermometers, Deschanel being quoted in support of the opinion that mercury is a very good conductor. Prof. Everett, in a recent translation of the works of the author mentioned, assumes that the conductivity of quicksilver in the bulb of a thermometer is the same as a vessel "with thin metallic sides containing water which is stirred" (see Prof. Everett's translation of "Deschanel's Natural Philosophy," Part II., pp. 245–387). The subject is so intimately connected with the determination of solar temperature and solar energy that it has become necessary to settle the question by some reliable, practical test. I have accordingly constructed the apparatus illustrated on Plate 28, by means of which the relative conducting power of a column of copper and one of mercury has been ascertained with critical nicety. Before entering on a description, it will be instructive to point out that the heat communicated to the bulb of a thermometer by solar radiation is transmitted to its contents chiefly by convection; hence that the altitude of the sun during the observation influences the accuracy of the indication. This will be readily comprehended. Fig. 2 represents the bulb of a thermometer exposed to the rays when the sun's zenith distance is 65 deg.; Fig. 3 representing the bulb when the zenith distance is 18 deg. 23 min., the latter being the minimum at the observatory of the Roman College, where the thermoheliometer described in Chapter XV. has been long employed for the purpose of ascertaining

FIG. 3

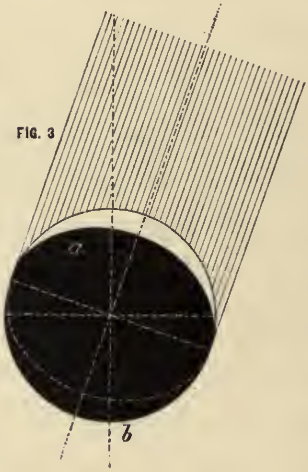
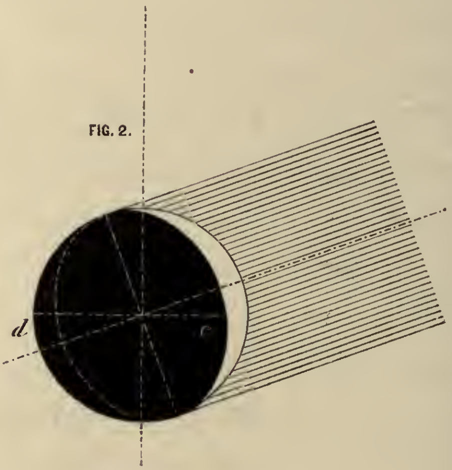


FIG. 2.



the intensity of solar radiation. Referring to Fig. 2, it will be seen that the blank crescent *c*, whose varying thickness indicates very nearly the relative amount of heat imparted at each point of the spherical surface presented towards the sun, occupies an almost vertical position. The mercury contained within the space indicated by the said crescent, having its specific gravity reduced by the heat transmitted by the solar rays, will ascend; while the mercury on the opposite side, which retains its specific gravity, will descend; thus a circulation will be established by means of which the heat received from the sun will be gradually communicated to the entire mass of mercury in the bulb. But when the latter is exposed to the sun's rays under a zenith distance of about 18 deg., as shown in Fig. 3, the heated mass of mercury contained within the crescent *a* has so slight an inclination that scarcely any circulation takes place. Consequently, if it can be shown practically that mercury is incapable of transmitting heat from particle to particle with sufficient velocity, it will be evident that thermometers and thermoheliometers with spherical bulbs are worthless as means of measuring maximum intensity of solar radiation. It will be perceived that if the bulb in Fig. 3 be surrounded by an enclosure, as in the thermoheliometer, the mercury contained within the space indicated by the crescent *b* will radiate far less heat towards such enclosure than the mercury within the opposite heated crescent *a*. It will also be perceived that, by increasing the size of the bulb, the transmission of heat from *a* to *b* will be retarded unless the conductivity of mercury be perfect. Hence the *size* of the bulb is an element affecting the accuracy of the indication—a circumstance fatal to the employment of a spherical bulb in the thermoheliometer.

The nature of the illustrated apparatus constructed for the determination of the conductivity of mercury will be readily understood by the following description: Fig. 1, Plate 28, represents a longitudinal section through the vertical plane. *a* is a boiler, with a flat bottom and semicircular ends, supported on two columns *f* and *g*, resting on the bottom of the cisterns *c* and *d*. The column *f* is composed of wrought copper plated with silver, highly polished. The column *g* consists of a cylindrical vessel of glass open at the top, filled with mercury, and surrounded with a socket *h*, composed of polished silver. The cisterns *c* and *d*, supported on non-conducting substances, are plated with polished silver, and provided with funnel-shaped openings at the top, through which thermometers are inserted. These cisterns, as well as the columns *f* and *g*, are surrounded with non-conducting coverings *p*, *p* and *o*, *o*. A lamp *b* is applied between the cisterns for heating the water in the boiler. It is scarcely necessary to observe that the polished silver plating of the copper column, and the polished silver socket round the mercurial column, are intended to prevent loss of heat by radiation, while the coverings before mentioned are intended to prevent loss of heat by convection attending atmospheric currents. The inside diameter of the cylindrical vessel *g*, it should be noticed, is 0.5 in., corresponding exactly with the diameter of the copper column *f*, the top of which is on a level with that of the mercurial column. The lines *k l* and *m n* are in the same horizontal plane, their distance below the upper ends of the columns *f* and *g* being precisely 2 inches.

The object of the apparatus being that of comparing the conductivity of mercury to that of some other metal, *copper* has been selected, as its conducting property is better known than that of any other. The leading feature of the arrangement will be comprehended by a mere glance at the illustration. An equal amount of heat being applied to the top of each column, it is intended to show by the elevation of the temperature of the water in the cisterns *c* and *d* what relation exists between the conductivity of mercury and copper. Regarding the application of the heat, it will be evident that an equal amount must infallibly be imparted to each column if the lamp be sufficiently powerful to keep the water in a state of continuous ebullition. Obviously the heat from the lamp, if urged, will cause a rapid upward motion of the water in the middle of the boiler, and a correspondingly rapid descending current at each end. Accordingly, lateral currents, varying in velocity with the strength of the flame, applied under the boiler, will flow inwards over the upper ends of the columns *f* and *g*.

Several experiments have been made under different barometric pressure and different atmospheric temperature, yet the results as regards the comparative conductivity of mercury and copper have proved to be very nearly alike in all. The accompanying tables record the result of the last trial,

TABLE I.—COPPER COLUMN.

Time.	Temperature of water in cistern.	Increment of temperature in cistern.	Energy transmitted past *k l*.	Differential temperature between boiler and cistern.	Energy transmitted past *k l* per half minute.	Energy transmitted per sq. ft. per half minute.
Min.	*° Fah.*	*° Fah.*	*Therm. units.*	*° Fah.*	*Therm. units.*	*Therm. units.*
	73.50	...	...	138.50	...	...
0.5	75.15	1.65	0.143	136.85	0.143	104.873
1.0	77.25	3.75	0.326	134.75	0.183	134.208
1.5	80.14	6.64	0.577	131.80	0.251	184.078
2.0	83.84	10.34	0.898	128.10	0.321	235.415
2.5	88.14	14.64	1.272	123.80	0.374	274.284
3.0	92.81	19.31	1.678	119.00	0.406	297.752
3.5	97.67	24.17	2.100	114.25	0.422	309.486
4.0	102.56	29.06	2.525	109.44	0.425	311.686

TABLE II.—MERCURIAL COLUMN.

Time.	Temperature of water in cistern.	Increment of temperature in cistern.	Energy transmitted past *m n*.	Differential temperature between boiler and cistern.	Energy transmitted past *m n* per half minute.	Energy transmitted per sq. ft. per half minute.
Min.	*° Fah.*	*° Fah.*	*Therm. units.*	*° Fah.*	*Therm. units.*	*Therm. units.*
	73.50	...	...	138.50	...	...
0.5	73.52	0.02	0.002	138.48	0.002	1.466
1.0	73.56	0.06	0.005	138.44	0.003	2.200
1.5	73.64	0.14	0.012	138.36	0.007	5.133
2.0	73.75	0.25	0.022	138.25	0.010	7.334
2.5	73.90	0.40	0.035	138.10	0.013	9.534
3.0	74.08	0.58	0.051	137.92	0.016	11.734
3.5	74.28	0.78	0.068	137.72	0.017	12.467
4.0	74.50	1.00	0.087	137.50	0.019	13.934

conducted as carefully as practicable. The headings of the several columns explain so clearly the object of the tables that it will only be necessary to state that the energy inserted in the fourth column is the energy developed from the beginning of the experiment

Referring to Table I., it will be seen that at the termination of 4 minutes from the commencement of the experiment, the temperature of the water in the cistern *c* had increased 29°.06, the differential temperature being then 212° – 102°.56 = 109°.44 F. During the same period an amount of dynamic energy represented by 2.525 thermal units had been transmitted past the line *k l*, communicated to (1) the water in the cistern; (2) the part of the copper column immersed; (3) the metal composing the cistern; (4) the immersed part of the thermometer. But, while the entire energy transmitted past the line *k l* during the 4 minutes thus amounted to 2.525 units, the rate of transmission was actually 0.850 unit per minute at the termination of the fourth minute. This apparent discrepancy was caused by the heat absorbed by that part of the column which extends above the line *k l*, the temperature at the commencement of the experiment being the same as that of the surrounding air, 73°.50. Referring to Table II., it will be seen that the energy transmitted through the mercurial column past the line *m n*, during 4 minutes, was only 0.087 unit against 2.525 units for the copper column, although the differential temperature of the water in the cistern *d* was 137°.50 – 109°.44 = 28°.06 higher than in the cistern *c*. Accordingly, the conductivity of the copper composing the column *f* has proved to be $\frac{2.526}{0.087}$ = 29.06 times greater than the conductivity of the mercury of the column *g*, notwithstanding the higher differential temperature to which the latter was exposed. It will be observed that the glass, 0.02 in. thick, composing the cylindrical vessel which contains the mercury, will conduct some heat downward, tending to increase the temperature in the cistern *d*. This tendency, however, will be balanced by the loss of heat occasioned by the radiation of the glass cylinder, since the application of the polished silver socket and the non-conducting covering cannot wholly prevent the refrigerating action of the surrounding air. It is important to observe, regarding the loss of heat from the latter cause, that the cisterns, previous to trial, are charged with water of the same temperature as the atmosphere. Now, considering that the increment of temperature in the cistern *d* does not average more than 0°.40 above that of the atmosphere during the trial, it will be evident that the amount of error caused by radiation will be quite inappreciable. We are therefore warranted in concluding that the conductivity of mercury, determined by the increment of temperature in cistern *d*, and by the dynamic energy transmitted past the line *m n*, cannot be far from correct. It will be asked why columns of such small diameter have been employed. The principal object has been that of presenting a sectional area in the mercurial column *g* corresponding as nearly as possible to the size of the bulb of an ordinary thermometer. The investigation, then, has conclusively established the fact that mercury transmits heat from particle to particle too slowly to effect a sufficiently rapid indication of mercurial thermometers provided with *spherical* bulbs; and that, when the heat is applied from above, the indication of such thermometers is wholly unreliable.

A subject of great interest presents itself in connection with the rate of transmission of energy exhibited in the sixth column of Table I. It will be seen that, although the copper column f is only 0.5 in. in diameter = 0.19635 sq. in. section, the rate of transmission at the termination of the fourth minute is 0.850 unit per minute. Reducing this amount to the usual standard of one square foot, it will be found that the energy developed is $\frac{144}{0.19635} \times 0.850 = 623$ thermal units per minute for a sectional area of one square foot. It will be observed that this extraordinary amount of energy (theoretically capable of exerting $\frac{623}{42.7} = 14.5$ horse-power) is called forth by the moderate differential temperature of $212° - 102°.56 = 109°.44$ F. Now, let us compare the stated energy of 623 thermal units per minute to that produced by the radiation of a metallic surface coated with lamp-black, and maintained at a temperature of 212° within an enclosure of 102°. Actual trial shows that, under these conditions, the radiant energy emanating from the face of a plate composed of copper, containing 144 sq. ins., scarcely reaches 6 thermal units per minute. Our experiment has therefore incidentally established the fact that, under the stated conditions, a plate of wrought copper 2 ins. in thickness is capable of transmitting by *conduction* from one side to the other, in a given time, an amount of mechanical energy more than one hundred times greater than the mechanical energy transmitted by the *radiation* of the same plate during an equal interval of time.

CHAPTER XVIII.

INCANDESCENT CONCAVE SPHERICAL RADIATOR.

The illustration on Plate 29 represents an apparatus constructed for the purpose of proving the correctness of the indications furnished by the solar pyrometer described in Chapter X. Fig. 1 is a side elevation and Fig. 2 an end view of the apparatus. Objections have been raised against the solar pyrometer on account of the low temperature employed. It is contended that, unless the radiator is raised to the temperature of incandescence, emitting luminous rays, the radiant heat transmitted to the focus will not furnish an indication capable of determining the temperature of distant incandescent bodies. The reader is aware that the idea of ascertaining the temperature of the sun by the indications of a surface coated with lamp-black, maintained at only boiling heat, has been deemed absurd by certain physicists. Secchi, in a letter to *Nature*, says: "Very few indeed will allow that which Mr. Ericsson takes for granted, that the radiating power of the solar materials may be compared to that of pure lamp-black, as he assumes." Numerous experiments, however, show that, relatively, there is no appreciable difference between the energy of the dark heat-rays emanating from a metallic radiator of low temperature, presenting a thoroughly disintegrated or a blackened surface, and the energy of heat-rays accompanied by a light emanating from an incandescent metallic radiator. The temperature transmitted by the radiant heat to the focus is, in each case, directly proportional to the temperature of the radiant surface. An air thermometer placed in the focus of a concave spherical radiator composed of ice, and surrounded with very cold substances, say 100° below zero, will furnish an indication by which the temperature of distant incandescent bodies may be ascertained with as much certainty as by employing a radiator heated to such a degree as to emit luminous rays. It scarcely needs explanation that my reason for constructing the solar pyrometer with a radiator kept at the low temperature of boiling water is that of admitting of operating within a vacuum, besides rendering it possible to measure the temperatures with positive exactness. No doubt the instrument could be so arranged that the metallic radiator might be maintained at a temperature considerably above that of incandescence (Sir Humphry Davy, it will be remembered, fixed the temperature of incandescence at 812°); but we lack accurate means of measuring the intensity when metals are brought to white heat or bright orange. Nor would anything be gained by resorting to a mode of construction involving both complication and uncertainty, since dark heat-rays, with reference to temperature, in no manner differ from heat-rays accompanied by light. As already stated, no irregularity has been observed by me in the fall of the temperature of an incandescent radiator, and that of the focal thermometer exposed to the radiant heat, while the color gradually changes from bright orange to black. On the contrary, the temperatures of the radiator, and the recipient of the radiant heat, continue to bear the same relation to each other during both cooling and heating. The times, compared with the increment or diminution of intensity, differ a little; but, as stated, the proportion between the temperature of the radiant surface and that transmitted to the focus continues as nearly uniform as practical test can show.

The radiator of the instrument represented by our illustration on Pl. 29 consists of a solid cylindrical block *b*, composed of cast iron, 10 ins. diameter, 6 ins. long, placed horizontally on a pedestal, the front end forming a spherical concavity *a b c* of 18 ins. radius, precisely like the radiator of the solar pyrometer described in Chap. X. The under side of the cylindrical block is provided with a square projection corresponding with two guide pieces on the top of the pedestal shown on Fig. 2, intended to facilitate the operation of placing the block rapidly in a proper position after having been heated in an air-furnace. A focal thermometer *d*, similar to the one employed in the solar pyrometer, is secured to a bent arm attached to the front side of the pedestal; the distance *b d* between the centre of the bulb and the face *a b c* of the concave spherical radiator being also precisely as in the solar pyrometer.

The accompanying table exhibits the result of a trial of the apparatus, conducted at a mechanical establishment in New York possessing air-furnaces well adapted for the investigation:

Appearance of radiator.	Temperature of radiator.		Atmospheric temperature.	Temperature of focal thermometer.	
	Actual.	Differential.		Actual.	Differential.
	° *Fah.*	° *Fah.*	° *Fah.*	° *Fah.*	° *Fah.*
Light orange....	2190	2149.3	40.7	178	137.3
Deep orange.....	2010	1969.3	40.7	173	132.3
Br't cherry red..	1830	1789.3	40.7	166	125.3
Full cherry red.	1650	1609.5	40.5	156	115.5
Dull cherry red.	1470	1429.8	40.2	144	103.8
Dull red heat....	1290	1249.0	41.0	130	89.0
Mean..........	1740	1699.37	40.63	157.83	117.2

The following brief account of the manner of conducting the trial will show the simple nature of the investigation. The solid radiator, before being placed on the pedestal, was heated in the air-furnace to very nearly white heat, and then, by means of tongs, quickly removed from the furnace and placed in the position shown by the illustration. The focal thermometer was then closely observed, its indication being recorded when the radiator had cooled so as to present a color of light orange. The indications during the succeeding stages of brightness and color of the incandescent radiator were in like manner recorded. The temperature of the surrounding air was observed simultaneously with that of the focal thermometer. The time which elapsed between the first and last observation entered in the table was 29 minutes. It will be seen that the temperature transmitted by the radiator to the focal thermometer was recorded at six different stages of incandescence, the color presented by the radiant surface determining the time for observation. The *mean* temperature of the radiator during the experiment was 1,740° F. Deducting the mean atmospheric temperature, 40°.63 F., the actual mean differential temperature of the radiant surface, the luminous heat rays of which acted on the focal thermometer, was 1,699°.37. The mean temperature transmitted to the focal thermometer exposed to the radiant heat being 157°.83, while the atmospheric temperature, as already stated, was 40°.63, we find that a temperature of 117°.2 was imparted to the focal thermometer by a radiant intensity of 1,699°.37. It will be recollected that in the solar pyrometer a differential radiant intensity of 163°.9 transmitted a temperature of 12°.2 to the focal thermometer; hence $\frac{12°.2}{163.9} = 0.074$ of the temperature of the radiator was transmitted to its focus, against $\frac{117.2}{1699.37} = 0.069$ in the apparatus under consideration. Consequently, 0.074 — 0.069 = 0.005 less heat, relatively, is transmitted by the *incandescent* radiator than by the comparatively cool radiator of the solar pyrometer. As this small discrepancy can readily be accounted for, the result of the instituted test fully establishes the truth of the doctrine which forms the basis of the solar pyrometer—namely, that the calorific energy of both dark and luminous heat rays is directly proportional to the temperature of the radiant surface. The cause of the discrepancy adverted to will be readily comprehended by the following explanation relating to the solar pyrometer. The heat imparted by the radiant to the recipient surface is transmitted through ether alone; therefore neither the radiator nor the bulb of the focal thermometer are subjected to any loss by convection; while the incandescent concave radiator, as well as its focal thermometer, are exposed to the refrigerating influence of the atmospheric air. Obviously the heated bulb of the thermometer will cause an upward current of air, which, acting on its face, reduces its temperature and indication, while the intense heat of the radiator tends to augment the said current. Again, the rapid succession of cold particles passing over the intensely heated surface of the radiator will inevitably diminish the energy of the radiant heat, since the molecular motion within the heated mass cannot instantly restore the loss to which the molecules at the surface are continually being subjected by the cold current. The diminution of radiant energy from this cause, though not great, will be appreciable, and, added to the loss of heat, to which the bulb of the focal thermometer is subjected, satisfactorily accounts for the discrepancy adverted to; at the same time showing the necessity of carrying on investigations relating to radiant heat within a vacuum.

Let us now calculate the temperature of the sun agreeably to the indications furnished by the incandescent radiator of the illustrated apparatus, without reference to the indications of the instrument, the reliability of which we are discussing. But in place of basing our calculations on the angle subtended by the sun from the earth, and the angle subtended by the concave spherical radiator from its focus, let us determine the solar temperature on the basis of *areas* and *distances* alone. This method will be more satisfactory to practical men than the one which takes no direct cognizance of areas and distances. Assuming the sun's diameter to be 852,584 miles, the area of the great circle will be $15{,}912{,}929 \times 10^{12}$ sq. ft. The diameter of the spherical radiator being 10 ins. and the radius 18 ins., its face presents 80.06 sq. ins. = 0.556 sq. ft. Accordingly, the sun's area is $28{,}620{,}377 \times 10^{12}$ times greater than the area of the concave face of the radiator. The mean distance between the sun and the earth is 91,430,000 miles, or 482,750,400,000 ft.; the distance between the radiator and its focus is 1.5 ft. The radiant heat of the sun, therefore, acts through a distance 321,833,600,000 times greater than the radiant heat of the incandescent radiator. We have demonstrated in Chap. I. that the temperature transmitted to the foci of concave spherical radiators of equal area is inversely as the square of their radii; and we have shown that, owing to the great distance of the sun, every part of his face may, without material error in our computations, be considered as equidistant from the earth. Hence, if we square and invert the before-mentioned distances through which the radiant heat acts, we ascertain that for equal intensity and *equal area* the incandescent radiator will transmit $103{,}576{,}866 \times 10^{15}$ times higher temperature to its focus than that transmitted by the sun to the boundary of the earth's atmosphere. But the area of the sun, as we have stated, is $28{,}620{,}377 \times 10^{12}$ times greater than the area of the radiator; hence for *equal intensity* the radiant heat transmitted to the focus of the latter will be $\frac{103{,}576{,}866 \times 10^{15}}{28{,}620{,}377 \times 10^{12}} = 3{,}618.99$ times greater than that transmitted by the sun. It will be readily seen, on reflection, that unless the temperature of the sun is 3,618.99 times greater than that of the incandescent radiator, it cannot transmit to the atmospheric boundary the same temperature as that transmitted by the radiator to its focus, viz., 117°.2 F. The temperature produced by solar radiation when the earth is in aphelion is, however, only 84°.84 at the said boundary; hence the sun's temperature need be only $\frac{3{,}618.99 \times 84.84}{117.2} = 2{,}619.25$ times greater than that of the incandescent radiator (1,699°.37), in order to cause an elevation of 84°.84 on the Fahrenheit scale at the boundary of the earth's atmosphere. Multiplying 1,699°.37 by 2,619.25, we find that the indication of the incandescent concave spherical radiator of our illustrated device proves the sun's temperature to be 4,451,924° F. It will be seen, on referring to Chap. X., that the calculations based on the indications of the solar pyrometer prove the sun's temperature to be only 4,063,984°. The cause of this discrepancy of 0.087 has already been explained, viz., diminution of the radiant energy of the incandescent radiator, produced by currents of cold air sweeping over its face; together with the loss of heat to which the unprotected bulb of the focal thermometer is subjected by the refrigerating effect of the surrounding atmosphere. Making due allowances for these losses—inseparable from conducting the experiment in the presence of atmospheric influence—it will be found that the indications furnished by an incandescent concave spherical radiator assign very nearly the same temperature to the sun as the comparatively cold radiator of the solar pyrometer. The objection, then, urged against this instrument, that its temperature is not high enough, cannot be maintained in view of the fact which we have established, that the intensity deduced from its indication is not affected by employing an *incandescent* radiator in place of one raised to merely boiling heat.

CHAPTER XIX.

REFLECTIVE POWER OF SILVER AND OTHER METALS.

DESCHANEL informs us that the reflection of calorific rays has been satisfactorily determined by the investigations of Melloni, Laprovostaye, and Desains, and that these physicists have practically ascertained the reflective power of polished silver and other metals. He states, also, that Laprovostaye and Desains have shown that, "contrary to what was previously supposed, the reflecting power varies according to the source of heat." "Thus," he adds, "the reflecting power of polished silver, which is 0.97 for rays from a Locatelli lamp, is only 0.92 for solar rays." It follows from this announcement that while the loss of radiant energy is only 1.00 − 0.97 = 0.03 when the rays emanate from the lamp mentioned, it is 1.00 − 0.92 = 0.08 when the rays from the sun are reflected. Accordingly, the loss of energy attending reflection will be nearly three times greater for solar heat than for artificial heat. That such a difference does not exist is known to all persons conversant with reflectors. Besides, a moment's consideration of the properties of calorific rays suffices to show the untenable character of the proposition, compelling us to reject Laprovostaye's and Desains's investigation as unreliable, although generally accepted by physicists. Moreover, the table of reflective power of various metals presented by Deschanel as the result of the celebrated investigation furnishes additional evidence of its unreliable character. Let us select from Laprovostaye and Desains's tabular statement the relative reflecting capacity of silver and brass. The former is represented to be 0.97, while the latter is 0.93; consequently, the reflective powers of silver and brass are supposed to be in the ratio of 1.000 : 978, difference $= \frac{22}{1000}$. Manufacturers of reflectors practically acquainted with the subject are aware that silver possesses a far greater reflective power compared with brass than that indicated by the stated proportion.

The leading feature of my solar engine being that of developing mechanical power by concentrating the sun's radiant heat, the efficacy of various metals for this purpose engaged my attention during the early stages of my labors connected with utilizing solar energy for the production of motive power. Taking for granted the correctness of Laprovostaye's and Desains's statement of relative efficacy, I constructed reflectors composed solely of brass, in order to avoid the great cost of silver-plating. The difference of reflecting power agreeably to the researches referred to being $\frac{22}{1000}$

in favor of silver, I simply enlarged the reflectors in that proportion, expecting to produce the same result as with silver-plated metals presenting $\frac{22}{1000}$ less area. It proved, however, on the first trial, that the reflective capability of brass is far inferior, and that the required temperature could not be produced by brass reflectors; the machine, consequently, failing to operate as designed. A thorough investigation capable of determining the true reflective power of various metals, therefore, became necessary; but before commencing experiments, the method resorted to by Melloni, Laprovostaye, and Desains, referred to by Deschanel, was carefully examined. The said method is thus described in his "Elementary Treatise on Natural Philosophy": "The substance under investigation is placed upon a circular plate, which is graduated round the circumference. The thermo-electric pile is carried by a horizontal bar which turns about a pillar supporting the circular plate. This bar is so adjusted as to make the reflected rays impinge upon the pile, the adjustment being made by the help of the divisions marked on the circular plate. In making an observation, the bar is first placed so as to coincide with the prolongation of the said principal bar, and the intensity of *direct* radiation is thus observed. The pile is then placed so as to receive the reflected rays, and the ratio of intensity thus obtained to the intensity of direct radiation is the measure of the reflecting power." The accompanying sketch, Fig. 3, represents a top view of the arrangement referred to in the above explanation. *a* represents a Locatelli lamp, *b* the graduated circular plate on which is placed the polished reflecting substance *b′*, and *c* the thermo-electric pile. *d* shows a cluster of parallel calorific rays projected from the lamp, through a perforation in the screen *f*, towards the polished substance *b′*. The face of this polished substance being placed at an angle of 45 deg. to the course of the cluster of rays *d*, it will be evident that the rays will be deflected at the same angle; hence the cluster will be directed as shown by *h*, ultimately striking the face of the pile *c*. The latter, it should be mentioned, is protected against radiation from the lamp by a screen *g*. The temperature imparted by the deflected radiant heat having been recorded, the pile is allowed to cool, and then placed in the position *c′*, after which the polished substance *b′* is removed. As the radiant heat transmitted by the parallel rays *d* emanating from the lamp will now act directly on the face of the pile, a higher temperature will obviously be produced than when the pile occupied the position *c*. The difference

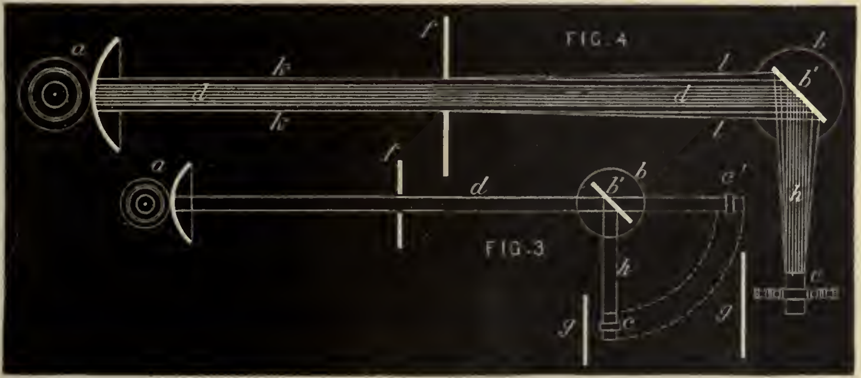


FIG. 4
FIG. 3

of temperature thus produced, we are told, indicates exactly the amount of loss of radiant intensity attending the reflection of the rays by the polished substance *b′*. Laprovostaye and Desains, as before stated, found that the heat transmitted directly is to that reflected as 1.000 to 0.978, hence the loss of energy = 0.022. The assumption of such perfect reflective power being palpably erroneous, let us examine carefully the adopted method in order to detect the cause of the false deduction. Fig. 4 represents a top view of Laprovostaye and Desains's arrangement, already described, but drawn to a larger scale than in Fig. 3, similar letters of reference being employed in both figures. *d d* represents the cluster of calorific rays transmitted by the lamp to the polished substance *b′*, and by it reflected, as shown by *h*, towards the face of the pile *c*. It will be evident that the section of the reflected central cluster of calorific rays depends upon, and corresponds with, the face of the pile *c*, provided the perforation in the screen *f* be sufficiently large. It will also be evident that the annular cluster *k k*, the external diameter of which depends on the size of the perforation of the screen *f*, will be projected towards the polished substance *b′*. Owing to defraction, the stated annular cluster will expand to the size *l l* before reaching the substance *b′*, and thus the rays become dispersed over a considerable portion of the angular face of *b′*. Consequently, the latter will become heated, and, since calorific rays radiate in all directions, a certain amount of heat will be transmitted to the pile wholly independent of that propagated by the *deflected* central cluster of rays represented by *h*. But, after taking away the polished substance *b′*, and moving the pile to the position *c′* (shown in Fig. 3), the pile will obviously receive heat only from the central cluster *d d*. We have thus demonstrated that more heat will be imparted to the pile when placed in the position *c* than when placed at *c′* in line with the cluster of rays *d d*, since in the latter case the calorific energy due to the section of rays corresponding with the area of the face of the pile can alone be transmitted to the same. Apart from this cause of error, it should be observed that, assuming the distance *a b′*, Fig. 3, to be three times greater than *b′ c′*, the diverging radiation from the heated metal of the lamp will subject the substance *b′* to a greater increase of temperature than that to which the pile is subjected when at *c′*, in the ratio of 4^2 to 3^2. The effect of this in causing undue transmission of heat to the pile, when placed at *c*, needs no explanation. Several other causes of error inseparable from Laprovostaye and Desains's method of determining the reflective power of metals might be shown. Among these, the inaccuracy resulting from the uncertain power of the lamp in developing a uniform amount of heat during the experiments may be mentioned. In view of the foregoing, it is evident that the thermo-electric method is unfit to determine accurately the reflective power of different substances. And it may be demonstrated that, unless the various substances under examination be exposed *simultaneously to a common source of heat*, the relative power of reflecting calorific rays possessed by the same cannot be ascertained with perfect accuracy by any method whatever. The instrument illustrated on Pl. 30 has been constructed in accordance with the condition thus presented, the source of heat employed being solar radiation. The following somewhat elaborate description and explanation have been deemed necessary to point out clearly its peculiar features. Fig. 1 represents a vertical section of the instrument and the table to which it is attached, the latter being provided with parallactic mechanism by means of which its face is kept at right angles to the sun during investigations. Fig. 2 shows a top view of the instrument as seen from a point situated in the prolongation of its axis, at right angles to the face of the table. *a a* is a conical reflector composed of cast iron, the sides of which are accurately turned to an angle of 45° to its axis, a flat bottom being attached provided with a central hub. An axle *b* is firmly keyed in the said hub, extending both above and below the same. The lower part of the axle turns in a boss formed on opposite sides of a cross-piece *c c*, the latter being supported by two columns bolted to the parallactic table. A hand-wheel *d*, secured to the axle *b*, enables the operator to turn the conical reflector during experiments. Four segmental heaters *f*, *g*, *h*, and *k*, *precisely* alike, composed of thin sheet metal, are secured to the bottom of the reflector, at equal distance from the centre, with intervening spaces, as shown in the drawing; these spaces to be filled with some non-conducting substance. Each heater is provided with a conical socket on the top, into which a perforated cork is inserted for the purpose of supporting thermometers entering the fluid, as shown in the sectional representation. It is important to observe that, before being attached to the reflector, each heater should be filled with water of a given temperature and accurately weighed. In case of any difference of weight, small quantities of soft solder should be gradually applied, until the deficient weight is made good and the four charged heaters balance each other exactly. Regarding the construction of the reflector represented by the illustration, it remains to be stated that four segmental plates f', g', h', and k', composed respectively of silver, brass, nickel, and steel, *precisely alike in size and form*, should be soldered to the inside of the cone n n. The plates being thus secured to the conical surface, the reflector should be put before a rotating polishing machine, for the purpose of having an equal polish imparted to each plate.

Referring to Fig. 2, it will be seen that the polished segmental plates, the reflective power of which it is intended to measure, are attached opposite to the heaters. Thus the plate f', composed of silver, is placed exactly opposite to the heater f; the brass plate g' opposite to the heater g; the remaining plates h' and k', composed respectively of nickel and steel, being likewise placed opposite to their corresponding heaters h and k.

Referring to the vertical section of the instrument shown in Fig. 1, supposed to be turned towards the sun, it will be seen that the solar rays m, n, indicated by dotted lines, are reflected by the polished segmental plates towards the semicircular faces of the heaters. The areas of the polished plates being alike, while the weight and areas of the heaters presented to the reflected solar heat are also alike, it follows that if the reflective power of the several plates does not vary, the thermometers inserted in the heaters will show an equal increase of temperature during equal intervals of time. But should the segmental plates not possess an equal power of reflecting the energy transmitted by the solar rays, the thermometers will, after a brief exposure to the sun, indicate different temperatures. Obviously the differential temperature reached by each thermometer in the same time will furnish a true indication of the relative reflective power of the several segmental plates, provided there are no disturbing causes affecting the heaters unequally. Before examining this important point, it will be proper to observe that the internal diameter of the conical reflector at *n n* is 2.5 times greater than the external diameter of the heaters at *o o;* hence the radiant intensity transmitted to their faces will be 2.5 times greater than the direct radiant intensity conveyed by the rays *m n.* It should be particularly observed that while the effect of this concentration of heat will influence the four heaters alike, it greatly increases the sensitiveness of the instrument, since the thermometers will be subjected to a radiant energy 2.5 greater than that produced by the direct action of the sun's rays, less the loss occasioned by the imperfect reflective power of the segmental plates, together with the losses of heat caused by convection and radiation. It will be seen, on inspecting the vertical section in Fig. 1, that the *lower* heater will be subjected to the cooling influence of the upward current of the air caused by the heat imparted by contact with the lower side of the heater. The upper heater, on the other hand, will not be subjected to any appreciable loss of heat by convection, other than that which is shared by the lower heater. It is hardly necessary to point out that the conical reflector itself cannot be maintained at a uniform temperature all over, owing to the powerful upward current of air unavoidable in a place exposed to the sun's rays. The apparently insuperable difficulties thus presented, and many others of minor importance, are overcome by the simple expedient of causing the reflector to *revolve* during the investigation. The rotary motion is effected, as already stated, by means of the hand-wheel *d*, which is kept revolving at the rate of about six turns per minute while the heaters are being exposed to the reflected and concentrated solar heat. It needs no demonstration to prove that by this expedient all disturbing influences will affect the four heaters *alike*, thereby neutralizing the same as completely as if no disturbance existed. The nature of the device having been thus minutely described, let us now consider the mode of managing the same during the investigation. (1) Before turning the reflector towards the sun, bring the parallactic table to a horizontal position. (2) Remove the corks and thermometers, and fill the heaters with water of the same temperature as the atmosphere. (3) Replace the corks and thermometers, and bring the table to an inclined position corresponding with the sun's zenith distance. (4) In order to ensure a perfect mixture of the particles of water in the heaters, turn the reflector for about two minutes. (5) The rotation being then stopped, note carefully the indication of the thermometers, and keep a separate record for each heater and corresponding segmental plate. (6) The initial temperatures having been thus ascertained, and the parallactic table and reflector turned to the sun, the hand-wheel should be kept in continuous motion, at the rate before mentioned, for a period of ten minutes. (7) At the expiration of the stated time the motion to be sufficiently reduced to admit of reading the thermometers, two observers being employed for that purpose. If the investigation be conducted at noon, during the winter season—the most favorable for accurate observation—it will be well to continue the experiment for fifty minutes, the indications of the thermometers being noted at the termination of every other minute, after the expiration of the first ten minutes before adverted to. It might be supposed that an observation at the expiration of the 10th and 50th minutes would suffice to ascertain the differential temperature imparted by the reflected and concentrated rays to each heater; and that by the observed difference of indication the comparative reflective power of the several segmental plates might be accurately determined. But it will be perceived, on due consideration, that in case of defects, such as imperceptible leaks or imperfect circulation, the recorded temperature would lead to a false determination of the comparative reflective properties. Numerous observations at definite intervals during the experiment will evidently serve as effectual checks. Of course, if equal reflective power of the respective plates results from *each* of these observations, then the accuracy of the determination may be regarded as absolutely certain. Regarding the initial temperature of the heaters, it will be perceived that if at starting the indications of all the thermometers corresponded, the comparison of the reflective power of the plates would be very simple; but experience has shown that a perfectly equal temperature at starting is impracticable. Consequently, each plate, with its corresponding heater and thermometer, calls for a separate record.

It is worthy of notice that investigations intended to determine the dynamic energy of solar radiation are rendered very difficult, because the heat acts on the upper part of any fluid intended to absorb it. Artificial means must therefore be employed to cause circulation, or mixture, of the particles within the mass exposed to the solar rays. The difficulty attending artificial circulation, and the complicated character of the means necessary to promote a thorough mixture of particles when a fluid is heated from above, has been shown in Chapter V. Nor can it be denied that, notwithstanding the elaborate character of those means, the object has been but partially attained. In the present instance, however, the circulation or mixture of heated and colder particles of the fluid within the heaters is absolutely perfect; since, for each revolution of the reflector, the colder particles are transferred from the bottom to the top of the vessel, and *vice versâ.*

Before presenting the result of our investigation of the comparative reflective power of silver and other metals, it will be necessary to explain the nature of the annexed tables. We have just stated that, owing to the impossibility of ensuring a uniform initial temperature, each of the four polished plates attached to the inside of the conical reflector has called for a separate record. The tables, accordingly, contain four distinct divisions, headed respectively *silver*, *brass*, *nickel*, and *steel*; each division having a different initial temperature, viz., silver, 65°.7; brass, 66°.1; nickel, 65°.4; and steel, 65°.1 F. As the temperatures recorded in the table commence at the termination of the *tenth* minute from starting, the original initial temperatures have not been entered, excepting that of the heater exposed to the solar rays reflected by the silver plate, which forms the standard of comparison. The headings of the several columns of the tables being sufficiently explanatory, it will only be necessary to point out the mode of determining the relative reflective power of the segmental plates. Let us select the nickel plate. Referring to the table, it will be found that, at the termination of the 30th minute from starting, the thermometer inserted in the heater *h* indicated 89°.5, while the initial temperature in that heater was 65°.4; hence an increase of $89.5 - 65.4 = 24°.1$ during 30 minutes. During the same period the temperature of the heater *f*, subjected to the reflected solar rays from the silver plate *f′*, it will be seen, by referring to the table, increased $96.4 - 65.7$

TABLE SHOWING THE RELATIVE REFLECTIVE POWER OF POLISHED METALS.

Time.	*SILVER.*			*BRASS.*		
	Observed temperature.	Increase of temperature.	Initial temperature.	Observed temperature.	Increase of temperature. Initial, 66°.1.	Reflective power. Silver as unit.
Min.	° *Fah.*	° *Fah.*	° *Fah.*	° *Fah.*	° *Fah.*	*Ratio.*
10	78.8	13.1	65.7	77.4	11.6	0.885
12	80.9	15.2	65.7	79.5	13.4	0.881
14	83.1	17.4	65.7	81.5	15.4	0.885
16	85.0	19.3	65.7	83.2	17.1	0.885
18	87.1	21.4	65.7	85.1	19.0	0.887
20	88.6	22.9	65.7	86.4	20.3	0.886
22	90.2	24.5	65.7	87.7	21.6	0.881
24	91.6	25.9	65.7	89.2	23.1	0.891
26	93.3	27.6	65.7	90.8	23.7	0.858
28	94.9	29.2	65.7	92.2	26.1	0.894
30	96.4	30.7	65.7	93.5	27.4	0.892
32	97.6	31.9	65.7	94.3	28.2	0.884
34	98.4	32.7	65.7	95.4	29.3	0.896
36	99.7	34.0	65.7	96.5	30.4	0.894
38	100.8	35.1	65.7	97.3	31.2	0.888
40	102.0	36.3	65.7	98.4	32.3	0.889
42	103.4	37.7	65.7	99.5	33.4	0.886
44	104.0	38.3	65.7	100.0	33.9	0.885
46	104.7	39.0	65.7	100.5	34.4	0.882
48	105.3	39.6	65.7	100.9	34.8	0.878
50	105.9	40.2	65.7	101.4	35.3	0.878
					Mean =	0.885

TABLE SHOWING THE RELATIVE REFLECTIVE POWER OF POLISHED METALS.

Time.	*NICKEL.*			*STEEL.*		
	Observed temperature.	Increase of temperature. Initial, 65°.4.	Reflective power. Silver as unit.	Observed temperature.	Increase of temperature. Initial, 65°.1.	Reflective power. Silver as unit.
Min.	° *Fah.*	° *Fah.*	*Ratio.*	° *Fah.*	° *Fah.*	*Ratio.*
10	75.5	10.1	0.771	74.1	9.0	0.687
12	77.2	11.8	0.776	75.6	10.5	0.684
14	78.8	13.4	0.770	77.0	11.9	0.683
16	80.3	14.9	0.772	78.4	13.3	0.689
18	82.0	16.6	0.776	79.9	14.8	0.691
20	83.2	17.8	0.777	81.1	16.0	0.699
22	84.5	19.1	0.779	82.3	17.2	0.702
24	85.7	20.3	0.783	83.4	18.3	0.706
26	86.7	21.3	0.772	84.2	19.1	0.692
28	87.6	22.2	0.760	85.9	20.8	0.712
30	89.5	24.1	0.785	87.1	22.0	0.716
32	90.4	25.0	0.783	87.7	22.6	0.708
34	91.4	26.0	0.795	88.5	23.4	0.715
36	92.3	26.9	0.791	89.5	24.4	0.717
38	93.2	27.8	0.792	90.1	25.0	0.712
40	94.2	28.8	0.793	91.0	25.9	0.713
42	95.3	29.9	0.799	91.8	26.7	0.708
44	95.7	30.3	0.791	92.5	27.4	0.715
46	96.1	30.7	0.787	92.8	27.7	0.710
48	97.0	31.6	0.797	93.3	28.2	0.712
50	97.5	32.1	0.798	94.0	28.9	0.718
		Mean = 0.786			Mean = 0.709	

= 30.7. Consequently, the reflective power of silver is to that of nickel as 30°.7 to 24°.1 = 1.000 to 0.785. Now, it will be found, on inspecting the table, that the reflective power of nickel, determined by the mean of twenty-five distinct observations, is 0.786 against the stated 0.785. This insignificant difference furnishes positive evidence of the reliable character of the investigation. The important question of comparative reflective power of *silver*, *brass*, *nickel*, and *steel* may therefore be regarded as permanently settled; while the reflective power of all other metals may be determined in like manner, by simply detaching the brass, nickel, and steel plates from the conical reflector and substituting others in their places; the silver plate, of course, remaining as a standard of comparison. It has already been stated that, according to Laprovostaye and Desains's investigation, the reflective power of brass is to that of silver as 0.978 to 1.000, difference = 0.022, while our exact method of measuring the energy lost by reflection shows that brass possesses a reflecting power of only $\frac{885}{1000}$ of that of silver, difference $1.000 - 0.885 = 0.115$ against 0.022. Considering the precision which distinguishes all Laprovostaye and Desains's investigations, this extraordinary discrepancy proves indisputably that the exact loss of calorific energy attending the reflection of radiant heat cannot be ascertained by the thermo-electric method.

CHAPTER XX.

RAPID-INDICATION ACTINOMETER.

PHYSICAL observatories cannot be regarded as fully equipped unless provided with actinometers by means of which the intensity of solar radiation may be quickly ascertained, say in the course of one minute. The thermo-electric pile is of no avail for this purpose, from various reasons: (1) The temperature produced by solar radiation is too high to be correctly registered by the deflection of the galvanometric needle; (2) The degree of *actual* temperature inferred from the arc described by the needle is mere guess-work at the high temperature developed by a vertical sun; (3) The disturbing effects of movable masses of iron, the presence of which are unavoidable; (4) The rotation of the observatory and consequent irregular change of the magnetic meridian.

The illustration on Pl. 31 represents a vertical section of an instrument constructed for the special purpose of ascertaining the intensity of the radiant heat after a very brief exposure to the sun's rays. The leading feature of the device is that of concentrating the rays before reaching the bulb of the thermometer employed to measure the intensity. It will be readily understood that by employing a lens of proper form the degree of concentration may be such that in the space of sixty seconds the mercurial column of the thermometer subjected to the concentrated rays will rise to the same height as the column of another thermometer exposed to the direct influence of the sun's radiant heat during a period sufficient to produce maximum indication. Hence, assuming that a proper degree of concentration has been attained in the new instrument, its exposure to the sun during sixty seconds will obviously furnish an indication of the intensity of the sun's rays as correctly as the actinometer described in Chap. III., whatever be the zenith distance or other conditions at the time of making the observation. The concentration of the sun's rays, it should be observed, must take place within an exhausted vessel maintained at a constant temperature corresponding with that of the actinometer referred to. It is hardly necessary to point out that it would be impossible to determine theoretically the precise distance between the lens employed to concentrate the rays and the thermometer which receives the accumulated heat. The instrument should therefore be so constructed that the lens may be readily moved away from or towards the thermometer during observations. This property of the instrument under consideration may be regarded as another leading feature indispensable to render accurate adjustment practicable. Referring to the illustration, it will be seen that the exhausted vessel enclosing the recording thermometer is surrounded by an external casing, the form of which, like the internal vessel, is cylindrical. The intervening space is filled with water maintained at a constant temperature by a similar process of circulation as that adopted in the actinometer described in Chap. III. Couplings for attaching the circulating tubes are applied at the bottom and top of the external casing, as shown in the illustration. The inclination of the cylindrical vessel is regulated by a tangential screw working through a nut turning in bearings attached to the side of the external vessel. By means of the graduated quadrant represented in the illustration, the sun's zenith distance may be ascertained by mere inspection, at all times, during observations. A journal applied under the exhausted vessel coinciding with the centre of the graduated quadrant, and turning in appropriate bearings, supports the instrument. These bearings are secured to the top of a vertical column resting on a revolving circular plate, to which a small pinion is applied, as shown in the illustration. This pinion, intended to be operated by hand, works into cogs formed at the circumference of the circular bed-plate attached to the top of a substantial table. The tangential screw, it will be seen, is provided with a small hand-wheel at the lower end, enabling the operator to give any desired inclination to the instrument, while the small hand-wheel of the pinion, before referred to, enables him to follow the earth's diurnal motion. Let us now examine the mode of regulating the distance between the lens and the thermometer which is employed to show the intensity of the concentrated radiant heat. We have already pointed out that it is impossible to determine theoretically the said distance. Of course, it may be calculated approximately, but not sufficiently near to dispense with means admitting of a very considerable movement of the lens up and down during the process of adjustment. In order to meet this condition, the lens is inserted in a perforated piston fitting air-tight in the exhausted cylindrical vessel; the latter being bored out accurately like the barrel of an air-pump. The adjustment of the position of the lens, it will be seen by referring to the illustration, is effected by screws secured in the piston, the nuts employed for raising the same acting against substantial brackets bolted to the top flange at the upper end of the exhausted cylinder. Convenient means being thus arranged for raising or lowering the lens in the exhausted cylinder, it will be perceived on reflection that although the thermometer subjected to the action of the concentrated heat is graduated in the ordinary manner, its indication may be made to correspond exactly with that of an actinometer exposed to the direct action of the sun's rays, provided the piston be placed correctly, viz., at such a distance that the energy of the converged rays under the lens be sufficient to raise the mercurial column of the enclosed thermometer as high during an interval of sixty seconds as that of an actinometer exposed to the direct solar heat during a period sufficient to produce maximum indication. It will be admitted that but for the introduction of a movable lens it would be impracticable to construct an instrument furnishing maximum indication of solar intensity during the exact interval of *sixty seconds.* The expedient, however, of inserting the lens in a piston capable of being placed at any desirable distance in order to subject the bulb of the enclosed thermometer to any requisite temperature, it will be perceived, renders that adjustment easy which is necessary to secure a given indication in a stipulated time.

It has been pointed out in previous chapters that, owing to the rapid change of zenith distance, and the consequent variation of the depth of atmosphere penetrated by the sun's rays, the indication of an actinometer is too low during the forenoon and too high in the afternoon. It will be obvious, therefore, that the *lens-instrument* under consideration should be adjusted when the sun passes the meridian, since the actinometer employed for comparison then indicates correctly the solar intensity at the moment of making the observation. The adjustment is effected in the following manner: Having placed the lens-instrument by the side of the standard actinometer selected for comparison, the casings or water-jackets of the two should be connected, by means of flexible tubes, in such a manner that the outlet pipe of the actinometer is made to communicate with the inlet pipe of the lens-instrument. Both instruments having been turned towards the sun, and the usual connections to the cistern and hand-pump of the actinometer having been completed, the refrigerating current should be circulated through the jackets until the actinometer indicates maximum differential temperature. In the meantime, the operator attending to the circulation should screen the lens-instrument from the sun by a disc of pasteboard. A second operator, as soon as maximum temperature has been reached by the actinometer, starts the chronograph and calls time, the pasteboard screen being at once lowered. At the termination of sixty seconds, time is again called, and the protecting screen instantly raised. Let us now suppose that the actinometer has continued to indicate a differential temperature of 56° during the experiment, and that the thermometer of the lens-instrument indicates only 52° at the end of sixty seconds' exposure to the concentrated solar radiation. It needs no explanation to show that the observed difference of $56 - 52 = 4°$ is owing to the want of adequate concentration, and that the discrepancy will be remedied simply by moving the lens further from the enclosed thermometer. This is effected by turning each of the nuts at the top of the exhausted cylinder, say once round, thereby increasing the distance. The chronograph should again be started, the screen removed, and the operation already described repeated as quickly as possible, and the result recorded. Should it now be found that the enclosed thermometer indicates 54°, another turn of the adjusting nuts should be given, and the operation repeated a third time. Due diligence being exercised by the operators, the proper position of the lens may thus be determined before a change of the sun's zenith distance takes place sufficient to affect the indication of the standard actinometer to an extent preventing accurate adjustment. In view of the fact that the form of the lens, and its distance from the thermometer which indicates the intensity of the concentrated radiation, may be approximately determined by calculation, it is evident that the lens might be *stationary* and the recording thermometer graduated by repeated exposure to the sun during intervals of 60 seconds, so as to correspond with the indication of a standard actinometer. I have constructed small lens-actinometers on this plan, useful for ordinary observations, but for physical observatories and investigations requiring perfect accuracy the instrument having a movable lens, as represented by the illustration in Pl. 31, is far preferable.

CHAPTER XXI.

SOLAR RADIATION AND DIATHERMANCY OF FLAMES.

The readers of "Comptes Rendus" are aware that Père Secchi addressed a letter to the Academy of Sciences at Paris (see "Comp. Rend.," tome lxxiv., pp. 26–30), containing a review of my communications to *Nature*, published July 13, October 5, and November 16, 1871, in which he questions the correctness of my published reports containing tabulated statements of the temperature produced by solar radiation. His reason for questioning the reliability of my tables appears to rest on the supposition that my instruments do not furnish correct indications. "It is astonishing," he says, "that Mr. Ericsson should find with his instrument a higher stationary temperature in winter than in summer. This (even bearing in mind the greater proximity of the sun in winter) makes me think that there must be something very singular in his apparatus, making all its indications deceptive. Even under the beautiful sky of Madrid has M. Rico y Sinobas found; in December, for the solar radiation, 12 div., 19 by his actinometer, and, in June, 25 div., 56."

Père Secchi ought to have perceived "that there must be something very singular" in the actinometer employed by the Spanish physicist, or it could not have indicated an intensity twice as high in June as in December. Obviously, a correct actinometer will indicate a higher temperature during the winter solstice than at midsummer for equal zenith distance. The instrument employed at Madrid, if Secchi's figures are correct, must therefore be founded on utterly erroneous principles. In North America, in lat. 40 deg. 42 min. (the latitude of Madrid is 40 deg. 24 min.), solar intensity at *noon* during the latter part of June is 64°.5 when the sky is clear, while at noon during the latter part of December the temperature under similar atmospheric conditions reaches 57°.70. But observations made in the morning or evening during the month of June, at the hour when the sun's altitude is the same as at noon in December, show that the intensity of the radiant heat in June is only 53°.08, against 57°.49 F. in December. Actual observations have thus established the fact that for *corresponding zenith distance* the temperature produced by the radiant heat when the earth has nearly reached perihelion, is 57°.49 − 53°.08 = 4°.41 higher than at midsummer. Referring to Chap. IV., it will be seen that, owing to the greater proximity of the sun, the increase of absolute intensity of solar radiation is 4°.66 F. during the winter solstice. Père Secchi will do well to examine the subject more carefully, and make himself better acquainted with the character of the investigations which have led to an exact determination of the temperature produced by solar radiation.

The readers of "Comptes Rendus" who have examined the review referred to, ignorant of the articles in *Nature*, the contents of which Père Secchi criticises, will be surprised to learn that I have not, as the reviewer asserts, questioned the power of vapor to diminish solar intensity. Having stated the result of numerous observations of the sun's radiant power at corresponding zenith distance, and proved that the temperature during midwinter is higher than at midsummer, I made the following remark in *Nature*, Nov. 16, 1871: "In the face of such facts it is idle to contend that the temperature produced by solar radiation under corresponding zenith distance and a *clear sky* varies from any other cause than the varying distance between the sun and the earth." It is absurd to suppose that a person having devoted many years to the investigation of solar radiation should deny the retarding influence of vapor, since not one observation in a hundred indicates maximum solar intensity, owing to the presence of vapor in the atmosphere.

The following brief description of the actinometer which Père Secchi supposed to be constructed on erroneous principles was inserted in my reply to his criticism published in "Comptes Rendus," before referred to, in hopes that, on learning that there is *not* anything "very singular" in my apparatus, he would have seen fit to withdraw his statement questioning the correctness of my observations relating to solar intensity: "The principal part of the instrument consists of an air-tight cylindrical vessel, the axis of which is directed towards the sun, the upper end being provided with a thin lens covering an aperture 3 ins. in diameter. The bulb and part of the stem of a mercurial thermometer is inserted through the upper side, at right angles to the axis, a small air-pump being applied for exhausting the air from the cylindrical vessel. The latter is surrounded by a casing through which water is circulated by means of an ordinary force-pump and flexible tubes, connected with a capacious cistern containing water kept at a constant temperature of 60° F. The bulb of the thermometer is cylindrical, 3 ins. long, its contents bearing a very small proportion to its convex area. The upper half is coated with lamp-black, while the lower half of the bulb is effectually protected against loss of heat from undue radiation. The diminution of energy attending the passage of the sun's rays through the lens is made good by the concentration effected by its curvature; hence the true energy of the radiant heat transmitted will be shown by the expansion of the mercury in the bulb. The inclination of the latter, it should be observed, promotes a rapid upward current of the contents on the top side, and a corresponding downward current on the lower side, thereby rendering the indication prompt and trustworthy. The water in the surrounding casing being maintained at a constant temperature of 60° F., it will be evident that the *zero* of the thermometric scale of the actinometer must correspond with the line which marks 60° on the Fahrenheit scale. It scarcely needs explanation that the height reached by the mercurial column after turning the instrument towards the sun will be due wholly to solar energy, since the radiation of the exhausted vessel towards the bulb of the thermometer is only capable of raising the column to the actinometric zero (60° Fahr.)"

The readers of *Nature* will remember that one of my articles reviewed by Père Secchi contains a demonstration accompanied by several diagrams, proving that the radiant heat emitted by the chromosphere and outward strata of the solar envelope is inappreciable at the surface of the earth. It will be remembered, also, that the mode adopted in settling the question whether the solar atmosphere is capable of emitting heat rays of appreciable energy was that of shutting out the rays from the photosphere and collecting those from the chromosphere and envelope, in the focus of a parabolic reflector. Scarcely any heat being produced, notwithstanding the great concentration by the reflector, I proved the fallacy of Père Secchi's remarkable assumption, that the high temperature at the surface of the photosphere is caused by *radiation* "received from all the transparent strata of the solar envelope." It is surprising that, notwithstanding the completeness and positive nature of my demonstration, no allusion whatever is made to the same in a review professing to scrutinize the subject critically. Ignoring the evidence furnished by actual trial in proof of the extreme feebleness of the radiating power, the reviewer proceeds to state "that the outward strata might be less hot, and that the effect which we measure is the aggregate of the quantities of heat which are added, emanating from the various transparent strata." How the outward colder strata cause an elevation of temperature by their radiation toward the solar surface is not explained, but reference is made to the result of an experiment with three small flames in support of the assertion that the high temperature of 10,000,000° C. assigned to the surface of the sun is owing to radiation received from all the transparent strata surrounding the photosphere. "A very simple experiment," the reviewer states, "made at my request by P. Provenzali, has shown that, if a heating of 2.5 deg. can be obtained with one flame, with two flames placed one before the other 4.5 deg. are obtained; with three flames, 5.4 deg.—a result easily foreseen, for everybody knows that flames are transparent."

My practical demonstration establishing the feebleness of the radiating power of the matter composing the solar envelope having received no consideration, while the reviewer, in support of his singular theory of solar temperature, points to the result of the rude experiment conducted by Père Provenzali, I have deemed it necessary to show that the transparency of flames is too imperfect to warrant the inferences drawn.

The illustration on Plate 32 represents an apparatus by means of which the exact degree of transparency of a series of flames has been ascertained.

Description: *b*, conical vessel, open at the top, the bottom communicating with a cylindrical chamber *f* by a narrow passage, the whole being enclosed in an exterior vessel *c*, charged with water kept at a constant temperature, precisely as in the actinometer. A thermometer is applied near the bottom of the cylindrical chamber, the centre of the bulb coinciding with the prolongation of the axis of the conical vessel. A gas-pipe *d*, provided with a series of vertical burners, is firmly secured to an inclined table in a position parallel to the axis of the conical vessel. The burners are provided with caps in order to admit of any desirable number of jets being ignited at one time. When gas of ordinary pressure is admitted into the pipe *d*, the side view of the flame will be as indicated by the dotted lines at *m m*, the thickness of each flame being nearly 0.20 in., while the width, shown by the dotted lines *n n*, somewhat exceeds 3 ins. from point to point. It will be observed that the prolongation of the axis of the conical vessel upwards passes through the central portion of the flames at the point of maximum thickness and intensity. Supposing that the instrument (attached to a table provided with parallactic mechanism) is directed towards the sun, it will be evident that all the rays of a pencil, the section of which corresponds with that of the bulb of a thermometer, will pass through the flames before reaching the said bulb. Now, the temperature of the flames at the point pierced by the solar rays is fully 2,000° F., while the actual intensity of the rays does not exceed 60°. It is hardly necessary to observe that the illustrated device enables us to ascertain whether the solar rays thus entering at a differential temperature 1,940° lower than that of the incandescent gas have their intensity augmented or diminished during the passage through the heated medium. But before we can determine this question, it will be necessary to ascertain what temperature is communicated to the thermometer by the radiant energy of the flames alone. Accordingly, a series of experiments have been made, the result of which is recorded in the annexed table.

The instrument turned away from the sun.			The instrument directed towards the sun.		
Number of flames acting from the top.	Distance of flame from bulb.	Temperature produced by radiation of the flames.	Temperature produced by the sun's rays acting directly on the bulb.	Temperature produced by the sun's rays passing through the flames.	Increment of temperature attending the passage of the solar rays through the flames.
	Inches.	*° Fah.*	*° Fah.*	*° Fah.*	*° Fah.*
1	24.8	1.76	21.60	21.90	0.30
2	23.8	2.88	21.61	22.20	0.59
3	22.8	3.80	21.62	22.49	0.87
4	21.8	4.58	21.63	22.75	1.12
5	20.8	5.24	21.64	22.99	1.35
6	19.8	5.84	21.65	23.32	1.57
7	18.8	6.38	21.66	23.43	1.77
8	17.8	6.91	21.67	23.63	1.96
9	16.8	7.40	21.68	23.82	2.14
10	15.8	7.90	21.69	24.00	2.31

The nature of the investigation will be readily understood by the following explanation: The instrument being turned away from the sun and the upper flame *m* ignited, while the external casing *c* is kept at a constant temperature of 60°, the column of the thermometer at *f* slowly rises to 61°.76. The radiant heat, therefore, of a single flame produces a differential temperature of 61°.76 — 60 = 1°.76. The second flame being ignited, the temperature rises to 62°.88, thus increasing the differential temperature to 2°.88. The ignition of the third flame augments the differential temperature to 3°.80. The remaining flames being ignited in regular order downwards, their combined radiant energy elevates the temperature to 67°.90. Deducting the temperature of the enclosure *c* (60°), the trial shows that, although the single flame at the maximum distance from the bulb is capable of producing a differential temperature of 1°.76, the energy of the *ten* flames together produces only 7°.90. This fact furnishes conclusive evidence of the imperfect transparency of the flames. Assuming that the heat rays are capable of passing freely through the incandescent medium, it will be perceived that the entire series of flames should produce a differential temperature of 1.76 × 10 = 17°.6, showing a retardation of 17.6 — 7.9 = 9°.7. And if we take into account the diminished distance of the lower flames from the bulb of the thermometer, it will be found that the actual retardation greatly exceeds this computation. We have thus demonstrated that flames are not transparent, as supposed by Père Secchi; consequently, the inferences drawn from the experiment to which the distinguished *savant* refers in his letter to the French Academy of Sciences are wholly unwarrantable.

Having disposed of the question of transparency, and ascertained the degree of temperature communicated to the thermometer by the radiant energy of the flames alone, let us now suppose that the instrument has been turned towards the sun. The temperature produced by the combined energy of solar radiation and the radiation of the flames, after directing the instrument towards the luminary, will be found recorded in the fifth column of the table. Dispensing with a detailed record of the energy transmitted for each flame separately, let us at once consider the effect produced by passing the sun's rays through the entire series. It has already been stated that the radiation of all the flames combined imparts a differential temperature of 7°.90 to the thermometer. By reference to the table, it will be seen that the temperature produced by the sun's rays is 21°.69 when the flames are extinguished. Consequently, the temperature produced after lighting the whole series ought to be 21.69 + 7.90 = 29°.59 instead of 24°.00, since solar heat, under analogous conditions, is capable of increasing the temperature of substances, whatever be their previous intensity. Our experiment, therefore, furnishes additional evidence of the imperfect transparency of flames. But notwithstanding this want of transparency, it will be found on referring to the table that an augmentation of temperature of 24.00 – 21.69 = 2°.31 takes place while the comparatively cold solar rays pass through the incandescent medium. This extraordinary fact points to an increase of molecular energy within the incandescent gas, although its temperature is fully 1,900° *higher* than the intensity of the sun's rays.

CHAPTER XXII.

CONSTANCY OF ROTATION OF THE EARTH INCOMPATIBLE WITH SOLAR INFLUENCE.

Laplace's demonstration, showing that the axial rotation of the earth is not affected by atmospheric currents and similar motions caused by solar heat, has been accepted by physicists as incontrovertible. The German mathematician, Dr. Mayer—celebrated for his demonstration establishing the equivalent of heat—says in a discourse on that branch of celestial mechanics which relates to the effect produced by contrary atmospheric currents: "The final result of the action of these opposed influences is, as regards the rotation of the earth, according to well-known mechanical principles = 0; for these currents counteract each other, and therefore cannot exert the least influence on the axial rotation of the earth. This important conclusion was proved by Laplace." "The same," he adds, "holds good for every imaginable action which is caused by the radiant heat of the sun, or by the heat which reaches the surface from the earth's interior, whether the action be in the air, in the water, or on the land. The effect of every single motion produced by these means on the rotation of the globe is exactly compensated by the effect of another motion in an opposite direction, so that the resultant of all these motions is, as far as axial rotation of the globe is concerned, = 0." I propose to show that this conclusion is fallacious, and that the sun's radiant heat develops forces capable of diminishing perceptibly the earth's rotary velocity; and that unless the retarding influences of solar heat, the existence of which I am going to establish, are counteracted by some cosmical force of which we have no knowledge, the earth's rotary velocity will be considerably reduced in the course of time.

There are two classes of force produced by solar heat, capable of retarding the axial rotation, differing, however, entirely as regards ultimate results. The first class includes animate exertion, mechanical force produced by heat developed by the combustion of organic substances, and the resistances of abraded solid matter transferred from its original position by the waters of rivers flowing towards the equator. The forces thus enumerated, it will be shown, retard the rotary velocity of the globe in all cases when they remove weight to a greater distance from the axis of rotation, *i.e.*, expand the circle of gyration, thereby diminishing the number of revolutions performed in a given time. Obviously, the *vis viva* of the rotating mass will remain undiminished, as the centre of gyration is merely removed to a greater distance from the axis of rotation. Accordingly, the axial rotation, though checked, can never be stopped by the class of retarding influences thus pointed out. The second class, however—which comprises the retardation produced by the atmospheric air during its course from the polar to the equatorial regions, and the retardation caused by the waters which flow towards the equator to restore the quantity lost by the powerful evaporation within the tropics—not only diminishes the rotary velocity, but, at the same time, deprives the earth of so great an amount of *vis viva* that the axial rotation must ultimately cease, unless some exterior compensating force exists—a supposition at variance with the principles of mechanics.

Let us now briefly examine the nature of the retarding influences of the first-named class, which, as stated, are unattended by any loss of the earth's *vis viva*—namely, animate force and mechanical energy, resulting from the combustion of organic substances when expended in raising weight to remain permanently in an elevated position; and the retardation caused by solid matter carried towards the equator. Before entering on this examination, it will be instructive to test by some familiar illustration the correctness of Mayer's assumption, that "every imaginable action affecting the rotation of the globe is exactly compensated by the effect of another motion in an opposite direction." A great variety of instances might be mentioned in which the development of mechanical energy, productive of heat, counteracts the rotary motion of the earth, and deprives it permanently of a certain amount of *vis viva*. Suppose, for instance, a locomotive train weighing 400 tons to be started from the western terminus of a railway running from west to east. Suppose, also, that when this train has acquired a velocity of 50 ft. per second, it encounters another similar train which is at rest. The result of such an encounter, in a dynamic point of view, is now well understood. Apart from a small amount of energy absorbed in overcoming the cohesive force between the particles composing the materials fractured by the concussion, the encounter will develop an amount of heat corresponding with the *vis viva* of the arrested train. It scarcely needs explanation that in putting the train in motion from the terminus eastward the rails—*i.e.*, the surface of the earth—will, in consequence of the adhesion between the wheels and the rail, be pushed westward; hence in a direction contrary to the earth's rotation. The amount of dynamic energy which the train thus imparts to the earth in an opposite direction to that of rotation may be readily ascertained by multiplying the arrested weight by the height necessary to produce a velocity of 50 ft. per second—namely, 39 ft.; hence 400 × 2,240 × 39 = 34,944,000 foot-pounds. Deducting the small amount of energy which favors the earth's rotation called forth by the rolling friction and adhesion of the wheels of the stationary train, during the short retrograde motion attending the concussion, it will be found that the earth loses an amount of *vis viva* of fully 34,000,000 foot-pounds. The assumption of Dr. Mayer, based on the theory of Laplace, that the resultant of all imaginable motions as regards the earth's axial rotation is = 0, has thus been proved to be untenable. It is not intended to question Laplace's conclusion as regards the existence of a compensating effect; he was mistaken only as to its nature—a mistake, however, of paramount importance, as we have shown that the compensation for the lost energy, in the case presented, is the generation of a certain amount of heat which, in less than three hours after the concussion, if the sky be clear, radiates into space, leaving the earth minus 34,000,000 foot-pounds of *vis viva.* The important fact should not be overlooked that the retardation thus established is the result of solar energy stored in the combustibles of the locomotive furnace. Numerous instances of a similar nature might be mentioned in support of the assertion that the earth is subjected to retarding influences and loss of *vis viva* by mechanical motions on the earth's surface which result in the production of heat radiated into space. But all these are insignificant compared with the stupendous amount of retardation caused by the conversion of mechanical energy into heat within the opposing atmospheric currents circulating between the equatorial and polar regions. In connection with this proposition, it will be proper to remark that our knowledge of the convertibility of mechanical energy and heat—in other words, the convertibility of mechanical and molecular energy—has completely upset Laplace's demonstration, on which physicists have based their assumption, that the rotary velocity of the earth cannot be affected by the sun's radiant heat.

Let us now examine, separately, those forces produced by solar heat which tend to check the earth's rotary velocity by removing weight from the axis of rotation—*i.e.*, expanding the circle of gyration—and those which occasion a diminution of the rate of axial rotation without disturbing the balance of the rotating mass. The first class: Animate or muscular energy, and the force generated by heat from the combustion of organic matter, controlled by the human mind, both resulting indirectly from the sun's radiant heat. That the hand and intellect of men have caused a disturbance of the position of the earth's centre of gyration will be deemed a startling assertion, yet it cannot be controverted in view of the following facts. The millions of tons of matter contained in the Pyramids, removed to a greater distance from the axis of rotation by the muscular exertion of the ancient Egyptians, disturbed the previous balance of the rotating mass, causing a tendency to check the earth's rotary velocity and to increase the length of day. Nor can it be questioned that if London had not been built, and if the building materials of Paris yet remained in the Catacombs, the sun would rise earlier than it now does, though the difference would be small beyond computation. The aggregate of the weight removed from below, and piled above the crust of the globe by the hand of man, is, however, so great that figures are competent to express the extent of the consequent retardation of the axial rotation, while the divisions of our common instruments for measuring distance are sufficiently minute to indicate the expansion of the earth's circle of gyration caused by the transfer of matter under consideration. A first-class modern city, for instance, contains upwards of 100,000 houses; each house contains on an average 400 tons of mineral matter; hence the total weight of brick, earth, or stone removed from below the surface to a considerable height above the earth's surface exceeds 40,000,000 tons—a mere fraction compared with the weight of the whole of human habitations and other structures raised above the surface of the earth chiefly by muscular effort. Let us add the weight of materials raised from mines to an increased distance from the axis of rotation, by animate exertion and by mechanical force controlled by intellect.

An element of greater importance, connected with the first class of retarding influences produced by the sun's radiant heat, next claims our attention—namely, the solid and sedimentary matter detached by the abrasion of rain-water, and afterwards conveyed by the currents of rivers to a position nearer the equator; hence removed to a greater distance from the axis of rotation. The question whether any estimate can be made of the aggregate weight of matter, the original position of which is being changed during definite periods by the cause referred to, is by no means so difficult to answer as might appear without due consideration. It is true, we do not know what quantity of water or sediment is carried towards the equator by the several rivers; but we can compute with sufficient exactness the extent of the river basins. Accordingly, if we could establish a mean of discharge per square mile of some very extensive basin comprising all the varieties of climate and soil, the question could be satisfactorily answered. Fortunately, one of the longest rivers on the globe, the Mississippi, which drains the greatest extent of surface with but two important exceptions, has been carefully surveyed by a corps of Topographical Engineers, by order of the United States Government. Not only has this great river been thus carefully examined, but the basin it drains comprises every variety of soil and climate—its source being among snows and lakes frozen during the greater portion of the year, while the outlet is near the tropics. That the Mississippi basin represents the average of the river systems of both hemispheres has been established by the fact that, although the rain-gauges at its northern extremity show only 13 ins. for twelve months, those of its southern boundary reach 66 ins., with every possible gradation of precipitation in the intermediate space. In addition to this important circumstance, the basin covers 21 deg. of latitude and 35 deg. of longitude, or 1,460 miles by 1,730 miles; hence comprising an area greater than the entire European Continent west of the rivers Vistula and Pruth. It may be confidently assumed, therefore, that the Mississippi basin represents the average discharge of water and sediment so nearly that calculations based thereon, applied to the river systems of both hemispheres—excepting some of the northern Asiatic and American rivers—will exhibit a general result differing but slightly from what would be established if each river had been examined.

The elaborate report of General Humphreys to the Bureau of Topographical Engineers, Washington, shows that the average quantity of earthy matter carried into the Gulf of Mexico, partly suspended in the water and partly pushed along the bottom of the river by the current, amounts for each twelve months to 903,100 millions of pounds. This enormous weight of matter is contributed by numerous large branches and upwards of 1,000 small tributaries. The mean distance of the streams along which the sediment is carried in its course to the sea exceeds 1,500 miles. The distance which determines the amount of force tending to check the earth's rotation is, however, considerably shorter.

The maps of the Mississippi River basin accompanying the report referred to show that its centre is situated 7 deg. 10 min. west of the mouth of the main river, and 11 deg. 15 min. north of the same, in latitude 40 deg. 15 min. It will be found on inspecting the section of the earth (see Pl. 33) that, agreeably to the stated latitude, the centre of the Mississippi basin rotates in a circle of 15,784,782 ft. radius; hence its velocity round the axis of the globe is 1,147.90 ft. per second. The mouth of the river, it will be found on calculation, rotates in a circle of 18,246,102 ft. radius, with a circumferential velocity of 1,326.89 ft. per second. Comparing these velocities, it will be seen that an increased circumferential velocity of 178.99—say 179—ft. per second is imparted to the water and to the sedimentary matter which it conveys during the course from the centre of the basin to the mouth of the river. As before stated, the annual discharge of earthy matter at the mouth of the river is 903,100 millions of pounds. The centre of the basin—lat. 40 deg. 15 min.—being 2,461,320 ft. nearer to the axis of rotation than the mouth of the river in lat. 29 deg. 0 min., it will be found that the increase of rotary velocity is 179 ft. per second, as already stated—a rate acquired by a fall of 500.6 ft. The elements are thus furnished for determining with exactness the amount of retardation attending the change of position of the abraded matter during its transfer from the basin to the mouth of the river. Multiplying 903,100 millions by 500.6, we ascertain that the counteracting force amounts to 452,000,000,000,000 foot-pounds annually = 452×10^{14} foot-pounds in a century. The earth's present *vis viva* being $18,875,361 \times 10^{22}$ foot-pounds (to be demonstrated hereafter), it is easy to calculate that the retardation occasioned by the stated reacting energy called forth by the sedimentary matter which is carried to the ocean by the Mississippi will amount to $\frac{36}{100000}$ of a second in a century. In view of this small fraction of time, it will be well to remind the reader that the retardation of the earth's rotary velocity, inferred from the apparent acceleration of the moon's mean motion, now generally admitted by astronomers, is somewhat under 12 seconds in a century. Insignificant as this retardation appears to be, it calls for a constant reacting force of 455,000,000,000 foot-pounds per second, as will be shown in the course of our investigation. Dividing this amount by the adopted standard of a horse-power—viz., 550 foot-pounds per second—it will be found that a constant energy represented by 827,000,000 horse-power, exerted in a contrary direction to that of rotation, is necessary to check the rotary motion to the extent mentioned—viz., $\frac{12}{86400} = \frac{1}{7200}$ of a revolution in the course of a century. Accordingly, 720,000 years, nearly, will elapse before one entire revolution shall have been lost, notwithstanding the existence of a constantly retarding force of 455,000 millions of foot-pounds per second. We can readily ascertain the aggregate of this force during the long period mentioned, if we multiply the same by the number of revolutions of the earth per annum, and the number of seconds for each revolution; thus, $455 \times 10^9 \times 365.24 \times 86{,}400 \times 720{,}000 = 103{,}379{,}867 \times 10^{17}$ foot-pounds. By dividing this amount of energy in the earth's *vis viva,* $18{,}875{,}361 \times 10^{22}$ foot-pounds, we ascertain that the stated enormous retardation overcome in the course of 720,000 years amounts to only $\frac{1}{18258}$ of the present rotary *vis viva* of our planet. Probably no other mode of presenting the subject could give so clear an idea of the vastness of the mechanical energy developed by the axial rotation of a sphere 8,000 miles in diameter, whose specific gravity is $2\frac{1}{4}$ times that of granite, revolving at a rate of one revolution in 24 hours. Let us bear in mind that the retardation produced by the sedimentary matter carried to the Gulf of Mexico by the Mississippi, and the precipitation which causes the abrasion of the solid matter and the currents by which it is conveyed, are the direct results of the sun's radiant heat.

With reference to the tables (see pages 342–353), it should be stated that the amounts of the retarding force entered in the last two columns but one are based on the data furnished by the examinations of the great Western river—viz., that 1 lb. of solid matter and 1,350 lbs. of water per second are carried to the sea for every 40.08 sq. miles of basin. All other particulars necessary in computing the retarding energy exerted by each river, separately for the two hemispheres, will be found in the tables. The mode adopted in determining the area drained by each river and tributaries will be readily comprehended by the following explanation: The extent of the several river basins, 136 in all in both hemispheres, has been ascertained from the best maps extant; the boundaries of the basin being determined by drawing a line on the map, and dividing the territory equally between the source of each river and tributaries and those of adjoining basins. The boundaries being thus defined, the areas have been calculated in English statute miles; the latitude and longitude of the centre of each basin being determined at the same time. By supposing the earth to be a perfect sphere 7,912.41 miles in diameter, according to Sir John Herschel's determination, the calculations have been rendered extremely simple. This will be seen by reference to the section of the earth before referred to, which contains all the elements for computing the rotary velocity of the centres of the river basins and of the outlets of the rivers. These velocities have been entered in the tables separately for each river basin; also the retardation, expressed in foot-pounds per second, caused by the increase of rotary velocity during the transfer of the sedimentary matter from the centre of the basin to the mouth of the river. The last column but one of the tables contains the result of computations of the amount of retardation occasioned by the volume of water which conveys the sedimentary matter—a subject to be considered under a separate head hereafter.

It should be observed that, owing to their trifling influence on the earth's rotation, and in order to save space, all the English and Scotch river basins whose sediment is transferred in the direction of the equator have been entered together in the tables; the rivers of Ireland likewise. But in computing the loss or gain of energy, each river basin has been calculated by itself, the amount of retardation entered being the result of the whole quantity of sediment transferred towards the equator by the several small basins referred to. Accordingly, the area which is entered in the table represents the total. The river basins of Sweden and Norway, being very numerous and unimportant, have also, in some districts, been entered together in the tables like those of Great Britain. Finally, the narrow-coast districts, in both hemispheres, have been computed and inserted in the table in a similar manner.

The quantities of sedimentary matter discharged by the Indus, Ganges, and Brahmapootra, being known with tolerable accuracy from actual observation, have not been computed according to the standard furnished by the Mississippi, which, as before stated, is 1 lb. of sediment per second for every 40.08 sq. miles of basin. Besides, local circumstances, such as the heated waters and profuse evaporation of the

Bay of Bengal, and the powerful condensation attending the close vicinity of the Himalaya Mountains, render the Ganges quite exceptional.

Respecting the African rivers, none of which have been entered in the tables, it may be briefly stated that they have no material influence on the earth's rotation, from the fact that the two principal rivers, the Nile and the Niger, flow in opposite directions—the former towards the pole and the latter towards the equator. There is, however, considerable difference of latitude, productive of an increased retarding influence of the Nile; but this cannot be far from balanced by the greater quantity of sedimentary matter brought down by the Niger, as proved by its delta of 240 miles of coast. The general course of the other important rivers of Africa—the Senegal, Zambesi, and the Orange River—is so nearly parallel with the equator that they exercise no appreciable influence on the axial rotation of the earth.

Australia, being drained by rivers the courses of which are directed to all points of the compass, consequently exercising no appreciable influence as regards the earth's rotary motion, has likewise been excluded from the tables. It should be observed that the basin of the important river Goolwa and its tributaries (excepting the Callewatta) is almost on the same parallel with the mouth of the main river; hence scarcely any retarding force is produced, notwithstanding the great extent of basin drained by the Goolwa. The Amazon, which drains more than two millions of square miles, strikingly illustrates the trifling influence on the earth's rotary velocity of rivers the centres of whose basins are nearly on the same parallel with their outlets, the enormous mass of solid matter carried to the ocean by this river—the greatest on the globe—exerting a retarding influence of only 70,000 foot-pounds per second.

The aggregate of solid matter removed from its original position by the river systems of both hemispheres, and carried towards the equator—consequently removed to a greater distance from the axis of rotation—exerts, as shown by the tables, a retarding influence of 39,894,658 foot-pounds per second. If we multiply this amount by 86,400 seconds, we learn that for each revolution the earth has to overcome a retarding energy represented by 3,446,898,451,200 foot-pounds; but the effect of this retardation as regards the length of the century cannot be properly considered until we have investigated the second class of force before adverted to, viz., that force which destroys the earth's *vis viva* without disturbing the position of its centre of gyration. We have, however, proceeded far enough with our investigation to show the fallacy of the accepted doctrine of compensation relative to the energies which affect the earth's rotary velocity. We have clearly shown that constancy of rotation of the earth is incompatible with solar influence.

Rivers flowing towards the Equator. Eastern Hemisphere.

Name of River or District.	River Basin.					
	Area.	Latitude of centre.	East of outlet.	West of outlet.	Rotary velocity.	
	Sq. Miles.	*Deg. M.*	*Deg. M.*	*Deg. M.*	*Feet per second.*	
Anadir	119,200	65 50	...	1 35	622	1
N. W. coast Sea of Kamtschatka	52,000	61 42	0 10	...	720	2
Penshina	50,100	63 20	0 20	...	681	3
W. coast Sea of Okhotsk	32,600	62 00	...	0 05	713	4
Yama	15,500	60 45	...	1 30	742	5
Tawi and Kowa	13,300	60 25	...	0 10	750	6
Ochola	21,500	60 48	...	0 40	741	7
Ud	25,400	55 25	...	2 35	862	8
Toumen	20,000	43 20	...	0 15	1,105	9
Yaloo	21,200	41 10	1 05	...	1,144	10
Sira Muren	78,700	42 40	...	1 06	1,117	11
Chanton	29,800	41 00	...	0 30	1,146	12
Pei-ho	124,000	38 40	...	2 45	1,186	13
Min Kiang	25,400	26 20	...	1 15	1,362	14
Han Kiang	26,200	24 18	0 05	...	1,384	15
Tche Kiang	144,400	24 10	...	3 50	1,386	16
Hoang Ho	448,200	36 50	...	10 25	1,216	17
Sang Koi	76,300	22 40	...	2 28	1,402	18
Coast Rivers, Gulf of Tonquin	26,000	20 12	...	1 50	1,426	19
Menam Kong	329,500	16 38	...	3 15	1,455	20
Irawady	205,000	22 35	...	0 30	1,403	21
Brahmapootra	379,000	29 12	1 05	...	1,326	22
Ganges above Ghazepoor	187,100	27 25	...	5 25	1,346	23
Ganges below Ghazepoor	237,200	27 30	...	5 12	1,347	24

RIVERS FLOWING TOWARDS THE EQUATOR. EASTERN HEMISPHERE.

	Mouth of River.			Retardation.		
	Latitude.	Rotary velocity.	Increase of velocity.	By sediment.	By water.	Total.
	Deg. M.	*Feet per second.*	*Feet per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*
1	64 30	654	32	47,680	64,368,000	64,415,680
2	60 45	742	22	9,828	13,267,800	13,277,628
3	61 46	719	38	28,256	38,145,600	38,173,856
4	61 20	729	16	3,260	4,401,000	4,404,260
5	59 40	767	25	3,786	5,111,100	5,114,886
6	59 40	767	17	1,503	2,029,050	2,030,553
7	59 45	765	24	4,838	6,531,300	6,536,138
8	55 20	864	2	40	54,000	54,040
9	42 55	1,112	7	385	519,700	520,085
10	40 10	1,161	17	2,396	3,234,600	3,236,996
11	40 50	1,149	32	31,480	42,498,000	42,529,480
12	39 10	1,178	32	11,920	16,092,000	16,103,920
13	38 25	1,187	1	48	64,800	64,848
14	26 00	1,364	2	40	54,000	54,040
15	23 20	1,395	13	173	233,550	233,723
16	22 53	1,399	13	9,530	12,865,500	12,875,030
17	33 45	1,263	47	386,797	522,175,950	522,562,747
18	20 32	1,423	21	13,143	17,743,050	17,756,193
19	20 00	1,427	1	10	13,500	13,510
20	10 05	1,496	41	216,399	292,138,650	292,355,049
21	16 10	1,459	56	251,125	339,018,750	339,269,875
22	22 00	1,408	82	5,187,040	7,002,504,000	7,007,691,040
23	22 00	1,408	62	1,463,818	1,976,154,300	1,977,618,118
24	22 00	1,408	61	2,694,633	3,637,754,550	3,640,449,183

Rivers flowing towards the Equator. Eastern Hemisphere.

Name of River or District.	River Basin.					
	Area.	Latitude of centre.	East of outlet.	West of outlet.	Rotary velocity.	
	Sq. Miles.	Deg. M.	Deg. M.	Deg. M.	Feet per second.	
Khaladaing	27,400	21 15	...	0 20	1,416	1
Braming and Coyle	31,000	22 12	...	1 26	1,406	2
Mahanuddy	41,300	21 02	...	3 55	1,418	3
N. W. coast Bay of Bengal	24,000	19 15	...	0 32	1,434	4
Godavery	133,000	19 35	...	3 25	1,431	5
Kishna	104,900	16 45	...	4 35	1,455	6
W. coast Bay of Bengal	8,300	15 45	...	0 18	1,462	7
Penaur	17,900	14 45	...	1 30	1,469	8
Palar	23,700	12 52	...	1 20	1,481	9
Cauvery	25,000	11 45	...	1 53	1,487	10
Tapty	23,600	21 15	2 50	...	1,416	11
Nurbudda	21,600	22 14	3 45	...	1,406	12
Sukernully	29,700	23 27	0 25	...	1,394	13
Jahu	48,300	26 25	2 20	...	1,360	14
Indus	346,300	33 30	5 20	...	1,267	15
Helmund	124,000	32 42	3 25	...	1,278	16
N. coast of Arabian Sea	93,000	26 30	1 00	...	1,359	17
N. E. coast of Persian Gulf	66,000	29 00	0 45	...	1,329	18
S. coast of Arabia	96,000	15 20	...	0 50	1,465	19
Euphrates and Tigris	282,100	35 05	...	4 35	1,243	20
Kour	95,400	39 55	...	3 32	1,165	21
Oural	126,300	50 04	2 01	...	975	22
Don	195,400	48 56	1 48	...	998	23
Emba district	37,800	47 50	3 00	...	1,020	24

RIVERS FLOWING TOWARDS THE EQUATOR. EASTERN HEMISPHERE.

	MOUTH OF RIVER.			RETARDATION.		
	Latitude.	Rotary velocity.	Increase of velocity.	By sediment.	By water.	Total.
	Deg. M.	*Feet per second.*	*Feet per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*
1	20 30	1,423	7	527	711,450	711,977
2	21 15	1,416	10	1,209	1,632,150	1,633,359
3	20 28	1,423	5	403	544,050	544,453
4	18 20	1,442	8	600	810,000	810,600
5	16 50	1,454	23	27,498	37,122,300	37,149,798
6	16 10	1,459	4	656	885,600	886,256
7	15 30	1,464	2	13	17,550	17,563
8	14 35	1,470	1	7	9,450	9,457
9	12 40	1,482	1	9	12,150	12,159
10	10 55	1,492	5	244	329,400	329,644
11	21 10	1,417	1	9	12,150	12,159
12	21 48	1,410	4	135	182,250	182,385
13	22 30	1,403	9	943	1,273,050	1,273,993
14	24 52	1,378	18	6,110	8,248,500	8,254,610
15	24 00	1,388	121	5,140,969	6,940,308,150	6,945,449,119
16	31 52	1,290	12	6,975	9,416,250	9,423,225
17	25 15	1,374	15	8,184	11,048,400	11,056,584
18	27 50	1,343	14	5,049	6,816,150	6,821,199
19	13 50	1,475	10	3,744	5,054,400	5,058,144
20	30 05	1,314	71	555,525	749,958,750	750,514,275
21	39 52	1,166	1	37	49,950	49,987
22	47 02	1,035	60	177,609	239,772,150	239,949,759
23	47 06	1,034	39	98,921	133,543,350	133,642,271
24	46 50	1,039	19	5,330	7,195,500	7,200,830

RIVERS FLOWING TOWARDS THE EQUATOR. EASTERN HEMISPHERE.

NAME OF RIVER OR DISTRICT.	RIVER BASIN.					
	Area.	Latitude of centre.	East of outlet.	West of outlet.	Rotary velocity.	
	Sq. Miles.	*Deg. M.*	*Deg. M.*	*Deg. M.*	*Feet per second.*	
Volga	557,700	55 00	...	0 10	871	1
Kuban	34,600	44 50	2 55	...	1,077	2
Rioni	17,900	42 38	0 50	...	1,118	3
Syrian Mediterranean rivers	8,800	33 40	1 10	...	1,265	4
Jordan district	12,400	32 20	0 35	...	1,285	5
Schoon	12,000	47 40	0 15	...	1,023	6
Axon and others	23,600	47 32	2 00	...	1,026	7
Minder	9,900	47 40	1 35	...	1,023	8
Sarabat	8,300	48 22	1 15	...	1,009	9
Dnieper	181,000	51 25	...	0 33	947	10
Bug and Indul	27,400	49 05	...	1 21	995	11
Dneister	30,500	48 32	...	2 08	1,006	12
Maritza	23,700	42 00	...	0 22	1,129	13
Striman	13,000	41 28	...	0 30	1,138	14
Vardar	12,300	41 20	...	0 10	1,141	15
Drin	9,500	42 10	0 25	...	1,126	16
Donau	293,100	46 25	...	9 50	1,047	17
Tornea and Kemi district	41,700	67 20	...	0 05	585	18
Wester Botten	36,900	65 50	...	2 55	622	19
Wester Norrland	26,200	63 30	...	1 58	678	20
River Dahl district	20,300	61 16	..	2 00	730	21
Clara and Gotha Elv	16,700	59 40	1 45	...	767	22
Mälar district	9,400	59 45	...	1 10	765	23
Eastern part of South Sweden	5,800	56 55	...	1 00	829	24

Rivers flowing towards the Equator. Eastern Hemisphere.

	Mouth of River.			Retardation.		
	Latitude.	Rotary velocity.	Increase of velocity.	By sediment.	By water.	Total.
	Deg. M.	*Feet per second.*	*Feet per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*
1	46 10	1,052	181	7,137,026	9,634,985,100	9,642,122,126
2	44 42	1,080	3	121	163,350	163,471
3	42 15	1,124	6	251	338,850	339,101
4	33 22	1,268	3	30	40,500	40,530
5	31 48	1,290	5	121	163,350	163,471
6	46 45	1,041	18	1,518	2,049,300	2,050,818
7	46 40	1,042	16	2,360	3,186,000	3,188,360
8	47 30	1,026	3	35	47,250	47,285
9	48 18	1,010	1	3	4,050	4,053
10	46 40	1,042	95	638,115	861,455,250	862,093,365
11	46 42	1,042	47	23,646	31,922,100	31,945,746
12	46 20	1,049	43	22,029	29,739,150	29,761,179
13	40 45	1,148	19	3,342	4,511,700	4,515,042
14	40 55	1,148	10	507	684,450	684,957
15	40 32	1,154	13	812	1,096,200	1,097,012
16	41 40	1,135	9	302	407,700	408,002
17	45 15	1,069	22	55,396	74,784,600	74,839,996
18	65 52	621	36	21,111	28,499,850	28,520,961
19	64 40	650	28	11,301	15,256,350	15,267,651
20	62 20	705	27	7,460	10,071,000	10,078,460
21	60 35	750	20	3,172	4,282,200	4,285,372
22	57 48	809	42	11,506	15,533,100	15,544,606
23	59 25	773	8	235	317,250	317,485
24	56 15	844	15	510	688,500	689,010

RIVERS FLOWING TOWARDS THE EQUATOR. EASTERN HEMISPHERE.

NAME OF RIVER OR DISTRICT.	RIVER BASIN.					
	Area.	Latitude of centre.	East of outlet.	West of outlet.	Rotary velocity.	
	Sq. Miles.	*Deg. M.*	*Deg. M.*	*Deg. M.*	*Feet per second.*	
Western part of South Sweden.	6,600	57 30	0 42	...	817	1
Glommen and Lauven district..	21,300	60 52	...	0 04	740	2
Southern part of Norway......	9,500	59 18	...	0 15	776	3
E. coast of Adriatic............	17,200	43 50	0 20	...	1,096	4
Gulf of Taranto and Ionian Sea.	7,500	40 00	...	0 25	1,164	5
Western part of South Italy...	11,900	41 15	0 30	...	1,142	6
Tiber.........................	7,200	42 42	0 17	...	1,116	7
Arno and W. coast Central Italy	8,900	43 25	0 32	...	1,103	8
Etsch district.................	12,000	46 15	...	0 34	1,050	9
Po...........................	28,100	45 25	...	3 10	1,065	10
Rhone.......................	38,000	45 42	0 41	...	1,061	11
Ter and Slobregat............	11,200	42 45	...	0 25	1,115	12
Ebro	33,200	42 06	...	2 20	1,127	13
Guadalaviar..................	8,900	40 10	...	0 54	1,161	14
Jucar.........................	8,100	39 15	...	1 15	1,176	15
Segura	8,200	38 10	...	1 20	1,194	16
Guadalquiver.................	20,000	37 40	2 02	...	1,202	17
Guadiana....................	25,700	38 25	2 00	...	1,190	18
Caldoa........................	7,100	37 48	0 20	...	1,200	19
Tagus.........................	28,900	40 00	3 50	...	1,164	20
Duero.........................	38,700	41 30	3 05	...	1,139	21
Minho	10,600	42 41	1 15	...	1,117	22
Rivers of Great Britain.........	46,015	...	...	...	...	23
Rivers of Ireland.............	16,224	...	...	...	...	24

RIVERS FLOWING TOWARDS THE EQUATOR. EASTERN HEMISPHERE.

	MOUTH OF RIVER.			RETARDATION.		
	Latitude.	Rotary velocity.	Increase of velocity.	By sediment.	By water.	Total.
	Deg. M.	*Feet per second.*	*Feet per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*
1	56 40	835	18	835	1,127,250	1,128,085
2	59 10	779	39	12,658	17,088,300	17,100,958
3	58 10	801	25	2,320	3,132,000	3,134,320
4	43 30	1,102	6	241	325,350	325,591
5	39 30	1,172	8	188	253,800	253,988
6	40 40	1,152	10	467	630,450	630,917
7	41 45	1,133	17	814	1,098,900	1,099,714
8	43 00	1,111	8	223	301,050	301,273
9	45 00	1,074	24	2,700	3,645,000	3,647,700
10	44 50	1,077	12	1,412	1,906,200	1,907,612
11	43 25	1,103	42	26,182	35,345,700	35,371,882
12	42 40	1,117	2	18	24,300	24,318
13	41 02	1,146	19	4,681	6,319,350	6,324,031
14	39 20	1,175	14	681	919,350	920,031
15	39 00	1,180	4	51	68,850	68,901
16	38 06	1,195	1	3	4,050	4,053
17	36 42	1,218	16	2,000	2,700,000	2,702,000
18	36 48	1,216	26	6,785	9,159,750	9,166,535
19	37 40	1,202	2	11	14,850	14,861
20	38 50	1,183	19	4,075	5,501,250	5,505,325
21	41 15	1,142	3	135	182,250	182,385
22	42 28	1,121	4	66	89,100	89,166
23	...	...	...	1,181	1,594,350	1,595,531
24	...	...	...	921	1,243,350	1,244,271

RIVERS FLOWING TOWARDS THE EQUATOR. WESTERN HEMISPHERE.

NAME OF RIVER OR DISTRICT.	RIVER BASIN.					
	Area.	Latitude of centre.	East of outlet.	West of outlet.	Rotary velocity.	
	Sq. Miles.	*Deg. M.*	*Deg. M.*	*Deg. M.*	*Feet per second.*	
Bastard, Pentecost	33,000	50 50	...	0 05	959	1
Saguenay	27,800	49 02	...	2 45	996	2
St. John, Penobscot	34,400	46 40	...	1 00	1,042	3
Kennebec, Androscoggin, Saco	13,000	44 45	...	0 20	1,078	4
Merrimack	7,100	43 20	...	0 38	1,105	5
Connecticut	10,800	43 20	0 02	...	1,105	6
Hudson, Housatonic	16,000	42 30	0 04	...	1,120	7
Delaware	11,500	41 00	0 03	...	1,146	8
Susquehanna	27,200	41 14	...	0 52	1,142	9
Potomac, Rappahannock	16,000	39 00	...	1 15	1,180	10
James	13,100	37 32	...	1 32	1,204	11
Roanoke, Tar	18,800	36 36	...	1 40	1,220	12
Santee, Neuse	44,100	34 40	...	1 25	1,249	13
Savannah and others	51,200	32 51	...	1 05	1,276	14
Alabama district	128,700	31 30	0 25	...	1,295	15
Mississippi	1,244,000	40 55	...	7 10	1,148	16
Colorado, Brazos, Trinidad ..	191,200	31 12	...	1 50	1,300	17
Rio del Norte	215,500	29 50	...	6 40	1,318	18
Colorado	267,000	36 04	1 06	...	1,228	19
E. coast Gulf of California ...	140,000	28 06	1 10	...	1,340	20

RIVERS FLOWING TOWARDS THE EQUATOR. WESTERN HEMISPHERE.

	Mouth of River.			Retardation.		
	Latitude.	Rotary velocity.	Increase of velocity.	By sediment.	By water.	Total.
	Deg. M.	*Feet per second.*	*Feet per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*
1	49 08	994	35	15,790	21,316,500	21,332,290
2	48 00	1,017	21	4,788	6,463,800	6,468,588
3	45 20	1,068	26	9,081	12,259,350	12,268,431
4	43 55	1,094	16	1,300	1,755,000	1,756,300
5	42 48	1,114	9	225	303,750	303,975
6	41 10	1,143	38	6,091	8,222,850	8,228,941
7	40 42	1,152	32	6,400	8,640,000	8,646,400
8	39 35	1,172	26	3,036	4,098,600	4,101,636
9	39 32	1,172	30	9,561	12,907,350	12,916,911
10	38 02	1,197	17	1,806	2,438,100	2,439,906
11	36 52	1,215	11	619	835,650	836,269
12	35 52	1,221	11	888	1,198,800	1,199,688
13	33 42	1,264	15	3,881	5,239,350	5,243,231
14	31 52	1,290	14	3,917	5,287,950	5,291,867
15	30 15	1,312	17	14,543	19,633,050	19,647,593
16	29 08	1,327	179	14,323,668	19,336,951,800	19,351,275,468
17	28 40	1,333	33	81,354	109,827,900	109,909,254
18	25 30	1,371	53	236,457	319,216,950	319,453,407
19	32 15	1,285	57	338,890	457,501,500	457,840,390
20	27 00	1,353	13	9,240	12,474,000	12,483,240

Rivers flowing towards the Equator. Western Hemisphere.

Name of River or District.	River Basin.					
	Area.	Latitude of centre.	East of outlet.	West of outlet.	Rotary velocity.	
	Sq. Miles.	*Deg. M.*	*Deg. M.*	*Deg. M.*	*Feet per second.*	
Kalamath and Tsashtl.......	42,900	42 00	1 15	...	1,129	1
Columbia..................	283,400	45 52	7 02	...	1,058	2
Frazer.....................	138,300	51 28	...	0 40	946	3
Simpson and Frances district.	53,600	56 40	2 00	...	835	4
Atna or Copper............	34,900	62 12	0 05	...	708	5
Bolsas, Yopez, Verde........	71,500	18 00	0 05	...	1,445	6
Sirano district	24,700	14 00	0 10	...	1,474	7
San Juan de Nicaragua......	23,700	12 00	...	1 20	1,486	8
Sacramento	33,000	40 00	...	0 08	1,164	9
Parahyba and Grande.......	37,600	6 40	...	1 50	1,509	10
Ciara, Croayhu..............	33,700	5 08	...	0 05	1,513	11
Jaguaribe..................	19,900	5 50	...	0 30	1,511	12
Belmonte and Doce dist......	114,400	17 25	...	1 48	1,449	13
Parahyba (South)	35,800	22 00	...	2 12	1,408	14
San Francisco...............	247,600	14 00	...	7 00	1,475	15
Paranahyba	157,300	8 05	...	2 30	1,504	16
Maranhao and Itaqieura.....	59,600	5 00	...	0 40	1,513	17
Gurupy and Turyassu.......	49,000	3 20	...	1 00	1,516	18
Tocantins..................	376,000	10 10	...	1 00	1,495	19
Amazon	2,236,000	6 20	...	12 50	1,510	20

RIVERS FLOWING TOWARDS THE EQUATOR. WESTERN HEMISPHERE.

	MOUTH OF RIVER.			RETARDATION.		
	Latitude.	Rotary velocity.	Increase of velocity.	By sediment.	By water.	Total.
	Deg. M.	*Feet per second.*	*Feet per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*	*Foot-pounds per second.*
1	41 45	1,133	4	268	361,800	362,068
2	45 48	1,059	1	111	149,850	149,961
3	49 02	996	50	135,050	182,317,500	182,452,550
4	55 10	871	36	27,135	36,632,250	36,659,385
5	60 20	752	44	26,393	35,630,550	35,656,943
6	16 42	1,455	10	2,788	3,763,800	3,766,588
7	13 30	1,477	3	86	116,100	116,186
8	11 15	1,490	4	148	199,800	199,948
9	37 50	1,200	36	16,706	22,553,100	22,569,806
10	5 40	1,512	3	132	178,200	178,332
11	3 10	1,517	4	211	284,850	285,061
12	4 30	1,514	3	70	94,500	94,570
13	17 00	1,453	4	715	965,250	965,965
14	21 30	1,413	5	349	417,150	417,499
15	10 20	1,494	19	34,912	47,131,200	47,166,112
16	2 58	1,517	13	10,382	14,015,700	14,026,082
17	2 50	1,517	4	373	503,520	503,893
18	1 00	1,519	3	172	232,200	232,372
19	2 00	1,518	23	77,738	104,946,200	105,023,938
20	1 25	1,519	9	70,993	95,840,550	95,911,543

The *last* column of the preceding tables contains the amount of retardation caused by the waters of rivers flowing towards the equator. The computation of the retarding energy being based on the weight of water discharged and the increase of rotary velocity acquired during the transfer from the source to the outlet, no question can be raised as to the existence of the retardation entered in the tables; but whether compensating energies are called forth by the returning vapors before the condensation takes place which results in the precipitation on the river basins, demands careful consideration. Dr. Mayer, in his discourse previously adverted to, positively asserts that, agreeably to the demonstration of Laplace, based on abstract mechanical principles, the compensating energy corresponds in every instance with the amount of retardation to which the rotary motion of the globe may be subjected. Admitting this conclusion to be correct, we must assume the adequacy of the *vapors* which rise within the tropics to restore, during their transfer to the temperate and polar regions, the loss of *vis viva* occasioned by the condensed water which, in the form of rivers, flows towards the equator. Obviously, such restoration of energy could only be effected by friction or pressure of the vapors against projections on the earth's surface directly, or through the intervention of particles of the atmospheric air put in motion by the vapors. The Astronomer-Royal of Sweden, in an elaborate demonstration presented to the Royal Academy of Sciences at Stockholm, in refutation of my assertion that solar influence is capable of diminishing perceptibly the rotary velocity of the earth, thus states the case: "The globe and its atmosphere constitute a combined system in motion, in which no part can by any outside cause be disturbed in its relative position without the motion of the entire system being thereby influenced. Consequently, a body of air which, for instance, is carried from the direction of the equator towards either of the poles must, by degrees, positively part with the excess of rotary *vis viva* which it possessed at the commencement of the motion, compared with the rotary velocity of the region to which it has been transferred, and must impart the entire surplus to the earth undiminished, the rotation of which must consequently be accelerated by this current of air; and, conversely, a current of air of contrary direction, or from either of the poles towards the equator, must produce retardation. No difference can exist in this respect between a current of water and a current of air." The Swedish astronomer, like Laplace, thus puts the whole question in a nutshell, asserting that air and water, water and air, may circulate in any manner whatever between the equator and the poles, and between the poles and the equator, without influencing the axial rotation of the globe. It is very true that the earth, with its rivers and atmosphere, constitute a "combined system in motion"; but we must not lose sight of the important fact that an *outside* energy—the sun's radiant heat—is being continually exerted, which interferes with the motions within that combined system. Accordingly, no argument can prove the correctness of the statement laid before the

Royal Academy of Sciences at Stockholm short of a positive demonstration showing that particles of vapor corresponding in weight with the water discharged by some river—say the Mississippi—are capable of imparting by friction against the earth's surface, directly or through the agency of the atmosphere, a rotary force exactly balancing the retarding energy which we have established.

The advocates of the theory of compensation, while admitting that they cannot furnish any *practical* evidence of the truth of their doctrine, assert that the subject is not susceptible of experimental test. It would, indeed, be a fruitless task to undertake the construction of anemometers, or similar instruments, showing that the pressure and friction of the particles of the returning vapor, exerted directly or through atmospheric intervention against the surface of the Mississippi river basin, from west to east, are capable of compensating the established retardation of 19,336,000,000 foot-pounds per second.

The admitted impossibility of proving by direct measurement the existence of compensating force has suggested the resort to some indirect method. I have accordingly constructed an instrument which practically demonstrates the truth of the following proposition, on which the solution of the problem unquestionably depends: The retarding influence produced by currents of *water*, confined within channels which convey a given weight in a given time, from the pole to the equator of a rotating sphere, cannot be compensated by opposite currents of *vapor* transferring an equal weight in equal time over the surface of the said sphere from its equator to its pole.

The illustration on Plate 34 represents the instrument adverted to; but before entering on a description, it will be well to define clearly the problem intended to be solved by experimental demonstration. The rotary velocity of the surface of the earth, for instance, on the 45th parallel is 1,074 ft. per second, that of the equator 1,519 ft. per second; hence the water of a river flowing from lat. 45 deg. to the equator will have its velocity round the axis of the earth increased 1,519 — 1,074 = 445 ft. per second. It needs no demonstration to show that the expenditure of energy necessary to produce this increase of rotary velocity will cause the earth to rotate at a diminished rate; the amount of retarding force being readily ascertained by multiplying the weight of water transferred by the height necessary to generate a velocity of 445 ft. per second, viz., 3,094 ft. Consequently, each pound of water transferred from lat. 45 deg. to the equator demands the expenditure of a dynamic energy of 3,094 foot-pounds. The question now presents itself, whether a pound of water evaporated on the equator, and returned in the form of vapor to lat. 45 deg., can, during the return movement, impart a rotary energy of 3,094 foot-pounds to the earth. Of course the vapor, on leaving the equator, possesses a rotary velocity of 1,519 ft. per second, while the surface of the earth in lat. 45 deg. rotates, as before stated, at a rate of only 1,074 ft. per second. It will be evident, therefore, that during the return movement the vapor, by contact with the earth, will have its rotary velocity diminished in the ratio of 1,519 : 1,074. On purely theoretical considerations, it must be admitted that this contact, by which the returning pound of *vapor* has its rotary velocity diminished 445 ft. per second, will restore to the earth the whole of the energy which was previously expended in augmenting the speed of the pound of *water* from 1,074 to 1,519 ft. per second during its transfer from lat. 45 deg. to the equator. But practice shows that rotary motion cannot be imparted to cylindrical or spherical bodies, however rough their surface may be, by currents of air or steam, without great loss of mechanical energy. Conversely, currents of air or steam cannot be produced by the action of similar rotating bodies without a corresponding loss of mechanical energy.

Practical engineers familiar with these facts fully appreciate the difficulty of instituting experiments intended to determine exactly what amount of force is expended in causing rotary motion by currents, and what amount of force is developed by currents produced by rotating bodies, as supposed. The illustrated dynamic register, Plate 34, obviates this difficult comparison between energy expended and developed, by the simple expedient of applying heat and cold in such a manner that the *retarding* influence of a current of *water* flowing from the pole to the equator acts simultaneously with the *accelerating* influence of an opposite current of *vapor*, transferring equal weight in equal time, from the equator towards the pole. The detail of the instrument will be understood by the following description: Fig. I. shows a section of a hollow sphere 6.25 ins. diameter, composed of very thin brass partially filled with a light non-conducting substance, made to revolve on its vertical axis; the upper half being covered with a light semi-spherical casing, extending a short distance below the horizontal central plane of the sphere. A cylindrical cistern, provided with a flat cover, is attached to the top of the semi-spherical casing. The mode of supporting the lower pivot on which the sphere turns, as also the axle at the top, will be seen by reference to the drawing. Rotary motion is imparted to the sphere by a horizontal toothed rack (see top view, Fig. II.) working into the teeth of a wheel attached to the vertical axle; the motive power consisting of a weight suspended by a light cord passing over a pulley and secured to the rack. A circular gas-pipe, provided with a series of burners, surrounds the sphere some distance below its centre. Referring to Fig. II., it will be seen that the guide-pieces which support the horizontal rack, and through which it slides, act as stops which regulate the extent of the movement. It should be particularly noticed that the arrangement is such that when the motion is checked by the right-hand stop the last cog of the rack has just slipped out of the cog-wheel, thus allowing the sphere to turn freely. The extent of motion of the rack is 0.186 ft., and the weight exactly 2 lbs. It will be seen, therefore, that the motive force is 0.186 × 2 = 0.372 foot-pound, or 2 × 7,000 × 0.186 = 2,604 foot-grains. Deducting the loss by friction—64 foot-grains—the effective motive power will be 2,540 foot-grains. The axis of the sphere being exactly vertical, there is obviously no friction whatever at the upper bearing after the slipping of the last cog of the rack, while the lower pivot presents a mere point of hardened steel to the step under it; hence the overcoming the atmospheric resistance against the outside of the sphere and the cistern may be considered as the only work to be performed by the stated available motive power of 2,540 foot-grains. It only remains to be noticed that when the sphere is to be put in motion the rack is geared into the cog-wheel and brought up against the left-hand stop, as represented in the drawing, the check-lever (Fig. IV.) being at the same time placed in the position shown by the dotted lines. The moment for starting, indicated by the chronometer, having arrived, the check-lever is brought to the horizontal position as quickly as possible, in order to prevent dragging at the moment of liberating the toothed rack. As shown by the illustration, a small quantity of water is confined within the surrounding casing of the sphere, thus forming an aqueous belt round its equator; the polar cistern being filled with water.

The object of the instrument having been clearly set forth, it scarcely needs explanation that the device is intended to show that when the heat of the gas-flames is applied to the aqueous belt, causing evaporation, while condensation is effected by the cold water in the polar cistern, the motive energy (2,540 foot-grains) will be incapable of turning the sphere as fast and as long as when heat and refrigeration are not applied. This assumption, it will be perceived, is in direct opposition to the views held by the Astronomer Royal at Stockholm and other followers of Laplace, who contend that "no difference can exist" as regards the effect on the axial rotation of the globe between currents of water and currents of aëriform matter transferring equal weight in equal time.

The mode of conducting the experiment with the dynamic register will be readily understood by the following explanation: The polar cistern is charged with boiling water, and the gas-flames applied for a few minutes until the water round the equator is brought near boiling heat. The gas is then shut off, and the toothed rack geared and afterwards locked by the check-lever. The chronometer being then carefully observed, the check-lever should be quickly pushed down when the hand marks exact time. The motive weight, being thus liberated, puts the sphere in motion through the intervention of the rack and cog-wheel, the time elapsing between the commencement of the movement and the slipping of the last tooth of the rack occupying about one second. The observation of the chronometer should continue, in order to ascertain the exact time when the sphere is brought to rest. In the meantime, the number of turns must be accurately counted. The first experiment being concluded, the sphere is again put in motion, as before, without changing the water in the polar cistern or applying the gas-flames, the object of employing heat before starting being merely that of expanding the sphere to proper dimensions. The experiment having been repeated six times, the *mean* of time occupied and number of turns performed, resulting from the expended energy of 2,540 foot-grains, should be determined with the utmost precision. The procedure will then be changed: the polar cistern will be charged with *cold* water, and the gas-flames applied and kept burning. The sphere, under these altered conditions, is again started, but not until boiling temperature in the equatorial belt has been attained and evaporation commenced. The experiment, as before, will be repeated six times, and the mean of time and the number of turns ascertained.

The law of compensation relating to solar influence on the axial rotation of the earth, expounded by Dr. Mayer, is evidently strictly applicable to the dynamic register, since the equatorial belt of the rotating sphere is being continually heated, while the polar region is being exposed to continuous refrigeration, vapor being thus formed at the equator, and currents produced which condense on reaching the cold semi-spherical covering over the pole. The water thus formed, divided into small streams, flows back on the surface of the sphere to the equator, where it is again converted into vapor; hence a continued circulation of opposite currents of vapor and water will be kept up. It should be particularly observed that the vapor in its passage towards the pole not only acts against the surface of the sphere, but also against the inside of the semi-spherical covering, thereby affording a double chance of imparting motion to the rotating mass. But this notwithstanding, the experiments have shown that the *retarding* energy of the condensed water flowing in small streams from the pole to the equator on the surface of the sphere, greatly exceeds the *accelerating* energy imparted by the excess of rotary velocity of the vapor in its course towards the pole, and the consequent friction of its particles against the surfaces of the sphere and the semi-spherical casing. Agreeably to Dr. Mayer's conclusions, founded on the theory of Laplace, the opposite currents which result from high temperature on the equator, and the refrigeration over the temperate zone and the poles, cannot affect the axial rotation of the globe. "The effect of every single motion by these means on the rotation of the globe," he says, "is exactly compensated by the effect of another motion in an opposite direction." Nor can the Swedish Astronomer, as we have seen, perceive any difference between currents of water and currents of aëriform matter. In direct opposition to the conclusions of these physicists, our experiments prove that, although the weight transferred from the pole to the equator of the sphere of the dynamic register is precisely the same as the weight which is transferred in the opposite direction, the contact and friction of the particles of vapor against the surfaces of the convex and concave spheres is incapable of restoring the loss of *vis viva* consequent on imparting rotary motion to the particles of water transferred from the pole to the equator.

Too much space would be occupied by a detailed account of the experiments which have been made with the dynamic register; hence only the most important facts bearing directly on the question will be presented. The number of turns of the rotating sphere produced by the motive force of 2,540 foot-grains has been 660.5, occupying 10 min. 37 sec., the barometer at the time indicating 29.8, the temperature of the surrounding atmosphere being 62° F. The mean of the force expended for each turn will therefore amount to $\frac{2,540}{660.5} = 3.84$ foot-grains. It will be asked, in view of this insignificant motive power, chiefly expended in overcoming the atmospheric resistance against the rotating sphere and cistern, how the excess of retarding energy of the condensed water flowing over the surface of the sphere, from the pole to the equator, can possibly be measured. The answer is that we need not consider the amount of energy developed by the motive weight; we merely count the number of turns and note the time required to bring the sphere to a state of rest from the moment of starting, the gas-flames being kept burning and the refrigerating medium retained in the polar cistern during the observations. Then, removing the cooling medium and replacing the same with boiling water, we again put the sphere in motion, count the number of turns, and note the time. The result of this change of procedure will be, as shown by our experiments, that the sphere will run much longer and perform a greater number of turns—a startling fact, since the motive energy of 2,540 foot-grains has not been increased. To practical minds the explanation will at once suggest itself, that because there is an *expenditure of heat* while condensation is kept up, which ceases when the refrigerating medium is withdrawn, some additional work is being performed while the cold medium remains at the pole. Now, what is the nature of this work? Evidently the condensed water, while flowing from the pole to the equator, has its rotary speed successively increased corresponding with that of the surface of the sphere; hence work must be performed while refrigeration is kept up at the pole. Satisfactory as this explanation appears, it is met by the cardinal objection that, since force cannot be annihilated, the opposite current of *vapor*, which simultaneously transfers an equal weight from the equator to the pole of the rotating sphere, must, by friction or contact of some kind, positively return the whole of the mechanical energy expended in augmenting the rotary velocity of the particles of water moving in a contrary direction. This notwithstanding, we must accept the *fact* proved by the dynamic register, that a certain amount of mechanical energy *disappears* when the rotating sphere is subjected to the action of differential temperatures. There was a time when we could not account for such disappearance of energy, but—thanks to the labors of Joule and Mayer—the mechanical theory of heat has thrown light on the subject. The theoretical deductions of Laplace have lost their potency. We no longer confine ourselves to the balance and rule in measuring the result of expended force. Joule and Mayer have taught us to consult also the *ther-*

mometer during our investigations. Bearing in mind, then, what the new theory of heat teaches, the disappearance of mechanical energy during the experiments with the dynamic register ceases to be a puzzle. Close investigation shows that the heat resulting from the arrested motion of the circulating vapor, which, on leaving the aqueous belt, possesses a rotary velocity equal with that of the circumference of the sphere, represents very nearly an equivalent of the observed loss of energy, the difference being made up by heat generated by the particles of the circulating vapor as they successively impinge against the minute projections of the surface of the convex and concave spheres. Obviously, the heat thus generated is carried off by the cold semi-spherical casing surrounding the sphere of the dynamic register, precisely as heat produced by analogous motions within the terrestrial atmosphere is carried off by radiation into space. In either case the heat lost is an equivalent of the mechanical energy abstracted from the rotating sphere.

Illustrations and descriptions have been prepared explanatory of important modifications of the dynamic register delineated on Pl. 34, adopted in order to control the irregular resistance of the atmospheric air against the rotating sphere, unavoidable in employing gas-flames for heating the equatorial belt; but the subject having already occupied too much space, I now propose to state only the result of the experiments which have been made with the modified instrument, the dimensions of which, it should be observed, have been considerably increased, the motive power, however, remaining unchanged. It is scarcely necessary to remark that a complete demonstration and record of an investigation of this complicated nature would present an array of figures inadmissible in this work. The diagram on Pl. 35 has, therefore, been devised to dispense with figures; the relations of time, velocity, and resistance being presented in such a manner that, among other facts, the amount of mechanical energy which disappears during the experiment may be ascertained by mere inspection. For the purpose of saving space and facilitating direct comparison, this diagram has, moreover, been so arranged that the record of the experiments in which heat and refrigeration have been employed is placed on the same base-line with the record of the experiments in which difference of temperature was presented. The divisions on the base-line *a b* mark the time of rotation, the large spaces indicating minutes and the smaller divisions 10 sec. each. The length of the ordinates of the curve *c b* resting on the base-line represents the number of turns performed in a given time when the rotating sphere is not subjected to the action of heat and refrigeration; while the length of the ordinates of the curve *d e* represents the number of turns when heat and cold are being applied. It will be readily perceived that, for instance, the ordinate between 1 and the curve *c b* represents the number of turns per minute at the commencement of the second minute, while the ordinate 2 represents the number of turns per minute at the commencement of the third minute, and so on for all the other ordinates.

The *permanent* friction of the instrument—*i.e.*, the friction of the pivot on which the sphere turns—being practically inappreciable, it will be evident that the resistance opposing the rotation will vary in the ratio of the square of the velocities. Hence, as the respective ordinates between the curves *c b* and *d e* and the base-line represent the *velocities*, it will only be necessary to square these ordinates in order to determine the exact amount of resistance to the periods indicated by the divisions on the base. Accordingly, the ordinates mentioned have been prolonged in the ratio of their squares, the curves *f b* and *g e* being the result of this prolongation. Obviously, the lengths of the ordinates of these curves resting on the line *a b* represent accurately the amount of resistance opposed to the rotation of the sphere at the times indicated by their intersection with that line. The rate of velocity—*i.e.*, the number of turns per minute performed by the sphere at the commencement and at the termination of each minute—will be found by referring to the figures marked on the vertical lines *f a* and *l b*. Thus, for instance, the rate of velocity at the termination of the second minute is 75.4 turns when refrigeration is *not* applied, while the rate is 68.0 when the cooling medium is applied at the pole. As might be expected from the irregular nature of the external resistance opposed to the rotating mass, the curves *f b* and *g e* do not correspond with any of the conic sections. The available motive power of 2,540 foot-grains *expended* during the experiment is represented by the superficies *f a b*, the energy *developed* being represented by the superficies *g a e*. Assuming the former to be 1.000, the latter, as shown by our diagram, will be 0.763, difference = 0.237; hence the amount of lost energy is 0.237 × 2,540 = 601.98 foot-grains. Now, if the weight of water which is condensed at the pole and returned to the equator, multiplied by the height necessary to generate the rotary velocity acquired during the transit, should amount to 601.98 foot-grains, the fact will be established that the current of vapor has not, during its passage from the equator to the pole, restored any of the energy abstracted from the sphere by the current of water flowing in the contrary direction. The quantity of water condensed and returned to the equatorial belt being readily ascertained by observing the increment of temperature of the contents of the polar cistern, it is easy to show that the energy abstracted from the rotating mass by the water thus transferred from the pole to the equator corresponds so nearly with the differential mechanical energy represented by the superficies *f g e b*, that the compensation resulting from the tangential force exerted by the particles of the currents of vapor against the surface of the sphere of the dynamic register is inappreciable; precisely as we find that the compensating tangential force of the currents of vapor which sweep over the basin of the Mississippi from west to east (neutralized by the currents which pass from east to west) is an inappreciable fraction of the retarding energy of 19,336,000,000 foot-pounds per second, exerted by the *water* which the Mississippi carries in the direction of the equator.

Having thus analyzed the opposing energies called forth by the waters flowing towards the equator, and of the returning vapors, the condensation of which replenishes the river basins, we may now enter on a computation of the aggregate amount of the retarding energy, and the consequent diminution of the rotary velocity, of the earth, caused by the rivers enumerated in the preceding table. The total of the retarding force entered in the column next the last, it will be found, amounts to 53,857,788,300 foot-pounds per sec., which sum, multiplied by 86,400 sec., shows that the earth has to overcome a resistance of $4,653,313 \times 10^9$ foot-pounds during each revolution. Multiplying this resistance by 36,524 days, we ascertain that the retarding energy of the water transferred in the direction of the equator by the entire Southern river systems of both hemispheres amounts to $16,995,760,069 \times 10^{10}$ foot-pounds in a century. Now, in order to determine the diminution of rotary velocity consequent on this counteracting energy, it will be indispensable to compute the earth's rotary *vis viva.* The elements necessary in this computation are: volume, time of revolution, specific gravity, and the position of the centre of gyration of the rotating mass. The two first-named elements are known with desirable accuracy; the third element, specific gravity, has been ascertained with tolerable accuracy; but the position of the centre of gyration, which depends on the internal temperature of the globe and the disposition of its constituent parts, has not yet been determined. Physicists assume that the density of the globe increases towards the centre in arithmetical progression; but this assumption is not sustained by sound reasoning. Our space not admitting of discussing this complicated question at length, let us merely consider the leading fact, that, at a distance of only $\frac{1}{20}$ of the earth's radius = 1,044,400 ft. from the surface, the weight of a superincumbent mass of fused granite will exceed 900,000 lbs. to the sq. in. = 60,000 atmospheres. Under this pressure the weight of air will be 70 times that of water, and 3.5 times that of the heaviest metals. Gold, at the point of fusion, is 7 times heavier than fused granite, while neither of these solids loses more than $\frac{3}{100}$ of specific gravity at melting heat—a fact which proves conclusively that high temperature of metals and minerals is not incompatible with great density. Hence fused granite, in the earth's interior, may be many times heavier than the cold mineral at the surface. Unless, therefore, we are prepared to dispute the assumption that fused granite, under a pressure of 900,000 lbs. to the sq. in., will have its specific gravity doubled—involving a density less than one-third of fused gold not subjected to compression—we must admit that the specific gravity of the earth at the depth of $\frac{1}{20}$ of the radius is so great that, if the density, as physicists have assumed, increases in arithmetical progression towards the centre, our planet would be many times heavier than it is. We are compelled, therefore, to reject the accepted theory, more especially as the stated enormous pressure consequent on superincumbent weight takes place at only $\frac{1}{20}$ of the earth's radius below the surface.

In accordance with the foregoing reasoning, our computation of the earth's rotary *vis viva* will be based on the assumption that the mass is *homogeneous.* It is true that the specific gravity at the surface is somewhat less than one-half that of the entire mass; but we have shown that at a depth of $\frac{1}{20}$ of the radius from the surface the density is so great that if it continued to augment in arithmetical progression, the specific gravity of the globe would far exceed that which has been determined by careful investigation. Nor should we lose sight of the important fact that the temperature corresponding with the compression produced by the superincumbent weight is so great that the component parts of the central mass may be as light as pumice, notwithstanding the enormous external pressure. Consequently, it may be satisfactorily demonstrated that the earth's circle of gyration extends considerably *beyond*, in place of being within, that of a *homogeneous* sphere, agreeably to the accepted theory of augmented density towards the centre. In our computations, however, we will assume that the circle of gyration is that corresponding with homogeneity, which, in accordance with the property of spheres, is 0.6325 of the great circle. Sir John Herschel's determination shows that the mean diameter of the earth, considered as a perfect sphere, is 7,912.41 statute miles, or 41,777,524 ft.; hence, if we assume the specific gravity to be 5.5, we can readily calculate that the weight is $1{,}308{,}608 \times 10^{19}$ lbs. Multiplying the equatorial velocity—1,519.07 ft. per second—by 0.6325, we ascertain that the mean rotary velocity of the entire mass of the earth is 960.81 ft. per second—a rate acquired by a fall of 14,424 ft. The earth's rotary *vis viva* will accordingly amount to $14{,}424 \times 1{,}308{,}608 \times 10^{19} = 18{,}875{,}361 \times 10^{22}$ foot-pounds. The mind being utterly incapable of conceiving this stupendous energy without comparison with mechanical energies of less magnitude, let us ascertain to what extent it will be diminished by the retardation exhibited in the tables previously presented—namely, $16{,}995{,}760{,}069 \times 10^{10}$ foot-pounds, exerted in the course of a century by the southern river systems of both hemispheres. Dividing the stated retarding energy in the earth's *vis viva*, thus: $\frac{18{,}875{,}361 \times 10^{22}}{16{,}995{,}760{,}069 \times 10^{10}}$, we find that, notwithstanding the enormous amount of retardation exerted in a century, only $\frac{1}{11106000000}$ of the rotary energy of the earth will be destroyed in that time. And if we multiply the fraction thus presented by 10,000, we learn that at the end of 1,000,000 years the rotary energy of the earth will be only $\frac{1}{111060}$ less than at present! By no other comparison, probably, than the one we have instituted could we clearly comprehend the magnitude of $18{,}875{,}361 \times 10^{22}$ foot-pounds of mechanical energy.

Let us now calculate the effect of the tabulated resistance on the earth's rotary velocity with reference to *time.* The retardation observed by astronomers being, as before stated, about 12 sec. in a century, our object will be to ascertain how far this retardation may be attributed to the counteracting energy under consideration. Multiplying, then, the number of seconds in a century, 3,155,673,600, by the retarding energy of 53,857,780,300 foot-pounds per second, entered in the table, we establish the fact before adverted to, that the total retardation is $16,995,760,069 \times 10^{10}$ foot-pounds in one century. Dividing this retardation in the *vis viva*, it will be seen that the earth loses $\frac{1}{1110592343}$ of its rotary energy in the course of 100 years; but in calculating the *time* corresponding with this loss, we have to consider that the velocities are as the square root of the forces, and that consequently the rotary velocity will not be reduced as rapidly as the rotary energy. Evidently, if the diminution of energy and velocity corresponded exactly, the retardation of the earth's rotary motion during one century would be $\frac{3,155,673,600}{1,110,592,343} = 2.8414$ sec. But, in accordance with the laws of motion referred to, the diminution of velocity during the century will be in the ratio of the square roots of the earth's *vis viva* at the beginning and at the termination of that period. Now, this ratio being readily computed, as we know the amount of energy lost in one century, while the time in seconds is also known, we are enabled to show, by an easy calculation, that the earth suffers a retardation of 1.42071 sec. Adding the retardation occasioned by the tabulated sedimentary matter = 0.00105 sec., ascertained in the manner explained, the total retardation of the earth's rotary velocity in a century, at the *present* epoch, will be 1.42176 sec. The vastness of the rotary *vis viva* of the earth having already been discussed, it will not be necessary to offer any explanations with reference to the insignificance of the stated retardation in comparison with the magnitude of the counteracting energy exerted by the water and sediment of the entire river system presented in our tables.

We have now to consider the influence on the earth's rotary energy exercised by rivers, the course of which is in the direction of the poles. Evidently river water running *from* the equator will have its motion round the axis of rotation continually diminished as it reaches the northern parallels; hence rotary energy will be imparted to the earth by all rivers flowing towards the poles. At first sight, it will be imagined that the energy thus imparted will neutralize the retarding force exerted by the waters transferred towards the equator. Certain physical causes, however, prevent the imparted energy from restoring any of the earth's lost *vis viva.* The subject will be most readily comprehended by an examination of the nature of the neutralizing force exerted by the following great rivers, namely, the Lena, Yenesei, Obi, and Mackenzie, which furnish the principal amount of water discharged into the Arctic Ocean. These rivers drain an area of 3,840,000 sq. miles, the latitude of the centre of their basins and their outlets being very nearly in the same parallel. The mean of the former is 59 deg. 30 min., that of the latter 69 deg. 56 min. Accordingly, the mean circumferential velocity of outlet is 421.18 ft. per second, while that of the centre of basin is 770.95 ft. per second. It will be seen, therefore, that a diminution of rotary velocity of 770.95 − 521.18 = 249.77, say 250 ft. per second, takes place during the transfer of the water from the centre of the basins of these rivers to their outlets. Now, a velocity of 250 ft. per second is produced by a fall of 976.5 ft., hence each *pound* of water discharged into the Arctic Ocean by the before-named rivers will impart a mechanical energy of 976.5 foot-pounds. Apart from this powerful neutralizing force of a given weight, the quantity of water transferred is so great, owing to the vast extent of the basins, that, notwithstanding the moderate precipitation in high latitudes, the rotary energy imparted to the earth will balance the retardation of the 136 rivers entered in our tables. It scarcely requires explanation that the stated enormous force exerted by the water transferred by the great northern rivers is owing to the rapid diminution of rotary velocity in approaching the pole; a single degree of latitude at the point where, for instance, the river Lena discharges into the Arctic Sea having a greater fall than *ten* degrees have within the tropics. It would be waste of time, however, to compute the exact amount of energy imparted to the earth by the Arctic rivers, as will be seen by the following examination of the subject. Unquestionably, if the supposed pound of water, on entering the Arctic Ocean, at once evaporates and ascends into the atmosphere, we must admit that an impulse of 976.5 foot-pounds has been imparted to the earth by its transfer from the centre of the river basin; but if it should be found that, in place of evaporating on entering the cold polar sea, the pound of water commences a retrograde motion towards the equator through Behring's Straits or through the wide channel between Norway and Greenland; and if we should find, also, that when it crosses the 59 deg. 30 min. parallel (the same as that of the centre of the river basin) it has not yet been converted into vapor, we must then admit that the whole of the energy imparted to the earth by the *approach* towards the axis of rotation, during the original transfer to the polar sea, has been completely neutralized by the retardation consequent on the *retreat* from the axis of rotation during the southerly course to the last-mentioned latitude. Following our pound of water during the continuation of the motion towards the equator, we may discover that it has not changed its form into vapor, even when reaching latitude 47 deg. 45 min., at which point the circumferential velocity is exactly 250 ft. per second greater than that of the centre of the basin from whence the motion proceeded. In that case, not only has the imparted energy been neutralized, but a *retardation* of 976.5 foot-pounds has been called forth by the pound of water, the course of which may possibly continue until it mixes with the warm water within the tropics. Let us guard against confounding the movement of the water discharged into the Arctic Sea by the northern rivers with the currents produced by the combined influence of lunar attraction, winds, differential oceanic temperature, and solar attraction. It has long been recognized that the water poured into the Arctic Sea by the great Asiatic rivers is the result of condensation of vapors raised by the sun within or near the tropics. A corresponding amount of water must, therefore, be returned from the polar sea, or its surface would be elevated, and that of the tropical seas suffer a proportionate depression. The reader cannot fail to perceive the important bearing of these facts on the question of retardation of the earth's rotary velocity.

The result of the experiments with the dynamic register proves that the rotary motion possessed by the vapors on leaving the equatorial seas may be almost entirely destroyed by being converted into heat during their course towards the basins of the northern rivers; hence imparting no perceptible tangential force to the earth. Accordingly, the return to the tropical seas of the water which is continually being discharged by the northern rivers into the polar seas will, on account of the increased velocity round the axis of rotation imparted during the southern course, subject the earth to an amount of retardation far exceeding that produced by rivers flowing towards the equator. It may be asked, under these circumstances, why the latter rivers have been tabulated and their inferior retarding energy calculated. The rivers flowing in the direction of the poles have been examined, tabulated, and their counteracting energy calculated; but the question of attendant retardation of rotary velocity cannot properly be entertained until certain other counteracting influences shall have been examined. The publication of the table containing the southern rivers has been deemed necessary as a *point d'appui* facilitating demonstrations intended to establish the fact that, independently of the counteracting force of the tidal wave (hitherto greatly overestimated), the retarding energy called forth by the evaporation within the tropics, and the consequent condensation and precipitation in the temperate zones, fully account for the retardation of the earth's rotary velocity—12 seconds in a century—inferred from the apparent acceleration of the moon's mean motion.

The fact being well known, through European and American publications, that the results attained by the employment of the instruments described in the foregoing chapters rank among the most important scientific achievements of the latter part of the first century of the American Republic, I expected that the Centennial Commissioners would invite me to display those instruments during the Exhibition, and consequently caused the same to be repolished and arranged for the great occasion. It is proper to state that, although not wanted by the Commissioners, the time spent in preparing the collection for exhibition has not been wasted, since it is my intention to present the same to the Smithsonian Institution, after the completion of certain investigations.

CHAPTER XXIII.

DISTANCE INSTRUMENT,*

FOR MEASURING DISTANCES AT SEA. (SEE PLATE 36.)

THIS instrument is principally intended for the use of the naval officer in measuring the distance of an enemy's ship, to enable him to elevate his guns with precision. Modern naval tactics being principally based on *distant* firing, an accurate knowledge of the object to be aimed at becomes indispensable. Any device for obtaining it based on any process of *calculation* is evidently out of the question, considering that a single minute will bring two approaching vessels, moving at a rate of ten knots, full a quarter of a mile nearer each other. In firing beyond point-blank range, therefore, *seconds* are precious in determining the elevation of the guns. Accordingly, nothing will answer short of an instrument which, by a single observation and the reading off at sight, tells the distance. The instrument under consideration meets these somewhat severe conditions perfectly,

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* This instrument formed part of the original equipment of the steamship *Princeton.*

as will be seen by the following explanation. An observer stationed on the maintop or cross-tree of a ship, looking at a vessel—say a mile off—will perceive that his line of vision, directed to the horizon, passes over the point marked by the water-line of the hull, and he will also perceive that, as the vessel approaches, that point appears to sink lower and lower below the line directed to the horizon; in other words, the angle formed by that line and the line directed to the water-line of the approaching vessel continually increases. On the other hand, if the vessel recedes, it will be found gradually to diminish. Now, the observer's eye (see the plate before referred to) being placed at a definite height above the level of the sea, and his line of vision directed to the horizon being the tangent of the earth's curvature passing through the definite point *a*, it follows that the angles *h a c* and *g a c*, respectively, will determine the distance of *h* and *g* from *b*, when vertical to *a*. Now, the earth's curvature is constant, the height of *a* above the level of the sea is known, and the angles *h a c*, etc., may be readily measured by reflectors and the graduated arc. But there is no time for mathematical computation.

The Distance Instrument, it will be seen by the following description, performs the required computation with unerring certainty whilst the observer measures the angle, and it exhibits the result the instant he has performed his part. Every one familiar with nautical instruments will, by an attentive inspection of the drawing, readily understand its principle and operation; a very brief description will therefore suffice. A is an ordinary reflector, as used in quadrants; B, the object-glass, and C, the sight by which the angles *h a c*, etc., are measured; D, a spindle, to the end of which the reflector is firmly attached; E, lever for turning said spindle; F, sliding-nut made to move freely up and down in a slot at the lower end of lever E; G, thumbscrew working in the sliding-nut; H, pinion on said screw, working into cogs cut in the circumference of a graduated index-plate J; K, socket sliding on the main stem of the instrument and supporting the frame and centre of the revolving index-plate. Before noticing the operation of the instrument, it will be necessary to point out the manner of graduating the index-plate. Considering the extent of the point-blank range of naval ordnance, it is evident that no distance under 400 yards need be measured: supposing, therefore, that *h* is 400 yards distant from *b*, it will be seen that the operation or range of the instrument will be limited to the angle *h a c*, which thus determines the extent of movement or vibration of the lever E. This movement again determines the pitch of the thumbscrew and the relative diameter of the pinion, it being evident that the extreme vibration of lever E should not produce more than one revolution of the index-plate. Any convenient-sized index-plate being selected, a scale graduated into feet or yards is then constructed, corresponding to the circumference of the plate; the mode of dividing the scale being as follows: In the first place, a base-line of 100 feet (represented by *a b* in the diagram) is supposed, and the tangent *a c* determined accordingly. The known curve *b d c* is then divided into spaces *h g*, *g f*, *f e*, etc., of 10 yards each, commencing at a point, *h*, 400 yards from *b*. The sines of the angles *h a c*, *g a c*, etc., are next calculated and marked on the before-mentioned scale, and from thence ultimately transferred to the curved scale on the index-plate. The following directions for using the instrument are deemed sufficient: Turn the thumbscrew until the line marked "horizon" is placed directly under the fixed index. Then adjust the object-glass by means of the set screw M, so that the real and reflected horizons come in a line. This adjustment being made, the instrument is ready for use, and need not be readjusted unless disturbed. The process of measuring the distance consists simply in turning the thumbscrew G until the reflected water-line of the object observed is brought in a line with the real horizon seen through the object-glass. The point on the scale of the index-plate placed directly under the fixed index shows the distance desired. It must be conceded, on theoretical considerations, that if the base-line be previously known and the instrument made to correspond thereto, the measurement cannot fail to be accurate; but such is the nature of this base-line that it cannot be previously known; accordingly, the base-scale L has been introduced, by which the instrument may at all times be made to conform to the variable height of the base. It is evident that an increase of altitude would render the scale of the index-plate too short, and, on the other hand, too long if the altitude be diminished. It is also evident that by sliding the index-plate up, the effect of which will be to shorten the lever E, any *diminution* of the base may be compensated for, and the index-plate remain very nearly correct. The sliding the index down would in like manner compensate for any *increase* of the base. On mathematical considerations, it is obvious, however, that this mode of compensating for variations of the base cannot be carried very far. Index-plates of different graduations will, therefore, be employed to suit the height of the masts of different classes of vessels, and the base-scale only resorted to for compensation to meet irregularities occasioned by altered draught of water, consequent on diminution of ammunition, stores, etc. At first sight, it would appear that the base employed in this instrument is not sufficiently definite or accurate; on due consideration, however, it will be found to be fully as definite as required.

In the first place, the height of the maintop, cross-tree, or other point of a ship above the bottom of the keel may be ascertained to an inch, and, when once known, may be recorded, as well as tonnage, length, beam, etc. Secondly, the draught of water amidships is always known to a careful commander, within two inches or less. The draught of water, being deducted from the height above the keel, establishes the altitude above the water-line. The height of the observer's eye—ordinarily five feet six inches—being next added, determines the base within an inch or two. So far, then, the accuracy is all that can be desired for practical purposes. The effect of the rolling of the ship, which at sea always takes place to some extent, next demands attention.

It would be an extreme case to suppose the observer tossed through an arc of 20 feet whilst taking an observation—viz., 10 feet on each side of the vertical line. On calculation, it will be found that such oscillation would only produce a depression of six inches at the *lowest* point. Finally, the rising and falling of the ship deserves to be noticed. The vertical movement of the *midship body*, being at all times surprisingly small, will be found quite unimportant at times when the Distance Instrument is likely to be wanted. Again, as each observation only requires a few seconds, it may be frequently repeated. It is proper to add that an error of 6 inches in a base of 100 feet, and which will not ordinarily occur, only causes an error of distance of nine yards in a mile.

CHAPTER XXIV.

THE STEAM FIRE-ENGINE.

(SEE PLATE 37.)

THE Mechanics' Institute of New York offered its great gold medal, in January, 1840, as a prize for the best plan of a *steam* fire-engine. Having several years previously designed such machines in England, among which may be mentioned the steam fire-engine employed during the memorable fire at the Argyle Rooms in London, in 1830 (the first time fire had ever been extinguished by the mechanical power called forth by fire), I had no difficulty in producing plans complying with the conditions of the Mechanics' Institute in a manner warranting the award of the prize offered.

The following description—reference being had to the illustration on Pl. 37—shows the detail of the steam fire-engine thus accepted by the Mechanics' Institute of New York. A, double-acting force-pump, composed of gun-metal, firmly secured to the carriage-frame by four strong brackets cast on its sides; a a, suction-valves; a' a', suction-passages leading to the cylinder; a'', chamber containing the suction-valves, to which chamber are connected suction-pipes a''' a''', the hose being attached to the latter by screw-couplings in the usual manner, and closed by the ordinary screw-cap. The delivery-valves and passages at the top of the force-pump are similar to the suction-valves and passages mentioned. B, the air-vessel, composed of copper, its form being spherical; b b, delivery-pipes, to which the hose is attached. When only one jet is required, the opposite pipe may be closed by a screw-cap, as usual. The piston of the force-pump is provided with double leather packing, the piston-rod being made of copper. C, boiler, constructed on the principle of the ordinary locomotive boiler, containing an adequate number of tubes of suitable diameter. The top of the steam-chamber and the horizontal part of the boiler is covered with wood as usual, in order to prevent loss of heat by radiation. c, fire-door; c', ash-pan; c'', box attached to end of boiler, enclosing the exit of the tubes. The hot air from the tubes entering this box is passed off through a smoke-pipe c''', the exit of which makes a half-spiral turn round the air-vessel, as shown in the illustration. c'''', iron brackets, riveted to the boiler and supported by the carriage-frame. c^6, a wrought-iron brace, bolted to the carriage-frame, for supporting the horizontal part of the boiler. E, vertical pipe attached to the top of the steam-chamber, containing a conical steam-valve e, and also the safety-valve e'; e'', regulating screw and handle, connected to the steam-valve, for admitting or shutting off the steam; e''', induction-pipe for conveying the steam from the boiler. F, double-acting working cylinder, provided with steam-passages and slide-valve of the usual construction; it is firmly secured to the carriage-frame by means of brackets, in the same manner as the force-pump. f, eduction-pipe, for carrying off the steam to the atmosphere; f', piston, provided with metallic packing on Barton's plan; f'', piston-rod of steel, attached to the piston-rod of the force-pump by means of the cross-head G, composed of wrought iron; both piston-rods being inserted into the said cross-head and secured by keys. g, tappet-rod, attached to the cross-head, for moving the slide-valve of the steam-cylinder by means of the nuts g' g'. The latter may be placed at any desirable position on the tappet-rod, to ensure a regular action of the valve. A short axle of wrought iron, turning in bearings attached to the cover of the steam-cylinder, operates the steam-valve by appropriate levers acted upon alternately by the nuts g' g'. I, feed-pump for supplying the boiler, provided with spindle-valves on the ordinary plan, its suction-pipe communicating with the valve-chamber of the force-pump, the feed-water being carried into the horizontal part of the boiler. i, plunger of the force-pump, composed of gun-metal or copper, attached to the cross-head G.

Before proceeding with the description, it will be necessary to state that, although the efficiency of the "steam-blast" was well ascertained at the time, the prevailing opinion that, in common with the locomotive engine, red-hot sparks would emanate from a steam fire-engine, and prove dangerous among houses in a close-built city, I was compelled to resort to the employment of a blowing apparatus for generating the necessarily large quantity of steam indispensable to render the machine efficient.

J, blowing apparatus, consisting of a square wooden box, with panelled sides, in which a thin square piston *j* is applied, leather packing being employed to make air-tight joints. *j*′, circular holes through the sides for admitting atmospheric air into the box, these holes being covered on the inside by pieces of leather or India-rubber cloth acting as valves. *j*″, similar holes through the top of the box for passing off the air, at each stroke of the piston, into the receiver or regulator K, which is provided with a movable top *k*. The latter is composed of wood, joined by leather to the upper part of the box, a thin sheet of lead being attached thereto, in order to keep up a certain pressure of air in the regulator. *k*′, channel made of sheet-iron, attached to the blowing apparatus, communicating freely with the regulator K. To the said channel is connected a conducting-pipe, marked by dotted lines in the longitudinal section of the engine, for conveying the air from the receiver into the ash-pan under the furnace of the boiler at *k*″. The conducting-pipe, it should be observed, passes along the inside of the carriage-frame on either side.

L L, parallel iron rods, to which the piston of the blowing apparatus is attached. These rods work through guide-brasses *l l*, and may be attached to the cross-head G by keys at *l′ l′*. The holes at the end of the said cross-head admitting these rods are sufficiently large to allow a free movement whenever it is desirable to work the blowing apparatus independently of the engine. M, spindle of wrought iron, placed transversely, turning in bearings fixed under the carriage-frame. To this spindle are fixed two crank-levers *m m*, which, by means of two connecting-rods *m′ m′*, give motion to the rods L L attached to the piston of the blowing apparatus.

N, crank-lever secured to the end of spindle M, which, by means of a connecting-rod applied to a crank-pin, fixed in the hub of the carriage-wheel, on the outside, will communicate motion to the blowing apparatus whenever the carriage is in motion. By this simple expedient a powerful combustion will be kept up in the boiler furnace while the engine is on its way to the place of conflagration. By detaching the connecting-rod referred to, and applying a hand-lever to N, the blowing apparatus may be operated by manual labor. The carriage-frame should be made of oak, plated with iron all over the outside; the top plate to have small recesses, as shown in the drawing. The lock of the carriage, axles, and springs to be made as usual, only differing by having the large springs suspended *below* the axle. The carriage-wheels to be constructed on the suspension principle; spokes and outside of rim to be made of wrought iron, very light.

CHAPTER XXV.

THE STEAM-SHIP PRINCETON.

(SEE PLATES 38, 39, AND 40.)

In the sixty-sixth year of the American Republic—1842—the first steam ship-of-war provided with a submerged propeller and steam machinery located below water-line was built at Philadelphia. Complete success attended this undertaking, as will be seen from the following extract from a speech delivered in the Senate of the United States by Senator Mallory, of Florida, May 14, 1858:

"In 1839 Congress authorized the construction of three war-ships. In 1840 the Secretary of the Navy, in obedience to that law, ordered two to be constructed. There were two plans at that time. The question of whether steam could or could not be successfully applied to war-vessels had not then been solved; the fear of danger from ignition by fire prevailed in the minds of all naval men, and the problem was to be solved. Its solution was demanded by every naval power on earth. One of the officers of our navy, Captain William Hunter, submitted a plan by which wheels were to be inserted in the bilge of the vessel on each side—submerged wheels. Ericsson had demonstrated his plan to be feasible, practicable, and just, already. This was no experiment in the *Princeton.* The experiment had been made at great cost by Captain Ericsson. . . . The Secretary of the Navy, in authorizing the construction of these two vessels, directed one to be constructed on Hunter's plan—not model, as the Senator from Michigan says; the model was not in question at all; our models were as good then as they are now; but the point was the application of steam to naval purposes. One was to be built on Ericsson's plan, and one on Hunter's plan. Hunter's plan proved a total failure; Ericsson's plan laid the foundation of the present steam marine. She was the first war propeller ever built on the face of the earth. In the *Princeton* he brought forward not only his propeller invented by himself, but a great many appliances appurtenant to steam navigation which have since been used in our service.

"Now, to show the estimate in which this ship was held, I will mention that the American Institute, hearing of it, sent a committee to investigate the condition and success of what they deemed an experiment. I will not read the whole report of the committee of the American Institute. My purpose here is to show the value of Captain Ericsson's services to our country. The committee conclude by saying, after summing up the speed of thirteen knots:

"'In conclusion, your committee beg leave to present the *Princeton* as every way worthy of the highest honors of this Institute. She is a sublime conception, most successfully realized, an effort of genius skilfully executed, a grand, unique combination, honorable to the country as creditable to all engaged upon her.'

"This is signed by ten members of the Institute. Further to illustrate: Captain Stockton, in 1844, after describing the ship, her guns and her armament, says everything human language can to extol her in the eyes of the American people. As I said, the *Princeton* is the foundation of our present steam marine. It is the foundation of the steam marine of the whole world. She created universal surprise wherever she was seen. She revolutionized naval vessels; and hereafter, in maritime war, those who send sailing vessels to sea send them but to be captured."

The following extract from the work on "Naval and Mail Steamers," published 1853 by Charles B. Stuart, Engineer-in-Chief of the United States Navy, furnishes some important particulars relating to the *Princeton:*

"This vessel was designed by, and constructed under the superintendence of, Captain John Ericsson, of New York.

HULL.

Length on deck, ...	164	feet.		
Length between perpendiculars, . .	156	"		
Extreme beam on deck, . . .	30	"	6	inches.
Depth of lower hold to berth-deck, .	14	"		
Depth from berth to spar-deck, . .	7	"	6	"

Total depth of vessel,	21 feet 6 inches.
Measurement burthen,	673 tons.
Launching weight of hull,	418 "
Displacement at 16½ feet draught,	954 "
Displacement at 18 feet draught,	1,046 "
Immersed midship section at 16½ feet draught,	346 square ft.
" " " 18 "	390 "
Draught of water at deepest load, with 200 tons of coal on board,	19 feet 4 inches.
Draught of water with 100 tons of coal in, after-bunkers and provisions, and water for the crew, half out,	forward, 14¾ feet. aft, 18¼ "
Mean draught of water with half coal out, and all other weights full,	17 feet.

"The peculiarity of model consisted in a very flat floor amidships, with great sharpness forward and excessive leanness aft, the run being remarkably fine, with a great extent of dead-wood terminating in a stern-post of the unusual thickness of twenty-six inches at the centre of the propeller-shaft, but tapering above and below. This dead-wood and stern-post was pierced by a hole thirteen inches diameter for the passage of the propeller-shaft. The stern, measuring from a perpendicular from the aft end of the spar-deck, overhung the stern-post fifteen and one-half feet, and depending from it was a false stern-post, leaving a space of six feet, fore and aft, between it and the true stern-post. The propeller (fourteen feet in diameter, composed of bronze, with six propeller-blades, pitch thirty-five feet) was placed within this space.

The false stern-post, or rudder-post, was composed of a wrought-iron bar, covered with half-inch-thick copper plate; it was attached at top by brass flanges to a strong oak knee, securely bolted to the counter of the vessel; the lower part of it was attached by similar flanges to a solid oak timber placed as a continuation of the keel beyond the true stern-post; this timber was fourteen inches deep, and securely bolted to the keel and dead-wood. The metallic false stern-post was five and three-eighths inches broad athwart ship, and two feet long fore and aft; the forward part was brought to an acute angle to diminish its resistance to the water, while its after-part was square to receive the attachment of the rudder. The rudder was also composite in its construction, being formed of a wrought-iron frame, the interstices of which were filled in with pieces of five-inch-thick pine plank, the whole cased over with a copper plate three-sixteenths of an inch thick. The thickness of the rudder athwart ship was the same as that of the false stern-post, viz., five and three-eighths inches.

ENGINES.

"The semi-cylinder engine of the *Princeton* is unquestionably the most remarkable modification of the steam-engine that has ever been carried into successful practice. A vibrating piston of a rectangular form moving in a semi-cylinder is an old mechanical device. Mr. Watt, in his celebrated patent, embraced this plan for transmitting the motive force of steam to machinery. Since his time several engineers have attempted to build engines on this plan, but without success.

In common with Mr. Watt, they have adopted the single semi-cylinder with packing against the piston-shaft. Ericsson's plan differs materially from these various attempts, he having introduced double or compound semi-cylinders of different diameters, with double pistons placed in opposite directions on the piston-shaft, both being acted upon by the steam at the same time, their differential force being the effective motive power of the engine. The combination of two such double semi-cylinders, arranged so as to transmit their power in directions nearly rectangular to a crank-pin common to both, also contributes to the complete success of this singular engine.

"By reference to the plate, it will be seen that the upper semi-cylinder, which contains the reacting piston, is twenty inches in diameter, the lower or working semi-cylinder being seventy-two inches diameter, both ninety-six inches long in the clear. The radius of the reacting piston, being deducted from that of the working piston, leaving twenty-six inches *effective* width of piston, with its centre of pressure placed $10 + 13 = 23$ inches from the centre of the piston-shaft. The active piston area will thus be $26 \times 96 = 2{,}516$ superficial inches, moving at a mean distance of twenty-three inches from the centre through an arc of ninety degrees.

"On close examination this engine will be found to possess many peculiar properties, some of which merit particular notice. The vibration of the working piston will be found to correspond nearly to the beat of the pendulum, and thus, unlike the ordinary engine, the return movement of the piston at each termination of the stroke is materially assisted by the force of gravity. An undue accumulation of condensed water on the piston, so difficult to carry off in the ordinary engine, presents no inconvenience here, as the inclined position of the piston allows the condensed water to flow gradually down into the steam-passages before the piston reaches the termination of the stroke. The outward tendency of the packings, induced by centrifugal force, assists materially in forming tight joints, the main packing being held out by the force of gravity. The lateral yielding of the piston-shaft, caused by the pressure of the steam on opening the inlet-valve, tends to give additional tightness to the packings, the pistons being forced into reduced radial limits by the yielding alluded to. The crank-levers attached to the piston-shafts being placed nearly in the same position with the main pistons, it will be found that the crank-journals of those shafts are relieved from pressure, on principles analogous to the relieving of water-wheel journals, by transmitting the power at some point near the centre of pressure. The increase of force imparted to the crank-pin at each half-turn of the main crank, owing to the angular position of the piston-rod cranks, and happening, as it does, when the former presents short leverage, is a marked feature of this engine.

"The small angular movement (ninety degrees) of the main piston also deserves attention. A greater motion, while it would augment the power of any given-sized cylinder, would cause undue strain on all the principal bearings, as the force of the piston obviously increases in the inverse ratio of the sines of the angles of the piston-shaft cranks, with reference to the position of the connecting-rod. A very moderate increase of diameter makes up the loss consequent on the short arc through which the piston vibrates. Very deep cylinder-covers, giving great strength to resist the upward pressure of the steam, may also be named as an advantage resulting from the short vibration.

"As an instrument of producing, by *direct means*, the high speed requisite for screw-propellers, this engine commends itself to the engineer. In its fitness for screw-vessels it seems to fulfil every condition. The very limited number of working parts, and the small amount of matter to be kept in motion, are self-evident advantages, best understood by reference to the plate. It is important to notice that the piston-shaft journals are supported by bearings placed *outside* of the heads of the semi-cylinders, and that the brasses admit of adjustment in every direction; the exact position of the centre of the piston-shafts, with relation to the centre of the semi-cylinders, being indicated by an external index, enabling the engineer at all times to keep the shaft in line.

"The main packing is rendered accessible by lifting up one of the covers and removing the nearest side-plate forming the packing-groove. The upper packing becomes accessible by lifting up the centre-piece which forms the upper semi-cylinder. It may be stated with regard to the packings, that the *Princeton*, after having served during the war with Mexico, was despatched on a cruise to the Mediterranean without requiring new packings."

Mr. J. O. Sargent, in a lecture on "Steam Navigation and the Arts of Naval Warfare," delivered before the Boston Lyceum in 1844, stated with reference to the motive power of the *Princeton:* "The next peculiarity to be noticed in the *Princeton* is the absence of the ordinary tall smoke-pipe employed to produce the draught for keeping up combustion in the furnaces of the boilers. The smoke-pipe has hitherto formed a serious objection to a steamer as a ship-of-war; for the moment it is carried away the efficiency of the engines ceases from want of steam. The draught in the boilers of the *Princeton* is promoted by means of blowers placed in the bottom of the vessel, and is quite independent of the *height* of the smoke-pipe, which is only carried about five feet above the deck of the ship. If this inconsiderable projection should become partially deranged by a shot, the draught kept up by the blowers will continue as efficient as before.

"It is not out of place here to observe that Ericsson was the first to apply to marine engines centrifugal blowers, now so common in this country in all boilers using anthracite coal. In the year 1831 he applied such a blower, worked by a separate small steam-engine, to the steam-packet *Corsair*, of one hundred and twenty horse-power, plying between Liverpool and Belfast."

CHAPTER XXVI.

TWELVE-INCH WROUGHT-IRON GUN AND CARRIAGE.

(SEE PLATE 41.)

THE question has frequently been asked, When was wrought-iron ordnance first introduced on board ships-of-war? When was breeching first dispensed with and wrought-iron carriages introduced? The heading on the plate referred to gives an answer to these queries.

Captain Robert F. Stockton, of the United States Navy, on visiting England—1839—for the purpose of witnessing the trial of a small screw-steamer (the first iron vessel to cross the Atlantic) built for him by Messrs. Laird, to my design, consulted me regarding the possibility of constructing naval ordnance of wrought iron. Being an advocate of that material, I readily met the wishes of Captain Stockton, and at once prepared drawings of a gun of 12-inch calibre. The Mersey Iron-Works, near Liverpool, being willing to enter into a contract with Captain Stockton, received forthwith an order from that enterprising and spirited officer to build the gun at his expense. Experienced commodores at the time protested loudly against the proposition to mount "the monster gun" on board a vessel so lightly built as the *Princeton*, insisting that, among other difficulties, the breeching would tear her upper works to pieces. It was urged by the opponents of my new system that the handling of such guns at sea would prove impossible, the constructing carriages of sufficient strength being pointed out as impracticable; while the imprudence on the part of the Navy Department of entrusting such matters to mere engineering skill was severely criticised. In spite of remonstrances, however, Captain Stockton's influence with the Government prevailed. In the meantime the problem of handling the 12-inch gun received due attention. Calculations of the dynamic equivalent of the recoil convinced me that a moderate resistance, if continuous and uniform, would suffice to bring the piece to rest in less space than that required by breeching. *Friction*, being the simplest means of obtaining a continuous resistance, was accordingly resorted to. The method adopted will be readily comprehended by reference to the illustration already referred to, which represents a side elevation, top view, and end views of the gun, carriage, and slide, mounted on board the *Princeton* in 1843. Two pieces of timber of semi-circular section, placed a few inches apart, slightly taper towards the front end of the slide, are secured to the latter in such a manner as to admit of some vertical motion. A broad hoop of plate-iron, attached to the carriage, clasps the two timbers. An axle provided with a cam in the middle, operated by a lever, is placed across the front end of the slide passing through the space between the friction timbers. Obviously, these timbers will be pushed apart with considerable force if the transverse axle be turned so as to place the cam in a vertical position. The friction between the hoop and the timbers produced by the pressure of the cam, it is scarcely necessary to observe, will be greatly enhanced during the recoil of the gun, in consequence of the increasing vertical depth of the timbers towards the rear end of the slide. The transverse axle being turned so as to place the cam in a horizontal position, permitting the friction timbers to approach each other, will of course at once relieve the friction. The monitor gun-carriages, constructed, like the *Princeton's*, on the plan of checking the recoil by friction, differed as regards the mode of clasping the friction-timbers, a *screw* being employed to produce the requisite compression in place of the transverse axle and its cam. But in constructing gun-carriages for the celebrated thirty Spanish gunboats, and in all recent carriages, I have returned to the plan of employing a cam for setting up and relieving the friction, whereby, as in the case of the *Princeton* carriage, the operation becomes almost instantaneous.

The 12-in. wrought-iron gun of the *Princeton*, as stated, was manufactured at the Mersey Iron-Works, of the very best materials, it has been asserted; but, on being tested in this country, it proved too weak. I therefore resorted to the expedient of hooping the breech of the piece up to the trunnion-band; the hoops being made of the best quality of American wrought-iron put on in two tiers, shrunk one over the other in such a manner as to break joint. This expedient proved entirely successful, the gun having stood all tests to which it has been subjected. It was a solid cast-iron shot from this 12-in. gun which in 1842 pierced a wrought-iron target 4½ ins. thick, up to that period considered proof against naval ordnance.

The United States Government having been the first to introduce heavy wrought-iron ordnance for naval purposes, why does it not continue to build guns of that material? European artillerists repeatedly put this question. Probably the answer will be found in the fact that, although having in the meantime successfully constructed rifled wrought-iron ordnance of considerable size, the first essay at building heavy guns for naval purposes proved most disastrous. Immediately after the trial of the gun referred to, manufactured in England, a 12-in. smooth-bore, of much heavier metal, was forged at Hamersley Forge, bored and turned in New York, and considered at the time to be a remarkable specimen of good workmanship. It was at once mounted on board the *Princeton*, by the side of its slender companion, upon a similar carriage. Much confidence was placed in the strength of this magnificent gun on account of the supposed superior quality of American iron. It stood the proof-charge and some preliminary tests, but, on being fired on a festive occasion while the ship was at Washington, the admired piece burst, with the sad result recorded in the naval annals of the time.

CHAPTER XXVII.

APPLICATION OF THE SUBMERGED PROPELLER FOR COMMERCIAL PURPOSES.

DURING the construction of the *Princeton* numerous propeller-vessels were built for carrying freight on the rivers and inland waters of the country, the machinery at first being built in New York, Philadelphia, and Oswego. The line of propeller-steamers between Philadelphia and Baltimore, which seriously interfered with the freight traffic of the Philadelphia and Baltimore Railroad, merits special mention.

The annexed table of propeller-vessels built up to December, 1843, prepared by Lieutenant Johnson, of the Swedish Navy, in pursuance of orders from his Government, shows the extraordinary rapidity of the adoption of the propeller for commercial purposes.

The *Engineer*, in laying the table referred to before its readers, May 11, 1866, observes:

"The fate of mechanical inventions is much like that of the seed in the parable. The invention must fall on a proper soil, and be nurtured by favorable circumstances of time and place, in order to bloom into success. The application of the steam-engine to navigation was of greater necessity to the large extent of the rivers and lakes of the States than with ourselves; and Fulton did right to take his marine engine back to his own country. For similar reasons the screw-propeller worked its way into use there much quicker than with ourselves. This fact is very evident from the table furnished to Mr. Woodcroft by Captain Ericsson, prepared by Lieutenant Johnson, of the Swedish Navy, in 1843. Early in the following year (1844) a very large addition was made to the steam fleet provided with Ericsson's propeller both on the inland waters of America and on the ocean. Of the latter may be mentioned the bark *Edith* and the steamships *McKim*, *Marmora*, and *Massachusetts.* The last vessel was subsequently purchased by the United States Government. It became the flag-ship of General Scott at the landing of Vera Cruz, which resulted in the conquest of Mexico. It is worthy of notice that Ericsson applied his propeller to upwards of sixty vessels in America before any other form of propeller was adopted or a single attempt made at evading his patent. Nor is it less worthy of remark that the adaptation of his propeller proved a great commercial success from the start, many of the original vessels being now, after fifteen years of service, in good working condition."

List of Steam Vessels in North America provided with Ericsson's Screw-Propeller up to December, 1843.

Names of the vessels.	Destination.	Number of cylinders.	
Robert F. Stockton	Delaware and Schuylkill	2	1
Vandalia	Oswego to Chicago	2	2
Clarion	New York to Havana	1	3
Baron Toranto	Rideau Canal and St. Lawrence.	1	4
Royal Barge	Rideau Canal and St. Lawrence.	2	5
Propeller	Rideau Canal and St. Lawrence.	1	6
Ericsson	Rideau Canal and St. Lawrence.	1	7
Ironside	Philadelphia to Albany	1	8
Anthracite	Philadelphia to Albany	1	9
Black Diamond	Philadelphia to Hartford	1	10
Vulcan	Philadelphia to Hartford	1	11
Pioneer	Erie Canal	1	12
Oswego	Oswego to Chicago	2	13
Chicago	Oswego to Chicago	2	14
Cumberland	Philadelphia to Baltimore	2	15
Ericsson	Philadelphia to Baltimore	2	16
Pilot	New York to Canada	1	17
Phœnix	New York to Canada	1	18
Governor McDowell	James River Canal to Virginia.	1	19
Jefferson (Revenue Cutter)	Lake Erie	1	20
Legaré	Delaware River	1	21

List of Steam Vessels in North America provided with Ericsson's Screw-Propeller up to December, 1843.

	Horse-power.	Burthen in tons.	Length.	Beam.		Depth of hold.		Propeller diameter.		When built.
			Ft.	*Ft.*	*In.*	*Ft.*	*In.*	*Ft.*	*In.*	
1	60	42	70	10	0	7	0	6	4	1839
2	40	140	98	21	6	6	6	5	9	1841
3	60	250	104	24	6	13	0	6	4	“
4	18	70	72	16	6	4	6	5	9	“
5	36	70	72	16	6	4	6	5	9	“
6	18	70	72	16	6	4	6	5	9	“
7	18	70	72	16	6	4	6	5	9	“
8	40	200	100	22	6	6	0	6	0	1842
9	40	200	100	22	6	6	0	6	0	“
10	40	200	100	22	6	6	0	6	0	“
11	40	200	100	22	6	6	0	6	0	“
12	18	55	82	14	4	3	6	5	6	“
13	40	140	98	21	6	6	6	5	9	“
14	40	140	98	21	6	6	6	5	9	“
15	40	80	78	18	6	6	6	6	6	“
16	40	80	78	18	6	6	6	6	6	“
17	18	55	82	13	6	3	6	5	6	1843
18	18	55	82	13	6	3	6	5	6	“
19	18	20	90	13	6	1	2	5	0	“
20	150	342	140	24	0	7	6	9	6	“
21	150	342	140	24	0	7	6	9	6	“

LIST OF STEAM VESSELS IN NORTH AMERICA PROVIDED WITH ERICSSON'S SCREW-PROPELLER UP TO DECEMBER, 1843.

Names of the vessels.	Destination.	Number of cylinders.	
Hercules	Lake Erie	2	22
Perrysborough	Lake Erie	2	23
Cleveland	Lake Erie	1	24
Baltimore	Philadelphia to Baltimore	1	25
Princeton	Philadelphia Station	2	26
Lion	New York to Hartford	1	27
Eagle	New York to Hartford	1	28
Mohawk	Albany to Hartford	1	29
C. Bristol	Chicago and the Great Lakes	1	30
New London	Mobile	1	31
Uncas	Mobile	1	32
New London	Owners, Williams & Barns	2	33
Enterprise	Lake Ontario and St. Lawrence.	1	34
New York	Oswego to Chicago	2	35
Washington	Hudson River	1	36
Rufus Page, Owner	East Coast of America	1	37
Rufus Page, Owner	East Coast of America	1	38
—— Buck, Owner	East Coast of America	2	39
Captain Sanford, Owner	East Coast of America	2	40
Williams & Barns	East Coast of America	2	41
Captain Coit	East Coast of America	2	42

List of Steam Vessels in North America provided with Ericsson's Screw-Propeller up to December, 1843.

	Horse-power.	Burthen in tons.	Length.	Beam.		Depth of hold.		Propeller diameter.		When built.
			Ft.	*Ft.*	*In*	*Ft.*	*In.*	*Ft.*	*In.*	
22	50	250	...	...		8	0	6	0	1843
23	50	250	...	...		8	0	6	0	"
24	60	280	...	...		8	0	6	10	"
25	50	127	78	19	6	6	6	7	2	"
26	400	672	164	30	0	17	6	14	0	"
27	50	172	115	23	6	6	0	6	10	"
28	50	172	115	23	6	6	0	6	10	"
29	50	172	125	22	0	6	0	7	0	"
30	60	300	...	26	0	8	0	7	4	"
31	50	172	125	22	0	6	0	7	0	"
32	50	172	125	22	0	6	0	7	0	"
33	50	172	125	22	0	6	6	7	0	"
34	20	70	...	...		...		5	9	"
35	50	140	98	21	6	6	6	5	9	"
36	60	170	103	26	0	7	6	7	4	"
37	50	172	115	23	6	6	0	6	10	"
38	50	172	115	23	6	6	0	6	10	"
39	55	172	125	22	0	6	0	7	0	"
40	55	172	125	22	0	6	0	7	0	"
41	55	172	125	22	0	6	0	7	0	"
42	55	172	125	22	0	6	0	7	0	"

CHAPTER XXVIII.

IRON-CLAD STEAM BATTERY, WITH REVOLVING CUPOLA, SUBMITTED TO EMPEROR NAPOLEON III.

(ILLUSTRATION, SEE PLATE 42.)

THE illustration referred to is a fac-simile of a drawing forwarded to the French Emperor at Paris, September 26, 1854, accompanied by an elaborate description and demonstration of the utility of the battery.*

The following extracts from the description of the new system of naval attack, forwarded as stated, furnishes a correct idea of its nature:

The present system of *long* range is abortive. 1st, because large or heavy bodies cannot be projected to a great distance;

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* The Emperor promptly acknowledged the receipt of these documents through Gen. Favé, whose letter commences with the following flattering sentence:

"L'Empereur a examiné lui-même avec le plus grand soin le nouveau système d'attaque navale que vous lui avez communiqué.

"S. M. me charge d'avoir l'honneur de vous informer qu'elle a trouvé vos idées très-ingénieuses et dignes du nome célèbre de leur auteur."

2dly, because accurate aim at long range becomes absolutely impossible in practice. The recent trial of the Lancaster gun, when subjected to the unavoidable oscillation of a small vessel, may be cited as proof. Short range, "close quarters," will remove both difficulties, as it admits of large and heavy projectiles being employed, and because it ensures accurate aim. Besides these advantages, a near approach to the enemy renders attack *under* water practicable. These facts establish the following propositions: 1st, a complete system of *naval attack* demands a self-moving vessel capable of passing within range of guns of forts, and of moving at pleasure in defiance of the fire of broadsides. 2dly, with a vessel of such properties, a complete offensive system further requires adequate means of throwing projectiles of large size with absolute precision at short ranges, either point-blank or at very great elevation; the means of projecting shells (movable torpedoes) under water at short distances being also indispensable. 3dly. These conditions being fulfilled, the system yet demands a projectile that will infallibly explode at the instant of contact.

Accordingly, the writer has directed his experiments and labors to the solution of the following problems: I. A self-moving shot-proof vessel. II. An instrument capable of projecting very large shells at slow velocities, but very accurately, in accordance with previously-determined rate. III. A shell not subject to any rotation in the direction of its course, and so contrived as to explode with infallible certainty at the instant of contact. IV. A shell (torpedo) capable of being projected under water, and certain to explode by contact, together with an instrument for projecting such a shell from the vessel at a certain depth below the water-line.

The nature of the practical solution of the above problems will be readily comprehended by referring to the illustrations (see Plate 42). A brief extract of the document forwarded to the Emperor will therefore suffice.

The vessel to be composed entirely of iron. The midship section is triangular, with a broad, hollow keel, loaded with about 200 tons of cast-iron blocks to balance the heavy upper works. The ends of the vessel are moderately sharp. The deck, made of plate iron, is curved both longitudinally and transversely, the curvature being 5 feet; it is made to project 8 feet over the rudder and propeller. The entire deck is covered with a lining of sheet iron 3 inches thick, with an opening in the centre 16 feet diameter. Over this opening is placed a semi-globular turret of plate iron 6 inches thick, revolving on a vertical column by means of steam-power and appropriate gear-work. The vessel is propelled by a powerful steam-engine and screw-propeller. Air for the combustion in the boilers and for ventilation within the vessel is supplied by a large self-acting centrifugal blower, the fresh air being drawn in through numerous small holes in the turret. The products of combustion in the boilers and the impure air from the vessel are forced out through conductors leading to a cluster of small holes in the deck and turret. Surrounding objects are viewed through small perforations at appropriate places. Reflecting telescopes, capable of being protruded or withdrawn at pleasure, also afford a distinct view of surrounding objects. The rudder-stock passes through a water-tight stuffing-box, so as to admit of the helm being worked within the vessel. Shot striking the deck are deflected, whilst shell exploding on it will prove harmless.

Tube for projecting the shells to be made of cast iron or brass, 20 inches bore, 2 inches thick, and 10 feet long. It is open at one end, the other end being closed by a door moving on hinges provided with a cross-bar and set-screw, in order to be quickly opened and afterwards firmly secured. The shell is inserted through this door, and projected by the direct action of steam admitted from the boiler of the vessel through a large opening at the breech. The induction-valve is made with a double face of large areas, and moved by mechanism of instantaneous action, susceptible of accurate regulation in regard to opening. One tube of the above description is placed on a level on the platform of the revolving turret. Two similar tubes are placed in the body of the vessel, at a fixed inclination of 22 deg., revolving on vertical pivots. These tubes are supplied with steam through the centre of their vertical pivots, the admission of steam being regulated as before described.

The plan of throwing shells of several hundred pounds by the direct power of steam of *ordinary* pressure, demands special notice. Without reference to the result of actual trial, a brief investigation of the theory on which the plan is based will show that shells of enormous size may be projected with unerring precision.

THE SHELL, composed of cast iron, is formed as delineated.* A groove is made round the circumference at right angles to the axis, into which an india-rubber ring is inserted to form a steam-tight joint when the shell is put into the tube. In order effectually to prevent rotation in the line of flight, a tail in the form of a cross, composed of thin plate-iron, is attached to the shell. Opposite to this tail a cavity is formed, into which a cylindrical hammer is inserted. A percussion-wafer is placed under the hammer, which, being always in advance of the shell, is struck at the instant of contact, infallibly causing an explosion.

THE HYDROSTATIC JAVELIN (torpedo-carrier), for conveying the shell (torpedo) under water, consists of a cylindrical block of light wood, 16 inches diameter, 10 feet long. At one end of this block a 16-inch shell is attached, charged with powder, and furnished with a percussion-hammer, as above described. The other end of the block is pointed and loaded at the under-side sufficient to balance the instrument perfectly. The displacement being 1,000 pounds, the weight of the whole is made to correspond accurately, in order to ensure perfect suspension in the water. The javelin (torpedo-carrier), when required, is passed through the vessel's bow or side by means of a short tube, as shown by the drawing, the water from the sea being kept out during the insertion

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* Unfortunately, the copies of this and other delineations referred to have been lost, hence cannot be presented in this work.

by the obvious means of a slide-valve. The javelin (torpedo-carrier) is projected—pushed out—by means of a rod attached to the piston of a steam-cylinder of 18 inches diameter, 3 feet stroke. A force of 10,000 pounds acting through 3 feet is more than sufficient to propel the javelin 200 feet, at an average velocity of 12 feet per second. The javelin (torpedo-carrier) is readily kept at any particular depth during its progress by a simple application of the hydrostatic pressure on a tail or rudder acting in the horizontal plane. The load inserted at the tail end of the javelin (torpedo-conductor) to balance the shell (torpedo) being applied at the bottom, the instrument cannot turn in the water.

CONCLUDING REMARKS.

This new system of naval attack will place an entire fleet of sailing vessels, during calms and light winds, at the mercy of a single craft. "Boarding" as a means of defence will be impracticable, since the turret guns, which turn like the spokes in a wheel, commanding every point of the compass at once, may keep off and destroy any number of boats by firing slugs and combustibles. The loading at the breech and the dispensing with sponging ensures a rapidity in the discharge of missiles quite irresistible in an attempt at boarding. A fleet at anchor might be fired and put in a sinking condition before being able to get under way.

Of what avail would be the "steam guard-ships" if attacked on the new system? Alas! for the "wooden walls" that formerly "ruled the waves." The long-range Lancaster gun would scarcely hit the revolving iron turret once in six hours, and then, six chances to one, its shot or shell would be deflected by the varying angles of the face of the impregnable globe. When ultimately struck at right angles, the globe, which weighs upwards of 40 tons, will be less affected by the shock than a heavy anvil by the blow of a hammer. Consequently, a cast-iron shot would crumble to pieces, whilst an exploding *shell* would strew the arched deck with harmless fragments.

During contest the revolving turret should be kept in motion, the port-holes being turned away from the opponent except at the moment of discharge, which, however, should be made during full rotation, as the lateral aim in close quarters requires but little precision.*

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* Captain Coles, of the British Navy, having claimed priority of invention, the following statement was published in various nautical and mechanical journals (1862):

"ABSURDITY OF CAPTAIN COLES'S CLAIM.—Captain Coles states, in a letter to the *Times* of April 5, 1862, that his experience in the Baltic and Black Seas, in 1855, suggested to him the idea of building impregnable vessels, and that, towards the latter part of that year, he had 'a rough model made by the carpenter of the *Stromboli*,' and that he proposed to protect the guns by a stationary shield or cupola. Captain Coles, it appears, met with no encouragement from the Admiralty, and therefore consulted Mr. Brunel, the celebrated engineer, who warmly embraced the plan. 'He did more,' says Captain Coles in his letter to the *Times:* 'he assisted me in my calculations, and gave me the aid of his draughtsmen.' Captain Coles further states that, notwithstanding official neglect, he persevered, and in March, 1859, produced drawings of a 'shield fitted with turn-tables.' Lastly, in December, 1860, Captain Coles published in *Blackwood's Magazine* drawings of his 'gun-shield and revolving platform,' the platform being turned by manual power only."

CHAPTER XXIX.

SURFACE-CONDENSER, OPERATED BY INDEPENDENT STEAM-POWER.

(SEE PLATE 43.)

The following is an exact copy of the description accompanying the patent granted by the United States (1849) for the independent-action condenser illustrated on the plate referred to:

Fig. 1 is a longitudinal vertical section; Fig. 2, a cross-section of the condenser taken at the line (X X) of Fig. 1; and Fig. 3, a cross-section of the pumping part of the apparatus and the auxiliary engine by which it is operated. The same letters indicate like parts in all the figures.

The object of my invention is to condense the steam without admixture with the condensing-water, that the water produced by the condensation may be carried back to the boiler, to prevent the evil consequences arising from the use of water that contains in solution or suspension mineral or other solid matter, and to condense the steam which escapes from the safety-valve, and also for the production of fresh water for any other use.

In my fresh-water apparatus I use a tubular condenser, through the tubes of which the steam passes, and is condensed by the cooling influence of a current of cold water taken from the outside of the vessel or ship, and made to pass outside of the tubes; and to this end the first part of my invention consists in combining the condenser of a steam-engine for the propelling of a ship or vessel with a pump which receives the condensing water from outside the ship or other vessel, and causes it to pass through the condenser, the said pump being operated, irrespective of the engine that propels the vessel, by means of an auxiliary engine, whereby the amount of condensation can be regulated independently of the working of the engine that propels the vessel. The second part of my invention consists in connecting the condenser with the boiler or boilers, or any part thereof, in addition to its or their connection with the exhaust of the engine, when the pump which carries the condensing water through the condenser is operated by an auxiliary engine, by means of which double connection not only is the steam that escapes from the safety-valve condensed to be carried back to the boiler, but the boiler or boilers may be used to distil and produce fresh water for any purpose desired when the engine is not employed for propelling the vessel. And the last part of my invention consists in connecting the tubes of the condenser with the cylinder or outer case thereof by connecting one or both of the diaphragms to which the ends of the tubes are secured with the outer cylinder or case by means of a ring and flange, or the equivalent thereof, so that the said ring or flange may bend to adapt itself to the unequal contraction and expansion of the tubes and cylinder or outer case of the condenser.

In the drawings on Plate 43 (*a*) represents a horizontal cylinder, within which are arranged a series of small parallel tubes (*b*). One end of the said tubes is secured, in the usual way or any other desired and appropriate manner, to a diaphragm (*c*), which has a turned flange through which rivets or bolts (*d*) pass to secure it to the cylinder (*a*), and within such distance of the head as to leave a sufficient space between it and the head (*e*) of the cylinder for two chambers (*f*) and (*g*), these two chambers being separated by a horizontal diaphragm or partition (*h*). The other ends of the tubes are in like manner secured to another diaphragm (*i*) at the other end, which said diaphragm, instead of being bolted directly to the end of the cylinder in the usual way, is bolted to a ring (*j*) near its outer periphery, the inner periphery thereof being provided with a turned flange bolted to the end of the cylinder; but, instead of this, the end of the cylinder may be made with a flange corresponding in size and form with this ring, and the diaphragm bolted to its outer periphery. The said ring or flange should be slightly conical, or bent, that the diaphragm may be at some distance from the end of the cylinder, that it may move in and out to adapt itself to the unequal contraction and expansion of the tubes and cylinder by reason of the passage of the steam through the tubes and the water for the condensation through the cylinder. A chamber (*k*) is formed at this end of the cylinder by means of a head (*l*) secured to the diaphragm by means of a double-flanged ring (*m*) and screw-bolts, that it may be removed to give access to the tubes.

The upper chamber (*f*), at the end of the cylinder first described, communicates, by means of a pipe (*n*), in any desired manner with the exhaust-pipe of the engine, and, by another pipe (*n′*), also with the escape-pipe of the boiler, and these connections should be governed by appropriate cocks or valves, so that either can be opened or closed at pleasure. Either of these connections being opened, the steam passes into the chamber (*f*), thence through the range of tubes above the diaphragm or partition (*h*) to the chamber (*k*) at the other end, and thence back through the lower range of tubes to the lower chamber (*g*), which communicates by means of the pipe (*o*) with the air-pump and supply-pumps of the engine, or, this connection being closed, by means of a pipe (*o′*) with any desired recipient with which the pipe (*o′*) may communicate. The direction of the passage of steam, and the water produced by its condensation, through the tubes, is indicated by the dotted arrows.

The steam, in passing through the tubes, is condensed by the cooling influence of a constant current of cold water which passes outside of the tubes, and which travels in a direction the reverse of the current of steam, as indicated by the white arrows, so that the steam as it parts with its caloric is constantly approaching a cooler medium.

The water for the condensation is forced into the cylinder (*a*), near the diaphragm (*c*), through a pipe (*p*), and passes around the lower half of the series of tubes until it strikes the other diaphragm (*i*); thence it passes up around the end of a horizontal position-plate (*q*) on the same plate (*h*), which plate (*q*) extends from the diaphragm (*c*) to within a short distance of the other diaphragm (*i*), and from this the water passes around all the upper half of the tubes to the first, where it escapes at the top through a pipe (*r*) that discharges through the side of the vessel above the water-line.

The water from the condensation is impelled through the condenser by a rotating pump, the case (*s*) of which is provided with a tangential pipe (*t*) at the lower part connected with the part (*p*) by the condenser. And this case is also provided with another pipe (*u*) which extends from the centre thereof, to and through the side of the vessel, and so far down as to be always below the water-line, that the water may flow through it to the inside of the pump-case. To the centre of this case is adapted the shaft (*v*), the journals of which run in appropriate boxes (*w w*) in the case, and provided with stuffing-boxes to prevent the escape of water; and on this shaft is a hub (*x*), with four arms or vanes (*y*) accurately fitted to the case, and yet to rotate without touching it. By the rotation of these arms or vanes the water is drawn in near the centre, and by centrifugal force carried out through the tangential pipe (*t*) to and through the condenser. And the required rotation of the pump is given by an engine (*a′*) secured to the casing of the rotary pump as represented in the drawings, and the connecting-rod (*b′*), which is jointed in the usual manner to the cross-head (*c′*), takes hold of a crank (*d′*) on the shaft of the pump, the said shaft being, in the usual manner, provided with an eccentric (*e′*) for working the valves of the engine (*a′*), which are not represented, as they may be on any of the known plans. The water-supply pump, which receives the water from outside the vessel, and which is for that purpose below the water-line, is provided with a valve (*f′*), the stem (*g′*) of which passes through stuffing-boxes, and has a handle (*h′*) by means of which the pipe can be closed at pleasure when it becomes necessary to give access to the inside of the pump.

From the foregoing it will be seen that, by means of the auxiliary engine which operates the pump, a constant current of cold water is carried through the condenser independently of the working of the propelling engine of the vessel, and, as a necessary consequence, the more the propelling engine labors, by reason of head winds or rough water, the more perfect will be the condensation and the vacuum thereby produced, thus increasing the power of the propelling engine when the power is most needed; whereas if the current of cold water were dependent on the working of the propelling engine, the sum of the mass of water passing through the condenser would be exactly in proportion to the motion of the engine, and therefore the condensation and vacuum would be decreased in the ratio of the decreased motion of the propelling engine.

It will also be seen that, by reason of the working of the pump which impels the water for the condensation by means of an auxiliary engine, and the double connection of the condenser with the waste-pipe of the boiler or boilers, and with the exhaust of the propelling-engine, whenever the safety-valve is opened, the steam issuing therefrom, instead of being wasted, will be carried through the condenser and condensed, to be returned to the boiler, thus avoiding the necessity of a separate supply of water to make up for the waste by the escape of steam from the safety-valve; and that when the propelling-engine is at rest the condenser can be used for the distillation and production of fresh water for any desired purpose on board ship, for the condenser is thus, when desired, rendered entirely independent of the propelling-engine.

By passing the current of steam in a direction the reverse of the current of condensing-water, the greatest amount of caloric is extracted with the least amount of water.

The condensing-water in its passage through the condenser never reaches the point of evaporation, and therefore mineral and other matter held in solution will not be deposited to encrust the apparatus; and by ensuring a constant and rapid current of water around the tubes the danger of unequal contraction and expansion is reduced to the smallest amount, and so small as to prevent all injurious effects by the mode above described of connecting one of the diaphragms, to which one end of the tubes is attached, with the cylinder by means of the conical or bent ring or flange.

Although I have described the use of a rotary pump, operated by a reciprocating engine, for impelling the condensing-water through the condenser, I do not wish to confine myself to the use of either a rotary pump or a reciprocating engine for this purpose, as a rotary engine may be substituted for the reciprocating, and a reciprocating pump for the rotary; but I have described and represented this arrangement as the one which I have successfully essayed and deem the best.

CHAPTER XXX.

THE CALORIC ENGINE.

APPLICATION OF HEATED AIR AS A MOTOR.

(SEE PLATES 44 AND 45.)

ENGINEERS are aware that I built a caloric engine in London, 1833, operated by heated atmospheric air; Faraday, Ure, and Lardner taking great interest in the same in consequence of its being based on the principle of returning, at each stroke of the working piston, the heat not converted into mechanical work during the previous stroke. After my arrival in this country, 1839, I prosecuted the plan and built several caloric engines in succession, all of which promised ultimate success. At each step the dimensions were enlarged, until I produced an experimental engine, in 1851, having two working cylinders of seventy-two inches diameter, two feet stroke, and two compressing cylinders of fifty-eight inches diameter (see illustrations on Plates 44 and 45). The leading feature of this large caloric engine was that of circulating the heated air, as it passed off from the working cylinder, through a series of wire discs containing an aggregate of 13,520,000 meshes for each working cylinder. The cold air in entering the engine was admitted through the meshes of the heated discs, taking up nearly the whole of the heat previously imparted by the exhaust air in its passage through the meshes, on its way to the atmosphere.

DESCRIPTION OF THE ILLUSTRATIONS REFERRED TO.*

Fig. 1 represents a transverse section, and Fig. 2 a longitudinal section of the engine.

a, air-receiver. *b b*, supply-cylinder. *e*′, self-acting valve for letting air into, and *e*″ self-acting valve for letting air out of, the same. *c*, supply-piston; *c*′, piston-rod of the same, connected to the working-beam of the engine. *d d*, working-cylinder; *d*′ *d*′, holes at the junction of the two cylinders, through which the atmospheric air passes in and out freely. *e e*, working-piston; *d*″ *d*″, rods connecting the two pistons together. *e*‴, air-tight vessel, suspended below the working-piston, filled with clay and charcoal to prevent transmission of heat from below. *f f*, regenerator; *f*′, discs of wire-net, placed vertically in the regenerator-box. *g*, valve, worked by the engine, for admitting air into the regenerator and working-cylinder; *h*, valve for letting air out of the same. *i i*, pipe, open to the atmosphere, for carrying off the air after having passed through the engine; *k*, fire-place.

The operation of the engine is briefly as follows: A slow

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* Copied from *Appleton's Magazine* of 1853.

fire being kept up at *k* for about two hours, until the various parts contained within the brick-work shall have become moderately heated, the air-receiver is charged by means of a hand-pump. As soon as the internal pressure shall have reached about six pounds to the square inch—invariably effected in less than two minutes—the hand-pump is stopped, and the valve *g* opened by a starting lever, as in steam-engines; the compressed air from the receiver, thus admitted under the valve *g*, rushes through the partially heated wires *f′* into the working-cylinder, forcing its piston *e* upwards, as also the supply-piston *c*, by means of the connecting-rods *d″ d″*. The atmospheric air contained in the upper part of cylinder *b* will, by this upward movement of the supply-piston, be forced through the valve *e″* into the air-receiver. When the working-piston has reached three-fourths of the full stroke, the valve *g* is closed by the engine; and when the piston has arrived at the full up-stroke, the valve *h* is opened. A free communication with the atmosphere being thereby established by means of the open pipe *i i*, the air under the working-piston passes off, and, owing to the removal of pressure under the working-piston, it will instantly begin to descend by its own weight.

The heated air from under the working-piston, in passing off through the wires *f′*, gives out its caloric to the same so effectually that, on reaching the thermometer *m*, the temperature never exceeds that of the entering air at *l* by more than 30°; on the other hand, the cold air from the receiver, in circulating through the meshes of wires in its passage to the working cylinder, becomes so effectually heated that, on passing *n*, its temperature is invariably increased to upwards of 450° when the machine is in full operation.

It is evident that during the descent of the supply-piston *c* the outlet valve *e''* remains closed by the pressure from the receiver, whilst the inlet valve *e'* is kept open by suction, and *hence* that a fresh quantity of atmospheric air enters the supply-cylinder at each down-stroke of its piston, and by the up-stroke is forced into the receiver. There being two supply-cylinders of alternating action, a constant supply of fresh air into the receiver is obtained for feeding the working-cylinders.

It need hardly be stated that the smaller quantity obtained by the supply-cylinder suffices to fill the larger capacity of the working-cylinder, in consequence of the increase of volume attending the increase of temperature; nor need it be stated that an equal amount of force is exerted by the up-and-down movement, as there are two pairs of cylinders attached at opposite ends of a common working-beam.

The foregoing description being deemed sufficient to explain the mechanical operation of the engine, the result of its prolonged trial may now be considered; but, before doing so, it will be well to state some particulars in relation to the regenerator. The regenerator measures 26 inches in height and width internally; each disc of wire contains 676 superficial inches, and the net has 10 meshes to the inch; each superficial inch, therefore, contains 100 meshes, which, multiplied by 676, gives 67,600 meshes in each disc; 200 discs being employed, it follows that each regenerator contains 13,520,000 meshes, and, consequently, if we consider that there are as many small spaces *between* the discs as there are meshes, we shall find that the air within the regenerator is distributed in 27,000,000 minute cells. Theory clearly indicates that, owing to the small capacity for heat of atmospheric air (that beneficial property which the Great Mechanician gives to it as a fit medium for animated *warm* beings to live in), and in consequence, also, of the almost infinite subdivision among the wires, the temperature of the circulating air, in passing through the regenerator of the caloric engine, must be greatly changed. Practice has fully realized all that theory predicted, for the temperatures at x and z have never varied during the trials less than 350°, when the engine has been in full operation; indeed, it has been found *impossible* to obtain a differential temperature of less magnitude, with sufficient fires in the furnaces.

The reason is evident: the *cold* air from the receiver is half the time playing upon the wire discs at x, whilst the *heated* air from the working-cylinder is playing during the other half on the wire discs at z; as no heated air can reach the former without passing through the regenerator, and as no *cold* air can reach the discs at z before likewise passing all the wires, it follows that the establishing an equilibrium of temperature becomes impossible. The great number of discs, their isolated character, and the before-named distribution of the air in such a vast number of minute cells, readily explain the surprising fall and increase of temperature of the opposite currents passing the regenerator, and which constitutes the grand feature of the caloric engine, effecting, as it does, such an extraordinary saving of fuel by rendering the *caloric* not converted into mechanical work active over and over again.

In further explanation of the wonderful efficiency of the regenerator, it may be stated that each disc contains 1,140 feet of wire in length, and each regenerator 228,000 feet, or $41\frac{1}{2}$ miles, of wire; the superficial measurement of which is 2,014 square feet, which is equal to the entire surface of four steam-boilers forty feet long and four feet diameter; and yet the regenerator displaying that amount of heating surface is only two feet cube, less than $\frac{1}{1920}$ of the bulk of said boilers!

In regard to *loss of heat*, the result of ample trial has been that at no time has the temperature of the escaping air at *m* exceeded that of the entering air at *l* by more than 30°. As this differential temperature exhibits the *positive loss of heat*, it becomes important to ascertain its amount in pounds of coal: the area of the supply-piston is 2,626 square inches, and its stroke two feet; hence $36\frac{4}{10}$ cubic feet of atmospheric air is supplied for each stroke, and therefore at 30 strokes 1,092 cubic feet, and for both cylinders 2,184 cubic feet per minute = 131,040 cubic feet per hour. The weight of atmospheric air is nearly $13\frac{1}{2}$ cubic feet to the pound, and hence it will be seen that 9,706 pounds of air pass through the engine every hour. We know that one pound of coal will raise the temperature of 10 pounds of water 1,100°, while the specific heat of water is to that of the air as 26 : 100; hence it will be seen that $38\frac{4}{10}$ pounds of air will be elevated in temperature 1,100° with one pound of coal. Now, the observed loss of heat in the engine being 30°, the fact will be established that the loss will amount to one pound of coal for every 1,408 pounds of air passed through the engine, which, on 9,706 pounds, proves the actual loss of heat in both regenerators to be only $6\frac{3}{10}$ pounds of coal per hour. A pressure of 13 pounds being sustained in the receiver, exerting 60 horse-power with an actual waste of only 6.8 pounds per hour, it will be found that *two* ounces of coal per hour per horse-power is the quantity of fuel absolutely wasted in the process of transfer. The actual consumption of the engine is, however, nearly 40 pounds per hour, which is thus proved by the foregoing to be chiefly carried off by radiation of heat. On a large scale much of that radiation will be prevented. As the machine stands, an indicated horse-power is produced by a consumption of less than 11 ounces to the horse-power per hour.

The following particulars are of considerable practical importance:

1st. The valves g and h are *not* subjected to heat, the caloric being taken up by the wires before reaching the valves.

2d. The temperature of the packing of the working-pistons does not exceed boiling heat at any time, proving the efficacy of the heat-intercepter e'''.

3d. As only a slow radiating fire is needed, it has been found that common whitewash, applied to the under side of the heater, remains for several weeks, proving conclusively that the effect of the heat is quite harmless.

4th. A hole of half an inch diameter, kept open for several hours, in the valve-chest, under the inlet-valve *g*, does not sensibly affect the pressure in the receiver *a*, so abundant is the supply of air. This fact has surprised all practical men who have witnessed the operation of the engine. It proves completely that the machine need not be perfectly air-tight, as supposed by many.

5th. After putting a moderate quantity of fuel into the furnace, it has been found that the engine works with full power for three hours without fresh feed, and, after removing the fires entirely, it has frequently worked for one hour.

The regularity of action and perfect working of every part of this experimental engine, and, above all, its apparent great economy of fuel, induced some enterprising merchants of New York, in the latter part of 1851, to accept my proposition to construct a ship for navigating the ocean propelled by paddle-wheels actuated by the caloric engine. This work was commenced forthwith, and pushed with such vigor that within nine months from commencing the construction of the machinery, and within seven months from laying the keel, the paddle-wheels of the caloric ship *Ericsson* turned round at the dock! In view of the fact that the engines consisted of *four* working-cylinders of 168 inches diameter, 6 feet stroke, and *four* air-compressing cylinders of 137 inches diameter, 6 feet stroke, it may be claimed that, in point of magnitude and rapidity of construction, the motive machinery of the caloric ship stands unrivalled in the annals of marine engineering. It may be added that the principal engineers of New York all expressed the opinion that a better specimen of workmanship than that presented by the huge engines of the caloric ship had not been produced by our artisans up to that time.

The following data, published in *Appletons' Mechanics' Magazine*, will interest the professional reader:

DIMENSIONS OF THE ERICSSON.

Length on deck,	260 feet
Length of keel,	250 "
Breadth of beam,	40 "
Depth of hold,	27 "
Draught of water on trial-trip,	17 "
Diameter of wheels,	32 "
Length of bucket,	10½ "
Breadth of bucket,	20 ins.
Dip of wheel (supposed about),	2 feet.

ENGINES.

Number of working-cylinders or single-acting air-engines,	4
Diameter,	168 inches.
Area of piston,	22167.07 sq. in.
Stroke,	6 feet.

Portion of stroke from commencement at which air is "cut off" (about),	$\frac{63}{100}$
Cubical contents of each working-cylinder,	1596024 cub. in.
Cubical contents of $\frac{63}{100}$ of working-cylinder,	995495 "
Number of supply-cylinders or single-acting pumps,	4
Diameter,	137 inches.
Area of piston or plunger,	14741 sq. in.
Stroke, necessarily,	6 feet.
Cubical contents of each pump,	1061352 cub. in.
Number of regenerators,	4
Number of discs of iron-wire netting in each regenerator,	50
Height of each disc,	6 feet.
Width,	4 "
Size of wire,	$\frac{1}{16}$ inch.
Ratio of area of openings in the netting to total area of disc,	$\frac{1}{2}$ to 1
Total area of opening of "air-way" through each disc, $\frac{6 \times 4}{2} =$	12 sq. ft.
Greatest or total heat of air in working-cylinder above atmosphere,	384° F.
Heat of issuing air above atmosphere,	30° F.
Pressure necessary to move the engine,	$\frac{1}{2}$ lb.
Coal consumed in the four furnaces per day,	6 tons.
Maximum coal possible to consume in the four furnaces per day,	7 "

Number of smoke-pipes,	2
Number of air-pipes,	2
Height of each smoke and air pipe above deck,	12 feet.
Diameter " " " "	30 inches.
Amount of air passing through the four cylinders per hour,	50 to 75 tons.
Depth of working-piston, or thickness,	6 feet.
Thickness of cylinder-bottom,	1½ inches.
Distance of grate from bottom of cylinder,	5 feet.
Ordinary pressure of the engine per sq. inch,	12 lbs.
Actual pressure on the second trial-trip, January 11,	8 "
Number of revolutions under pressure of 8 lbs. on trial trip,	9
Number of revolutions expected with 12 lbs. pressure,	12
Miles per hour obtained on trial-trip, January 11, allowing for tide, etc.,	7
Miles per hour expected with 12 lbs. pressure,	10 to 12
Number of meshes in each disc,	500000
Temperature in working-cylinder, 60° + 384° =	444°
Common temperature of the atmosphere (usual assumption),	60°
Specific heat of air—water being 1000,	.2669
Common pressure of air per square inch = 14.73 lbs., say	15 lbs.
Weight per cubic foot, common pressure and temperature = .0752914 lbs., say	$\frac{1}{13}$ lb.

Density of air, temperature remaining constant, is directly as the pressure.	
Weight per cubic foot, at 12 lbs. pressure, common temperature, ...	$\frac{27}{195}$
Expansion of air at 32° for each degree added, according to Rudberg, . . .	$\frac{1}{493}$
Dalton and Gay-Lussac, .00208 ; Regnault, $\frac{1}{491}$; common estimate, ...	$\frac{1}{480}$
Expansion of air at 60°, for the 384° added,	$\frac{384}{508}$
Density of air at (60° + 384° =) 444°, compared with air at 60°, as . . .	$\frac{508}{508 + 384}$ to 1
Weight of a cubic foot at 12 lbs. pressure, temperature 444° = $\frac{508}{892} \times \frac{27}{195}$ = . .	$\frac{13716}{173840}$ lb.
Weight of 995495 cubic inches at 12 lbs. pressure, temperature 444° = $\frac{995495}{1728} \times \frac{13716}{173840}$ =	46 lbs.
Therefore, air passed through each cylinder each stroke, ...	46 "
Weight of 1061352 cubic inches, at common temperature and pressure = $\frac{1061352}{1728} \times \frac{1}{13}$ =	47.153 lbs.
Therefore, air passed each pump each stroke,	47 "
Allowance made for clearance, leakage, etc., per stroke, 47 − 46 = ...	1 lb.
Units of heat required to raise 47 lbs. air 384° = 47 × 384 × .2669 = ...	4817 units.
Units of heat retained by the 47 lbs. on escaping = 47 × 30 × .2669 = . . .	376 "
Units of heat transferred each stroke, . .	4441 "

Absolute theoretical consumption of heat per stroke, per cylinder, ...	376 units.
Mean pressure, per square inch, on working-piston, allowing for continued addition of heat while expanding, initial pressure being 13 lbs., about	10.8 lbs.
Mean force acting upon working-piston, 10.8 × 22167 = ...	239403.6 "
Mean resistance per square inch to supply piston, commencing with 0 and increasing to 12 lbs., at which pressure it continues to end of stroke.	
[The mean resistance in compressing an elastic fluid may be found by reversing the ordinary calculation on expansive working. The hyp. log. of $\frac{15}{27}$ is .588] 1.588 × 12 × $\frac{15}{27}$ =	10.55 lbs.
Mean resistance against supply-piston 10.55 × 14741 = ...	155598 "
Balance tending to move the engine, 239403 − 155598 = ...	83805 "
Units of power theoretically obtainable per stroke = 83805 × 6 = ...	502830 units.
Units of power theoretically obtainable from each unit of heat, ...	1337 "

The ship after completion made a successful trip from New York to Washington and back during the winter season; but the average speed at sea proving insufficient for commercial purposes, the owners, with regret, acceded to my proposition to remove the costly machinery, although it had proved perfect as a mechanical combination. The resources of modern engineering having been exhausted in producing the motors of the caloric ship, the important question has for ever been set at rest: Can heated air as a mechanical motor compete on a large scale with steam? The commercial world is indebted to American enterprise—to New York enterprise—for having settled a question of such vital importance. The marine engineer has thus been encouraged to renew his efforts to perfect the steam-engine, without fear of rivalry from a motor depending on the dilatation of atmospheric air by heat.

The engines of the caloric ship being an exact counterpart of the experimental engine of 1851, excepting dimensions, a description has been deemed superfluous. It may be mentioned, however, that the pair of engines in the caloric ship actuated a single crank in the middle of the paddle-shaft by connecting-rods working at right angles on a common crank-pin, as in all my marine engines.

CHAPTER XXXI.

CALORIC ENGINE FOR DOMESTIC PURPOSES.

(SEE PLATE 46.)

ALTHOUGH the caloric engine has proved inapplicable to navigation, it has been found to be of very great utility as a domestic motor, and for all purposes demanding a small amount of motive power.

The following interesting article from the New York *Tribune* of May 5, 1860, shows how rapidly the caloric engine was adopted after its adaptation to domestic purposes:

"THE NEW MOTOR.

"It is some eighty-six years since Mr. Boulton, at the great steam-engine works of Soho, made use of the memorable expression to Boswell: 'I sell here, sir, what all the world desires to have—POWER.' The mechanical world has been occupied from that time to the present with this problem of power, and mechanical ingenuity has tasked and exhausted itself with efforts to construct a machine that should prove an efficient auxiliary or rival of the steam-engine. And it is most extraordinary that, notwithstanding the amount of inventive genius and science that has been expended in this special field of labor, literally nothing had been accomplished of any practical importance till Ericsson produced the caloric engine, in the particular form and with the peculiar devices which distinguish it from all the engines actuated by heat, that have been built at such an enormous expense of time and money.

"Motive engines of a moderate or even of a small power play a very important part in the economy of human life. The frightful horrors of the slave-trade; the scarcely less frightful horrors of the traffic in Coolies; nay, the haggard features and jaded limbs that, in our great cities more especially, speak so distinctly of over-wrought human labor, and cry out so emphatically for relief—all these demonstrate that a compact, manageable, safe, and economical motor, adequate to the work of a *single* slave or Cooly, or overtasked white man or white woman, would do more to mitigate the suffering and diminish the drudgery of mankind than any other conceivable invention. After all the enormous accumulations of steam-power, water-power, wind-power, and horse-power, and their vast achievements, by how much the larger amount of power exercised in the world is the aggregate result of individual force applied to the thousands of little things that occupy the human family in the daily routine of living! Combine these forces, and what a stupendous whole they exhibit! Make an available motor that shall be of one-man power, and what a result is obtained! Make a motor perfectly safe, easily kept in order, requiring no water, and consuming but little fuel, of the power of a single horse, to what an extent the aggregate result is augmented, and what an importance in human affairs such a machine assumes!

"If Ericsson's caloric engine, then, claimed to be nothing but such a motor, it would be a subject well deserving the most earnest and serious investigation; but the proof is accumulated, of a nature that compels belief and defies contradiction, which demonstrates the existence in this engine of a power entirely sufficient for all but a very few of the thousand uses for which power is required.

"It is not material to our purpose to indulge in any retrospective review of Ericsson's labors. It is well known that this grand invention has occupied thirty years of his life, during which he has built many engines of the largest size and uncounted experimental engines of smaller power.

"We have seen an official statement in relation to an engine put up about a year since to supply the locomotives at the South Groton Station, on the Fitchburg Railroad. From April, 1859, to April, 1860, this engine pumped 1,600,000 gallons of water, at an expense to the company for fuel and oil of $25, and for an 'engineer' $25, and has not cost one cent for alteration or repairs.

"A result more important, in view of the number of engines employed, is exhibited on the New York Central Railroad, on the line of which there are now some twenty of these engines in daily use. Mr. Chauncey Vibbard, the Superintendent of that road, reports, over his official signature, after several months' experience with a number of these engines, that they perform an 'incredible' amount of labor 'for the small quantity of fuel consumed.' One of them, he says, for $\frac{96}{100}$ of a cent per hour, does the work formerly done by four men at an expense of $25 each per month. Another, of the same size, at the Savannah Station, at an expense of eleven cents a day, does the work of five men who received $125 a month. Other engines have been erected on several other railroads for pumping purposes with the same favorable result.

"The second application of the caloric engine was to the driving of printing-presses. The first trial of the engine for this purpose was made in the office of the Hartford *Times;* the first that was entirely successful was made in the office of T. W. Strong, No. 98 Nassau Street, in this city. The next engine built was set up in the office of Messrs. French & Wheat, No. 18 Ann Street, and the third in the office of Mr. C. C. Shelley, a job-printer in Barclay Street. The result has been the adoption of the engine in numerous job-offices in every part of the country. There are now no less than forty daily papers in the United States printed by Ericsson's engines, most of them of 24-inch, but three or four of 12 and 18 inch cylinders. One of the most recent testimonials to its value is from the proprietor of the Savannah *Evening Express,* who states that he regards it as the most perfect and economical motive power ever applied."

Several thousand caloric engines were subsequently constructed in this country and in Europe; but steam-engineers, finding by the extraordinary demand for caloric engines that very moderate power was a great desideratum, have perfected the steam-motor until it almost rivals the caloric engine in safety and adaptability; consequently, the demand for caloric engines has been greatly diminished of late. Yet this motor can never be superseded by the steam-engine, since it requires no water, besides being absolutely safe from explosion. There are innumerable localities in which an adequate quantity of water cannot be obtained, but where the necessities of civilized life call for mechanical motors; hence the caloric engine may be regarded as an institution inseparable from civilization. It should be stated that the caloric engine has been found to furnish the only reliable motive power for operating the fog-signals on our coasts. The following statement, presented to the Light-House Board, sets forth very clearly the advantages of the air motor for the purpose mentioned:

With reference to the important question whether steam is a proper motive power for actuating the mechanism connected with fog-signals, I beg to express the opinion that unless a safer motor can be found than the steam-engine—more particularly a high-pressure steam-engine—the great practical benefit which you expect from the contemplated system of fog-signals will never be realized. My reason for expressing this opinion will be found in the following brief summary: 1. A high-pressure steam-boiler, even when supplied with pure, fresh water, is an apparatus which demands the constant attention of an experienced person. Considering that any neglect in keeping up the feed in the boiler will inevitably result in an explosion, it is highly imprudent and scarcely humane to put such an instrument in the hands of a light-house keeper. Let us reflect on the well-known fact that when a boiler foams even the practised engineer is sometimes at a loss to determine the height of water within. 2. Apart from the difficulty and danger thus alluded to, another circumstance presents itself connected with the employment of steam, which is practically insuperable, viz., that brackish or salt water must be resorted to in most localities. Accordingly, unless a certain quantity of the salt water is regularly drawn off and replaced by water less impregnated with saline matter, the boiler will, at best, be rendered useless by the deposit formed. In most cases the first warning to the unskilful light-house keeper will probably be the explosion of the boiler.

In connection with this most important matter, I cannot omit adverting to the fact that the employment of salt water for land engines attended by skilful engineers has been found so impracticable that means of procuring fresh water—in many cases at very great cost—have been deemed indispensable. It is only in the steam-ship, where the most competent engineers are employed, provided with salinometers and other instruments, that it has been found practicable to employ *salt* water. But even in the steam-ship salt feed has been dispensed with by employing the surface-condenser as the only certain means of saving the boilers from incrustation.

3. During cold weather, another serious difficulty will be encountered if you employ *steam*, which calls for the application of costly and complicated contrivances. Unless the boiler is constantly under steam, it must be kept in some place adequately heated by stoves to prevent pumps, pipes, and cocks from freezing. Not only this, the cistern itself, which is to supply the boiler, will, on our inclement coast, freeze unless warmed by some means. I need scarcely remind you that, in many localities, the entire supply of water will wholly fail during continued cold, dry weather. In fine, the disadvantages of steam for any general system of fog-signals are so numerous and formidable as to render the very proposition to employ that agent an absurdity.

Having thus briefly disposed of the question of employing steam as the motive power for actuating the machinery of your proposed fog-signals, I have now to state that long practice has shown that the expansive force of heated atmospheric air furnishes a reliable *dry* motor wholly independent of atmospheric temperature. The advantages of such a motor, more especially as it requires no particular kind of fuel, are so obvious that I will not detain you by enumerating the same. Suffice it to say that it enables you to locate your fog-signal on the dry, barren rock as well as on the moist, sandy beach; and that its efficiency is not affected by the most intense cold, and that, so far from demanding a heating apparatus during the inclement season, the light-house keeper will find it a very desirable accessory in warming his quarters. Above all, while it thus adds to his comfort, it carries no danger with it. The worst that can happen is that the machine will stop for want of fuel, or that its speed will slacken for want of oil being applied to the bearings. The caloric engine is now so well known that I need not enter on a description of its construction. It will be necessary, however, to advert to the fact that the caloric engine is more bulky and of greater weight than the steam-engine, and that its cost is some 50 per cent. greater. These disadvantages, however, as regards the application to fog-signals, become trifling, in view of the before-named advantages. Indeed, in many places the cost of procuring a suitable supply of water will be far greater than the difference of price of engine—leaving out of sight the impossibility of procuring suitable water in many cases.

The leading features of the domestic caloric engine will be seen by reference to Plate 46, representing a longitudinal section through the central vertical plane. Professor Barnard having very thoroughly examined one of these engines at the Paris Exhibition, 1867, I propose to present a copy of his report:

" In its present form the Ericsson engine fails to present to the observer a combination at first view easily intelligible. It even seems to be characterized by a certain amount of complication, which might suggest greater liability to derangement than ought to belong to a prime mover. A closer examination, nevertheless, will show that the mechanism itself is in fact very simple, and that it is only the rather puzzling consecution of movements which confuses.

"Before referring to the figure of this engine, which is given in the illustration on the plate mentioned, the following general explanation of the mechanical principles of its construction will be understood. Let it be supposed that a piston moves air-tight in a cylinder which is closed at both ends. Call one end of the cylinder A, and the other B. Call the piston also C. In the end A let there be a valve opening inward, and in the end B a second valve opening outward. These two valves open, then, in absolute direction, the same way. Let the piston C, furthermore, have a valve opening in this common direction. Then, if the piston C move toward B, its own valve will naturally close, and that of B will open, because the movement tends to compress the air between B and C. Also the valve A will open at the same time, because the movement tends to rarefy the air between A and B. Thus, in this movement, continued to the end of the cylinder, all the air on the side toward B may be expelled; but at the same time the cylinder will be filled on the other side toward A, by the influx of air from without. If the piston C now reverse its motion, both the valves A and B will be closed, because the movement will tend to rarefy the air on the side of B, and to condense it on the side of A. But its own valve will be opened by the joint effect of these causes, so that the air will pass freely through the piston, and, if the motion continues, will ultimately be all transferred to the side of B. This operation may go on indefinitely.

"Now, if, on the side of A, the cylinder is closed by a second piston (which we may still call A), and not by a fixed cap, both pistons being movable, the same succession of occurrences will take place, only modified by the movements which may be given to A. If C and A both move in the direction of A, both their valves will open, and air from the exterior of the cylinder will pass through both into the space between B and C. If they both move toward B, but C faster than A, then air will enter on the side of A, and flow out on the side of B, the valve C only remaining closed. If both move toward A, but A faster than C, air will still enter the space between C and A, while, in less quantity, it is passing through C into the space between C and B.

"Let now the piston A be supposed to occupy a position, say, one-third advanced down the cylinder, the piston C being further advanced still, and let the valve of B be secured by a strong spring pressing upon it, so that it cannot be opened without the application of some considerable force; and in these circumstances let the cylinder, and consequently the air contained in it, be heated. The elasticity of the confined air, being increased by heat, will close the valve in A, and that piston will be moved in the direction of A, until, by the enlargement of volume, the elasticity shall be reduced to equality with that of the external air. If the heat be uniform throughout all the mass of confined air, the valve in C will be equally pressed on both sides. Under these circumstances, the piston C could be moved toward A, if there were any means of acting upon it, the air passing through the valve toward B. But if an attempt were made to move the piston itself toward B, it would encounter resistance, because its own valve would be closed by the movement, and the valve of B is supposed to be forcibly held down. Since now the external piston must move in the direction A, it is only necessary that it should be properly connected with a machine, in order that the force exerted by the heated and expanding air may be turned to some practical account.

" If, again, at the end of the movement the air could be immediately cooled without being discharged, the heat could be again applied and the effort repeated. But this not being practicable, the heated air may be allowed to escape by relieving the valve B of the pressure of the spring which confines it, and by causing the piston C to descend to the extremity B of the cylinder. This movement of C not only drives out the hot air, but it draws in through A a fresh supply of cold air; and if A descends simultaneously to the position originally supposed—*i.e.*, one-third advanced toward B—there will be a body of air filling the other two-thirds of the cylinder at the common temperature, ready to be acted on anew by heat.

"In this statement is embraced the general principle of the Ericsson engine. What remains is to explain the mechanical contrivances by which the movements of the pistons are governed, and to describe the heating apparatus which is employed to effect the prompt dilatation of the air. Inasmuch as the piston which we have called C is shut up in the cylinder behind A, it is necessary that the rods which give it motion should pass through A. They do so, being packed by means of stuffing-boxes to prevent leakage; and are connected at their external extremities with oscillating levers turning on a fixed centre of motion at their extremities, and kept in motion by the engine. The rod of the external piston A, which is the driving-piston, is also connected with an upright oscillating lever, turning on an axis of motion at its lower extremity, and carrying at its upper a horizontal connecting-rod, which acts on the crank of the main shaft of the engine. It would be simpler to connect the piston directly with this crank; but if that mode of connection were adopted, the stroke of the piston would have to take place in both directions, forward and back, in equal times. This condition is not favorable to the action of the machine; and inequality in this respect is still more important in the case of the supply-piston. The peculiar ingenuity of this machine is in fact manifested most signally at this point. By means of the systems of levers interposed between the pistons and the main shaft, provision is made for the perfect uniformity of the revolution of the shaft, while the pistons, on the other hand, are accelerated and retarded in such a manner as to fulfil the condition that the aspiration of the charge of air should occupy the minimum of time. The oscillating levers which connect with the piston-rods of the supply-piston are kept in oscillation by crank-motion from the main shaft, and in their oscillations they displace the inner piston, encountering no resistance but friction. In consequence of the un-uniform and unequal velocities of the two pistons, and their intentional adjustment, so that they do not begin and end their course together, the distance between them varies in a manner which is quite important: first, to the aspiration of the charge; and secondly, to the effectual exposure of the aspired air to the action of the furnace.

"It is of course of the highest importance that the positions of the cranks on the main shaft, and those of the axes of motion of the oscillating levers, should be so related to each other as to produce a rapid separation of the two pistons at the beginning of the negative stroke; because this is the time when the aspiration of the charge must take place. During this time, the inner piston, gaining on the outer, will not only draw in the fresh charge, but it will expel the exhausted one; the escape-valve being lifted for the purpose and kept raised during all the period of aspiration by means of a cam. When the pistons are at the maximum distance from each other, the aspiration is ended. From this time until the half revolution is complete, the confined air undergoes compression, and the movement is maintained by the fly-wheel. In the second half revolution the driving-piston is urged by the elasticity of the air which is exalted both by compression and by heat.

"The heating is accomplished as follows: The furnace is within the cylinder, at the end which we have called B, where the cylinder is prolonged to receive it. It is of iron, and is cylindrical also, a small annular space only intervening between its walls and those of the cylinder. This space is open to the interior, but is closed at the extreme end; so that it forms, in fact, a portion of the proper air-chamber. To the supply-piston C is attached by its crown a sheet-iron cylindrical bell, which enters the annular space just spoken of without touching the walls of the furnace or those of the surrounding cylinder. The valve in C opens above the crown of this bell; but any air which comes through the valve from the side of A can only reach the interior by passing down the annular space between the bell and the cylinder wall, and returning up the annular space between the bell and the wall of the furnace. In making this passage, it will be exposed in a very thin sheet to the action of the furnace heat, a very large proportion of the molecules being brought into direct contact with the heated iron.

"That we may understand how this movement of the air is made forcibly necessary, we need only consider the relative movements of the pistons during the period of a complete revolution. At the beginning of the negative stroke, or of the movement of A in the direction of B, the supply-piston takes the lead, air enters through the valve of A, and the aspiration is soon complete. The distance between the two pistons, which determines the amount of aspiration, is now of course at its maximum. A next begins to gain on C, but both movements have still for a short time the same (negative) direction. The space occupied by the air is gradually reduced; or, in other words, the air undergoes compression. The piston C reaches the limit of its course sooner than A. It begins to move in the positive direction, while the motion of A is still negative. The valve in C is opened by the pressure, the air passes through, and, having no other channel, descends the annular space outside of the bell, and returns by the annular space inside the bell, becoming heated, as above described, in its progress. Presently after this displacement commences, the piston A also reaches its limit of movement, and the direction of its motion becomes positive. But C moves the faster of the two, so that the displacement continues throughout the greater part of the positive stroke. A little before the end, the distance between the two pistons becomes minimum, and they are then nearly in contact. When the revolution is quite complete, this distance is slightly increased. Just before this time C will have recommenced its negative movement, while A continues still to be moving in the positive direction.

" The relative movements here described will be more advantageously compared by presenting them in tabular form, which we are enabled to do by the help of the determinations made by Mr. Mastaing, of Paris, upon the Ericsson engine, which was made the subject of experiment in 1861 at the Conservatoire des Arts et Métiers, by Mr. Tresca, sub-director of that institution. In the first column of this table are placed the angular positions of the driving-crank on the main shaft at different periods of the revolution; putting zero to represent the position of the crank when the piston A is about to commence its negative stroke. The second column gives the direction of motion of the driving-piston, and its motion relative to that of the other; and the third column gives the same particulars in regard to the supply-piston. The last column gives the variation of distance taking place between the two pistons at the several points indicated in the table.

Angular position of the crank.	Relative motion of the pistons.		Distance between the pistons.
Degs.	Driving-piston.	Supply-piston.	
0 to 70	Negative, losing...	Negative, gaining..	Increasing.
70	Negative, equal...	Negative, equal...	Maximum.
70 to 120	Negative, gaining..	Negative, losing...	Decreasing.
120	Negative, gaining..	Limit of course....	Decreasing.
120 to 170	Negative, contrary.	Positive, contrary.	Decreasing.
170	Limit of course....	Positive, gaining..	Decreasing.
170 to 310	Positive, losing....	Positive, gaining..	Decreasing.
310	Positive, losing....	Positive, gaining..	Minimum.
310 to 340	Positive, gaining..	Positive, losing....	Increasing.
340	Positive, gaining..	Limit of course....	Increasing.
340 to 360	Positive, contrary.	Negative, contrary.	Increasing.

"It will be seen that the negative stroke is completed in less than half a revolution for either piston, while the positive stroke requires more; also, that this inequality is considerably greater for the supply-piston than for the driving-piston. In the case of the driving-piston the inequality is as 170 to 190 deg.; in that of the supply-piston, as 160 to 200 deg. These inequalities, which could not exist if the connection between the main shaft and the pistons were made directly, as in the steam-engine, are the effect of the intermediate system of levers, and are intentionally produced. The increase of distance between the pistons from 310 deg. to the end of the revolution is not an advantage, but it is not a great increase, the total distance amounting finally only to about the one-sixth part of the maximum separation, and receiving the principal accession to its amount between 350 and 360 deg. As, after the second reversal of the movement of the supply-piston, the effective power of the engine is necessarily paralyzed, the escape valve is opened at 344 deg. by the action of the cam above spoken of, and the aspiration commences before the revolution is quite complete. The valve is closed again at 69 deg., just as the aspiration is becoming maximum.

"Inasmuch as the effective power of this engine is negative or zero from 344 deg. onward to 170 deg., or through a little more than half a revolution, it is necessary that the machine should be provided with a heavy fly-wheel to maintain the movement during these intervals. The fly-wheel is made to act also as a sort of counterweight, as well as by means of its moment of rotation, the side of the wheel which is descending during the period of paralysis being made considerably heavier than the other. A companion engine, to act positively during the inaction of the first, would render such an expedient unnecessary; but, unfortunately, the bulk is considerable relatively to the power, and it would, in general, be a disadvantage to double it.

"The engines of Ericsson are largely in use in the United States, but as yet they have not been constructed of any considerable power. As a general rule, they fall within three or four horse-power as an outer limit, though it is believed that there have been made some exceeding this limit. On account of their safety and convenience they have been regarded with favor; and it has been claimed for them as an additional recommendation that they are economical. Such did not appear to be the fact in the case of the particular engine which was the subject of the experiments of Mr. Tresca above referred to. In this machine, which was of two horse-power, the result of very careful trial showed a consumption of 4.13 kilograms (about nine pounds) of coal per horse-power per hour.* In comparison with steam, this cannot be called a large economy. The consumption of a good steam-engine ought not to exceed, per horse-power per hour, two kilograms at the outside. One and a half ought to suffice.

"It may be observed, in conclusion, that Ericsson makes no attempt to carry the temperature in this engine to a very high point. The mean maximum temperature in the experiments at the Conservatoire did not exceed 270° Fahrenheit, though doubtless portions of the air received a greater degree of heat than this. The expansion of volume was further determined to be but as 1 : 1.48—that is to say, about fifty per cent. of the original bulk.

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* There is not a single instance on record in the United States in which the consumption has exceeded four pounds of anthracite coal an hour per horse-power. It should be observed, however, that by forcing the combustion by an excess of fuel, put into the furnace under an imperfect draught, the consumption may be more than doubled.

"The general description here given will be made more intelligible by reference to the figures of the engine given in Plate 46.

"Of the two pistons shown at A and F, the first, A, is the driving-piston, and the second the supply-piston, which in the foregoing explanation we have called C. In A is seen a valve marked *a*.

"At B is an axis of motion, the office of which is to communicate movement to the piston A, by means of a crank *o*, a connecting-rod *p*, a second crank *q*, and another rod *r*.

"In the piston F the valve of communication is shown at *f*. The solid portion F′ is filled with plaster, or other badly-conducting substance, while F″ marks the bell-shaped prolongation which extends into the annular space surrounding the furnace. When, by the approach of the piston F to the piston A, the space between these two pistons is reduced, there is no escape for the air between them but that which is afforded by the annular cavities between this bell and the external wall of the machine *f*′, on the one hand, and the wall of the furnace itself on the other. The air passes first along the outer space to the mouth of the bell, and returns through the inner, forming a thin stratum in immediate contact with the hot wall of the furnace.

"Another axis of motion is shown at C, of which it is the office to communicate movement to the supply-piston F, through the crank *o*, the connecting-rod *s*, and the cranks *t* and *u*, which last two are fixed to the arbor C, at a fixed angle to each other of seven degrees.

"The escape-valve is placed at D, and kept in position by the spring *d*. A cam D′, acting on this valve through the lever D″, opens it just before the driving-piston commences its descent at the end of the positive stroke.

"The furnace is enclosed in the iron box G, the grate-bars being shown at *g*. G′ indicates plates of iron designed to protect the walls of the furnace.

"In order to bring the two pistons into a favorable position for starting, the fly-wheel is turned on its axis; and, for the purpose of facilitating this operation, the arbor K is introduced, which enables the attendant to act on the fly by means of the clicks marked *k*, and the notches *k*′.

"The furnace-door I is made double to reduce loss by radiation. The walls of the furnace are similarly protected by means of a double envelope.

"The products of combustion escape from the furnace through the flues *h*, protected by fire-brick, and are carried off by the chimney H."

The caloric engine thus described was patented 1858, the Rumford medal being awarded in 1862 for its successful practical application.

The following address by Professor Horsford, on presenting the medal, cannot properly be omitted in this work:

"At the time the vote of the American Academy of Arts and Sciences conferring upon you the Rumford Premium was passed, I had the honor to be Chairman of the Rumford Committee, and, you will remember, signified my wish to relieve myself of the trust imposed upon me; but, as this formal act and the simple ceremony appropriate to it have been postponed in consequence of the pressure of the war, in which you, sir, have borne so conspicuous a part, the custody of the vote and medal has been continued with me to the present time.

"I have the honor now to place in your hands a certified copy of the vote passed by the Academy at its annual meeting, June 10, 1862. It is as follows:

"'*Voted*, That the Rumford Premium be awarded to John Ericsson, for his improvements in the management of heat, particularly as shown in his caloric engine of 1858.'

"In now handing to you the gold and silver medals which have been prepared in accordance with the statutes of the Academy, I beg to congratulate you upon the honors you have won through a life of research and experiment, devoted to the promotion of the prosperity and well-being of mankind, in the field contemplated by the illustrious founder of the Rumford Premium."*

* A patent was granted June 15, 1869, to a German engineer, for a machine actuated by heated air, identical in principle and mechanical combination with my caloric engine of 1858, the only difference being that, like the solar engine delineated on Plate 67, and other air-engines constructed by me in the United States at various times—as far back as 1843—the patented engine uses the same air over and over. The patent referred to also embraces a supposed novel plan of applying a water-chamber round the open end of the cylinder for cooling the same. Now, the leading feature of a large caloric engine built by me at the Delamater Iron-Works, in New York, 1856, was that of cooling the open end of the cylinder by such a water-chamber. The patented engine, therefore, is a flagrant plagiarism on devices already carried into practice.

CHAPTER XXXII.

THE MONITOR SYSTEM OF IRON-CLADS.

(SEE PLATES 47 AND 48.)

THE *monitor system* is thus noticed in J. Scott Russell's great work on Naval Architecture:

"It is a creation altogether original, peculiarly American, admirably adapted to the special purpose which gave it birth. Like most American inventions, use has been allowed to dictate terms of construction, and purpose, not prejudice, has been allowed to rule invention.

"The ruling conditions of construction for the inventor of the American fleet were these: the vessels must be perfectly shot-proof, they must fight in shallow water, they must be able to endure a heavy sea, and pass through it, if not fight in it.

"The American iron-clad navy is a child of these conditions. Minimum draught of water means minimum extent of surface, protected by armor; perfect protection means thickness to resist the heaviest shot, and protection for the whole length of the ship; it also means perfect protection to guns and gunners. Had they added what our legislators exact—that the ports shall lie in the ship's side, nine feet above the water—the problem might at once have become impossible and absurd; but they wanted the work done as it could be done, and allowed the conditions of success to rule the methods of construction.

"The conditions of success in the given circumstances were these: that you should not require the sides of the ship to rise much above the water's edge; that you should not require more protection to the guns than would contain guns and gunners; that you should be content with as many guns as the ship could carry, and no more.

"To do the work, therefore, the full thickness of armor required to keep out the enemy's shot was taken, but the ship was made to rise a few inches above water, and no more; and so a narrow strip of thick armor, all along the upper edge of the ship's side, gave her complete protection. Thus the least quantity of thickest armor did most work in protecting the ship, engines, boilers, and magazine. Next, to protect the guns, a small circular fortress, shield, or tower encircled a couple of guns, and, if four guns were to be carried, two such turrets carried the armament and contained the gunners. Thus, again, weight of armor was spared to the utmost, and so both ship and armament were completely protected.

"But the consequences of these conditions are such as we, at least for sea-going ships, would reluctantly accept. The low ship's side will, in a sea-way, allow the sea to sweep over the ship, and the waves, not the sailors, will have possession of the deck. The American accepts the conditions, removes the sailors from the deck, allows the sea to have its way, and drives his vessel through, not over, the sea to her fighting destination, by steam, abandoning sails. The American also cheerfully accepts the small round turret as protection for guns and men; and pivots them on a central turn-table in the middle of his ship, raising his port high enough to be out of the water, and then fighting his gun through an aperture little larger than its muzzle.

"By thus frankly accepting the conditions he could not control, the American did his work and built his fleet. It is beyond doubt that the American *Monitor* class, with two turrets in each ship, and two guns in each turret, is a kind of vessel that can be made fast, shot-proof and sea-proof. It may be uncomfortable, but it can be made secure. The sea may possess its deck, but in the air, above the sea, the American raises a platform on the level of the top of his turrets, which he calls his hurricane deck, whence he can look down with indifference at the waves fruitlessly foaming and breaking themselves on the abandoned deck below. His vessel, too, has the advantage, as he thinks it, of not rolling with the waves; so that he can take his aim steadily and throw his shot surely. Thus, if he abandons much that we value, he secures what he values more.

"I think I have reason to know that the American turret ships, of the larger class, with two turrets and four guns, are successful vessels—successful beyond the measure of our English estimate of their success. Like so many American inventions, they are severely subject to the conditions of use, and successful by the rigidity and precision with which they fit the end and fulfil the purpose which was their aim.

"Plate 47 contains side elevation, deck plans, and cross-section of the original American *Monitor* of Captain Ericsson—the first turret ship that distinguished herself in action, having to engage with her single turret and pair of guns a large broadside ship of much heavier tonnage and armament, which she thoroughly defeated.

"Captain Ericsson, the builder of the *Monitor*, has long been distinguished equally in England and America. He was known as the builder and designer of one of the most remarkable engines, in the original competition, preliminary to the opening of the Liverpool and Manchester Railroad; he was afterwards distinguished in the introduction of the screw-propeller in steam navigation; and he has crowned his career by the successful construction of the class of turret ships, which appear to have been taken up with avidity, and prosecuted with energy, by the American Government; and during the course of their sad civil war the 'monitors' appear to have rendered to the Federal side very important services. The design of these vessels has about it all the characteristics of American audacity. Every conventionality of the ship has been despised and discarded; in the sailor's sense of the word, there is nothing 'ship-shape' about this original

Monitor; everything is unusual. She has neither keel, nor bilges, nor bulwarks. She is very nearly a London bridge, covered by a great horizontal platform of timber, projecting beyond her deck, and descending below the water-line. This great upper platform in no way conforms to the shape of the under-ship which carries it; it is obviously meant to shelter the rudder and the stern from every attempt to damage them by collision. At the bow the entire hull is equally protected by the overhanging platform of the deck, and the whole upper works of the ship are covered with thick iron armor on both sides, and the wooden deck is protected by iron plates. The rudder is a balanced rudder, and the ship is propelled by a single screw; the boilers are the double-tier boilers, of the ordinary construction, with four sets of flues. It will be noticed that the arrangements of the turret are very different from Captain Coles's arrangements. The whole turret is on the upper deck, exposed to shot; it is not carried on a revolving set of rollers, but is pivoted on the centre, which seems to carry most of its weight by means of an iron trussing, from which it is, as it were, suspended, and it slides on a smooth metal plate lying on the deck. The turret is worked by a small pair of donkey engines, working on tooth gear, and the ports are covered by hanging blocks. Like our turret,* the *Monitor* shield has two guns worked parallel to each other on slides. The man-

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* The English, in abandoning the *cupola* of Coles, and copying the monitor turret, also adopted the term turret. For some time, however, the English naval architects adhered to the word cupola; but in a short while the phrase cupola was dropped, hence "turret ship" in place of "cupola ship."

ner in which these turrets were afterwards improved and matured by experience is shown in Plate 49, and it is certain that Captain Ericsson rendered great service to his country by inventing at once, and successfully introducing, a class of vessels peculiarly suited to action in their inland waters and shallow navigations; and when we consider the extreme rapidity which attended the execution of the project, we must say that the original *Monitor* was a remarkable success, and that she was a type of an entirely new class of war-ship."

The origin of the name "monitor" calls for an explanation in this place. The Navy Department at Washington having, shortly before the launch, requested me to suggest an appropriate name for the impregnable turreted steam-battery, I addressed a letter to the Assistant Secretary of the Navy, saying: "The impregnable and aggressive character of this structure will admonish the leaders of the Southern Rebellion that the batteries on the banks of their rivers will no longer present barriers to the entrance of the Union forces.

"The iron-clad intruder will thus prove a severe monitor to those leaders. But there are other leaders who will also be startled and admonished by the booming of the guns from the impregnable iron turret. 'Downing Street' will hardly view with indifference this last 'Yankee notion,' this monitor. To the Lords of the Admiralty the new craft will be a monitor, suggesting doubts as to the propriety of completing those four steel ships at three and a half millions apiece.

"On these and many similar grounds I propose to name the new battery *Monitor*."

It will be recollected that this letter was regarded in England as possessing political significance, several members of Parliament having called for its reading in the House of Commons when the news of the result of the battle between the *Monitor* and the *Merrimack* appeared in the *Times*. Unquestionably, the advent of the *Monitor* materially counteracted the pressure which the French Emperor brought to bear on the British Ministry at the time, in favor of the Southern States.

John Bourne, the greatest authority on naval engineering of our time, in a critical examination of the monitor system published in London, 1866, observes:

"The confidence of the Americans in the shot-proof qualities of their monitors is manifested by many of the incidents of the late Rebellion, one of which is that Captain Worden, of the monitor *Montauk*, attacked and destroyed the Confederate vessel *Nashville*, when lying under the guns of Fort McAllister, in Georgia; and, although the fort was all the time pouring a fire upon the monitor from its heaviest guns, the monitor took no notice of it, but proceeded without interruption to the destruction of her antagonist. Another new feature in naval war is that, in the attack on Fort Fisher, the fire of the rest of the fleet was directed against the fort over the monitors; and although shot falling short and shells prematurely exploding could not be prevented in such an engagement, the monitors, it was felt, were able to encounter such risks with impunity. The monitors, during two years of active service, in all weathers, on a hostile and stormy coast—sometimes watching for blockade-runners in Cuba, sometimes engaged in the Gulf of Mexico, and often at sea in heavy gales—were, on an average, each twenty-five times in action: being a larger amount of service than that of any vessels recorded in history. Shot could not damage them; storms could not swamp them; and at the end of the war they were as effective as at the beginning. The following extract from a report of Admiral Dahlgren will show something of the kind of service in which some of the monitors were employed during three months in the summer of 1863, and the number of shots they fired and with impunity received:

Name of Monitor.	No. of shots fired.		Hits.	Hits, April 7, 1863.	Hits at Ogeechee.	Total hits received from the enemy.
	15-inch.	11-inch.				
Catskill.....	138	425	86	20	...	106
Montauk....	301	478	154	14	46	214
Lehigh	41	28	36	...	...	36
Passaic.....	119	107	90	35	9	134
Nahant.....	170	276	69	36	...	105
Patapsco ...	178	230	96	47	1	144
Weehawken	264	633	134	53	...	187
Nantucket..	44	155	53	51	...	104
	1,255	2,332	718	256	56	1,030

Mr. Bourne also presents the following extracts from the reports of Captain John Rodgers, of the monitor *Weehawken*, to the Secretary of the American Navy:

(1) June 20, 1863.

"The opinion formed then confirmed my anticipations, that a hull rising but little above the surface of the water (in this case only 16 inches), and having a central elevation, as in the monitors, is the shape to form a good sea-boat; and I am convinced that on this idea all successful iron-clads must be built. This form reduces the surface to be plated to a minimum, and puts the part having the necessary elevation above the sea for fighting guns where it can be carried without inconvenience, and in the *Weehawken* is easily carried. With us, I think, safety is solely a question of strength.

"I had relied upon former experience to correct any faulty motion which I might discover in a sea-way, by shifting or reducing weights. I abandoned, however, the idea of improvement. As I watched the action of the vessel it was perfect."

(2) July 22, 1863.

"On Thursday night, when off Chincoteague Shoals, we had a severe gale from east-northeast, with a very heavy sea, made confused and dangerous by the proximity of the land. The waves I measured after the storm abated. I found them 23 feet high. They were certainly 7 feet higher in the midst of the storm.

"During the heaviest of the gale I stood upon the turret and admired the behavior of the vessel. She rose and fell to the waves, and I concluded then that the monitor form had great sea-going qualities. If leaks were prevented, no hurricane could injure her. I presume in two days we shall be ready for any service, as we need no repairs, and only some little fittings."

"It may be added," says Mr. Bourne, "that, on the occasion of the heavy gale which occurred just before the attack on Fort Fisher, the monitors were the only vessels of the fleet which were able to ride it out without dragging their anchors; and on the occasion of a common steamer having been sent to escort a monitor, before confidence had yet been established in the seaworthiness of that class of vessel, the steamer, having broken down in a heavy sea, was taken in tow by the monitor, and was carried by her safely into port."

Mr. Bourne, in proof of the comfort and healthiness of the monitors, likewise presents the following extract from a report of the Secretary of the United States Navy to Congress:

"It is gratifying to know that an examination of the sick reports, covering a period of over thirty months, shows that so far from being unhealthy, there was less sickness on board the monitor vessels than in the same number of wooden ships with an equal number of men, and in similarly exposed positions. The exemption from sickness in the iron-clads is in some instances remarkable. There were on board the *Saugus*, from November 25, 1864, to April 1, 1865, a period of over four months, but four cases of sickness (excluding accidental injuries), and of these two were diseases from which the patients had suffered for years. In the *Montauk*, for a period of one hundred and sixty-five days prior to May

29, 1865, there was but one case of disease on board. Other vessels exhibit equally remarkable results, and the conclusion is reached that no wooden vessels in any squadron throughout the world can show an equal immunity from disease. The facts and tables presented are worthy of careful study."

The following vote of thanks was passed by the Thirty-seventh Congress, March 28, 1862:

"*Resolved*, by the Senate and House of Representatives of the United States of America in Congress assembled, That it is fit and proper that a public acknowledgment be made to Captain John Ericsson for the enterprise, skill, energy, and forecast displayed by him in the construction of his iron-clad boat, the *Monitor*, which, under gallant and able management, came so opportunely to the rescue of our fleet in Hampton Roads and, perchance, of all our coast defences near, and arrested the work of destruction then being successfully prosecuted by the enemy with their iron-clad steamer, seemingly irresistible by any other power at our command; and that the thanks of Congress are hereby presented to him for the great service which he has thus rendered to the country."

It will be proper to mention, also, that several iron-ship builders, in conjunction with the proprietors of some of the most important marine-engine establishments on the Atlantic coast, in token of their appreciation, honored me by presenting a model of the *Monitor*, weighing upwards of fourteen pounds, manufactured of pure gold.

CHAPTER XXXIII.

THE MONITOR TURRET AND THE CENTENNIAL EXHIBITION.

(SEE PLATE 49.)

The imperfect character of the monitor turret exhibited in Fairmount Park has been noticed with surprise by professional visitors. In view of the important results attained by the adoption of this structure during the war, it cannot be denied that a painted wooden representative is unworthy of the occasion. Nor need it be urged that some turret bearing the marks of actual conflict ought to have been transferred to the Exhibition. Experts are aware that, owing to the laminated character of these turrets, they may readily be taken down, and the plates transported and put up at any required distance from the vessel. Besides, it may be shown that this process would have been less expensive than erecting a complete representative turret and mechanism. Regarding the armament applied within the wooden turret, naval artillerists from abroad, who expected to have had an opportunity of examining the detail of the friction-gear peculiar to the monitor armament, have been greatly disappointed to find that, instead of the carriages on which the guns were mounted during the war, an experimental steam-carriage devised by an engineer from St. Louis, after the war, has been placed in the representative turret. In consequence of this misleading procedure on the part of the authorities, of excluding the carriages which had been used, the majority of visitors have naturally imagined that the monitor guns, during the war, were mounted on the experimental carriage referred to.* It should be mentioned that the plan of checking the recoil of our guns by *friction* has not been superseded in the navy, and that friction gun-carriages are at present being constructed for the Navy Department under my patents.

THE PILOT-HOUSE.

The pilot-house—wheel-house—of the monitors, and the steering-gear which it contains (see Plate 49), forming the most important features of the system, their exclusion from the turret at the Centennial Exhibition must be regarded as an untoward circumstance. It cannot be supposed that the officer charged with the duty of putting up the representative turret would incur the responsibility of excluding without authority that part of the system which most interests

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* My carriage, operated by a circular compressor, exhibited in the wooden turret, was applied in the *Dunderberg*, but not in the monitors during the war.

the professional visitor. The country is aware that Admiral Porter's report to the Secretary of the Navy, published while the preparations for the Centennial Exhibition were in progress, contained a recommendation to abolish the pilot-house of the monitor turrets. Possibly this recommendation, condemnatory of my invention, led to the exclusion of the steering machinery and the massive pilot-house from the representative turret in Fairmount Park. I do not propose to investigate the cause which has led to the exhibition of my invention in a mutilated state, but I feel called upon to show that the removal of the pilot-house from the turrets recommended by Admiral Porter is highly improper and incompatible with the monitor system.

Well-informed naval officers are aware that Worden failed to sink the *Merrimack* at Hampton Roads because he could not personally control the firing and at the same time direct the steering of his vessel from a point enabling him to observe properly the movement of his antagonist. This fact was well understood by the authorities at Washington, the Assistant Secretary of the Navy having himself witnessed the battle and the ineffectual firing. I was accordingly requested by the Navy Department, shortly after the conflict, to devise some means of *steering from the turret.* The despatch conveying this request contained several important suggestions, and closed with the following sentence: "The placing the wheel-house on the turret would double the formidable character of the vessel." Considering what happened at Hampton Roads, more might have been said; for had the *Monitor* been provided with a wheel-house on the top of the turret, Worden, instead of discontinuing the action almost blinded, would have forced the *Merrimack* to surrender as readily as Rodgers compelled the commander of the boasted impregnable *Atlanta* to haul down the Confederate flag by being enabled personally to direct the steering and the firing while watching from the elevated turret wheel-house of the monitor *Weehawken* the movements of his opponent. Again, it was from the turret wheel-house of the monitor *Montauk* that the hero of Hampton Roads detected the *Nashville*, and by a few fifteen-inch shells, fired under his own supervision, burnt the Confederate vessel and cargo. It was reserved for the Admiral of the Navy to discover that the arrangement which enables the commander of a monitor to direct the firing and the steering from an elevated position above the turret, affording an all-around view, is a great mistake, although it has proved so efficacious in actual conflict. It was reserved for him also to find out "that the placing of the pilot-house on the top of the monitor turret shows a lack of ingenuity"—a discovery apparently resulting from reflections connected with the fact mentioned in his report, "that this is the most exposed point in the vessel, and is liable to be swept away by the first heavy shot that strikes." The Admiral appears to have forgotten that the fleet of monitors at Charleston, commanded by Dahlgren, engaged the Confederate batteries some twenty times, at easy range, and yet the pilot-houses were not "swept away."

The section of the turret and wheel-house (pilot-house) of a monitor of the *Passaic* class (shown on Plate 49) represents the structure precisely as built, excepting that the turret wall, in order to protect the base of the wheel-house in accordance with my original plan, should be carried two feet above the turret roof. As the wheel-house and steering gear must remain stationary while the turret revolves, it will be perceived that the plan presents a mechanical problem of no ordinary character. This is understood by persons possessing correct mechanical knowledge, who have studied the arrangement, and know that it successfully passed the severe ordeal to which it was subjected during the war.

With reference to the original plan of extending the turret wall above the roof, it will be proper to mention that the managers of the plate-mills employed to manufacture the turret plating during the war refused to furnish plates of more than nine feet in length. Not only did they positively decline to roll plates of an *additional* length of *six* inches, but they limited the thickness to fifteen-sixteenths of an inch, owing to their inability to manufacture plating above a given weight. Those who criticise the strength of the armor of the monitors will do well to bear this in mind. A careful inspection of our illustration, representing a section of the turret of the *Passaic* class of monitors, at once disposes of the erroneous assertion that the pilot-house, the internal diameter of which is only six feet, may be "swept away." No target practice has yet shown that a cylinder of such small diameter, composed of solid iron eighteen inches thick (of course it might be made thicker), can be penetrated. At the same time, the inertia of such a cylinder, owing to its weight, is so great that a base-ring of very moderate section attached to the turret roof will effectually prevent dislodgment under the impact of shot.

In view of the foregoing, it would be waste of time to discuss the merits of the Admiral's recommendation to the Secretary of the Navy, "to place the steering apparatus below, with a small portion of the deck above it raised and heavily plated, with apertures to look through." But his reference to lack of strength calls for some notice. In reply, I will simply observe that by substituting solid for laminated armor, the original *Monitor*, "if in existence to-day," would be the most formidable iron-clad of her tonnage possessed by any naval power. Of course it must be attributed to inadvertency that Admiral Porter has not, in his report, reminded the Secretary of the Navy that the laminated armor of the turrets of the entire monitor fleet ought to be at once substituted by solid plating.

Naval constructors and engineers will find by examining our illustrations that, excepting the omission to place the pilot-house on the top of the turret, the original *Monitor* was a perfect fighting machine; and that not a single essential improvement has been added in building the subsequent monitor iron-clads. It will also be found that the propeller was better protected in the original *Monitor*, and that the anchor was handled with greater facility and more perfect protection to the crew, than in the recent turret vessels. Moreover, it is susceptible of positive demonstration that a vessel built precisely like the first *Monitor*, provided with a turret wheel-house and armor of adequate thickness, would present the most perfect vessel for harbor defence hitherto produced — whether for carrying heavy ordnance or for handling movable torpedoes employed against an attacking fleet.

It will be observed by those who have studied the matter that Admiral Porter's statement, at the commencement of his report, is materially modified by a subsequent paragraph, strongly recommending the *overhang* of the *Monitor*, "which," the report states, "prevented the hull being penetrated if the vessel was struck by a ram." The Admiral further observes: "The value of this contrivance was shown in the contest at Hampton Roads, where the *Merrimack* rammed the *Monitor*, merely turning the latter half round, and doing no damage whatever." It will be seen, by the illustration (Pl. 47) representing a transverse section of the original *Monitor*, that a collision like that between the *Iron Duke* and the *Vanguard*, which sent the latter to the bottom, would not be productive of greater danger than that caused by the *Merrimack's* ramming, since, owing to the overhang and inclined sides, the *Iron Duke's* spur could not reach the *Monitor's* hull.

CHAPTER XXXIV.

THE MONITOR ENGINE.

(SEE PLATES 50 AND 51, REPRESENTING A TOP VIEW AND SIDE ELEVATION.)

THE *Engineer* of April 20, 1866, contains the following discussion relating to the engines employed in the monitor iron-clads, accompanied by a brief description of the mechanical combination of these motors:

"The common feature of all Ericsson's screw-propeller engines, however otherwise different in arrangement and principle, consists in what he himself has described as 'bringing the power of two engines to bear at right angles on a common crank-pin'—a feature already noticeable in the engines built by him in 1839, at Liverpool, for the *Robert F. Stockton.* This very vessel, tried on the Thames so many years ago, is stated to be, even now, not only the most powerful tug of her class on the river Delaware, but also the fastest. Her engines consist of two steam-cylinders, placed diagonally, with cross-heads and side-rods connected to a common crank-pin on the propeller-shaft. In the *Edith* and *Massachusetts* Ericsson modified his diagonal form of engine by laying the cylinders against the ship's side, under the deck, bottom up, with the piston and connecting-rods working downwards, but still connected to a common crank-pin on the propeller-shaft. A countryman of Ericsson, Captain Carlsund, copied this arrangement, applied it in a number of Swedish vessels, exhibited it at the Paris Exhibition, and, with the usual perspicuity of Universal Exhibition juries, was rewarded for this exhibit by the great gold medal.

"While still adhering to the feature of bringing the power of two cylinders on to a common crank-pin, the present form of marine engine adopted by Captain Ericsson may be looked upon as an outgrowth of the peculiar engine, with semi-cylinders, which he first applied to the United States steam-frigate *Princeton*. Excellent illustrations of this engine appeared some years ago in a work called 'Imperial Cyclopædia of Machinery'; but as Captain Ericsson has himself observed, in a letter to Mr. Woodcroft, the description began by erroneously stating that 'Watt has described a similar arrangement in one of his earlier patents.' This is so far a mistake, as Watt—according to a practice he adopted, under the then state of the law, of inserting as many ideas as possible into his patents—merely described the bare idea of a piston vibrating within a semi-cylinder. As Captain Ericsson states, 'the *Princeton's* engine consists of compound or double semi-cylinder engines, of different diameters, with pistons attached to the common axle in opposite directions, both pistons being acted upon by the steam at the same time, their differential force constituting the effective motive power.' The writer of the description of the engines of the *Princeton* in the 'Cyclopædia,' while allowing that 'this species of engine is very compact,' and that it 'admits of being placed entirely below the water-line,' as also that, 'although very many other arrangements have been since brought out in this country, it is still a pre-eminently successful engine,' yet observes that 'the friction is, of course, more than in many others, inasmuch as it is found practically impossible to obtain the power of steam with so little friction in any form of chamber as a true cylinder.' To these objections Captain Ericsson replies: 'In the first place, the absence of pressure on the main journal of the piston-shaft is not understood by those who are not cognizant of the fact that a straight line drawn from the crank-pin to the opposite journal of the shaft passes through the centre of gravity of the piston.' Then, again, 'the weight of the piston, instead of scraping the bottom of the cylinder, is suspended in the journals, and there produces but a very small amount of friction.'

"'Nor have critics recognized the fact that during the passage of the crank-pin of the propeller-shaft through the lower part of the arc of vibration, it is nearly relieved from pressure by the opposing action of the connecting-rod—one pushing while the other is pulling. Lastly, the absence of the great friction produced by the diagonal thrust of the short connecting-rod against the guides of ordinary propeller engines also forms an important item of saving peculiar to the semi-cylinder engine.'

"The weak point in this very ingenious engine is undoubtedly the piston. The ends, for instance, must wear unequally and at a rate increasing with the radius of any given point from the centre of vibration.* Ericsson is too good a mechanic to shut his eyes to this fact; and accordingly, when, in 1859, the United States Navy Department submitted the problem of the best screw-propeller engine for solution by the engineers of America, he presented a plan of an engine similar to that of the *Princeton* in all essential features, with the exception of the introduction of full cylinders instead of semi-cylinders. Since that period the greatest success in America has accompanied this last form of steam-engine; it has been almost universally applied to the later vessels of war of the States, and also in the mercantile navy of that country. There is not a single American monitor without an engine of this kind, and all the Swedish monitors are engined on the same plan. It has been patented by the inventor, and the accompanying plans and descriptions are prepared from information sent by Captain Ericsson himself to Mr. Woodcroft (see Plates 50 and 51). He has also sent a beautiful model of it, which

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* In refutation of this objection, I have to state that the steamship *Princeton*, after serving in the Gulf during the Mexican War, was sent to the Mediterranean without repairing her pistons, the *end-packings* on examination proving to be in perfect order.

may be seen in the Patent Office Museum at South Kensington.

"'The several direct-acting screw-propeller engines hitherto constructed,' says Captain Ericsson, 'are all more or less objectionable in the following particulars, viz.: the horizontal engines occupy too much space transversely in the vessel to admit of being placed in the run; the vertical engines pass through decks, and project so far above the water-line as to be useless for war purposes; and all approved double-cylinder engines operate on cranks placed at right angles to each other, which involves a series of bearings, much friction, and liability to derangement from the shafts getting out of line. In addition to these imperfections, the extreme shortness of the cranks, with the attendant great friction on the crank-pins and journals, to say nothing of the heavy diagonal thrust of the connecting-rods, are serious defects in the direct-acting screw propeller engines in common use.' In Captain Ericsson's present form of screw-engine the two cylinders of a double engine are arranged in such a manner that their base or bottom ranges with a plane passing through the axis of the propeller-shaft, or nearly so, in combination with a certain arrangement of rock-shafts, crank-arms, and connecting-rods, for imparting motion from the pistons to the shaft, whereby he is enabled, first, to bring the cylinders nearer to the propeller-shaft, and hence to economize space and construct the frame of the engine of great strength and compactness; secondly, to avoid the diagonal thrust and friction of the slides, unavoidable when the connecting-rod is attached directly to the cross-head; thirdly, to operate the connecting-rods nearly at right angles to each other, which admits of the production of a continuous motion with a single crank on the propeller-shaft, and with a single crank-pin common to both engines; fourthly, to employ a crank on the propeller-shaft much longer than half the length of stroke of the piston, thereby diminishing the heavy pressure on crank-pins and on journals, which has hitherto caused so much trouble by the overheating of the bearings, and at the same time diminishing the strain on the engine-frame."

DESCRIPTION OF ILLUSTRATIONS ON PLATES 50 AND 51.

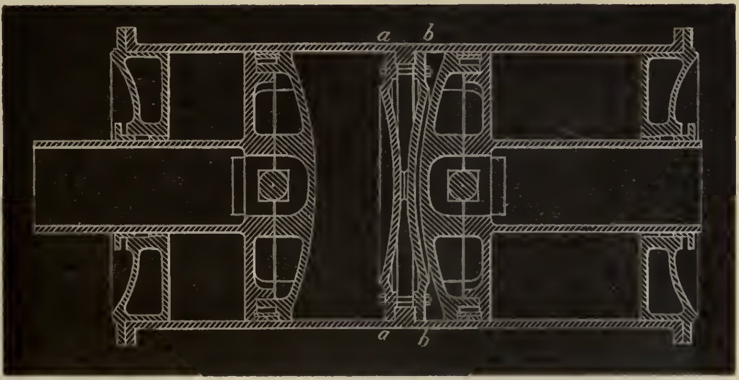
The general character of the *Monitor* engine will be readily comprehended by a reference to Pl. 50, representing a ground-plan, and Pl. 51, the side elevation, viewed from the bow of the vessel. The crank on the propeller-shaft and the main connecting-rods, being hidden by the steam-cylinders, are shown by dotted lines in the side elevation. The two cylinders are placed end to end transversely in the vessel, trunks or hollow piston-rods being cast on the pistons, as shown by the sectional plan on page 487, projecting outwards towards the side of the vessel. These trunks are sufficiently large to permit the vibration of links connecting the pistons and short vibrating levers attached to the forward end of the horizontal rock-shafts. Referring to the top view of the engine, it will be seen that vibrating levers of greater length are attached to the aft end of the rock-shafts. These levers are coupled to the common crank-pin on the propeller-shaft, the connecting-rods acting nearly at right angles to each other. By this arrangement the throw of the crank may be made much longer than in ordinary direct-acting engines; consequently, the strain on the crank-journal of the propeller-shaft will be correspondingly reduced. A prolongation of the crank-shaft forward—of small diameter—carries the eccentrics which actuate the steam-valves, while a prolongation of one of the rock-shafts towards the stern operates an air-pump common to both steam-cylinders. The bottom of the cylinders, or the division between them, is formed as shown by the sectional plan of the cylinders before referred to.

The Chief of the Bureau of Steam Engineering at Washington, Mr. B. F. Isherwood, having criticised the principle of the *Monitor* engine, I published the following reply in the *Engineer* of June 8, 1866:

"Referring to Mr. Isherwood's 'Experimental Researches on Steam-Engineering,' I find it stated, at page 340, that the cost of the horse-power in the engines of the *Monitor*, when cutting off at 0.425 of the stroke of the piston from the commencement, is 27.7 per cent. more than in the U. S. paddle-wheel steamer *Michigan*. 'Great as this excess appears,' says Mr. Isherwood, 'it is no more than what the conditions fully warrant us to expect, and should be decisive against the use of such a type of engine.' Mr. Isherwood accounts for this great loss of power in the following manner: 'From the description of the *Monitor* engine, it will be perceived that two cylinders occupy the same barrel, the separation being made by a simple partition of cast iron in the centre. Further, that during a large portion of the time the boiler-steam occupies one end of the cylinder, while the adjacent end of the other cylinder is open to the condenser. There is, consequently, one end of one cylinder maintained at the temperature of the boiler-steam, while the adjacent end of the other cylinder, separated only by a cast-iron partition, is exposed to the temperature of the condenser. This arrangement, immaterial as it appears—and is in a mechanical point of view—powerfully affects the economical result by its great influence on the cylinder-condensation. To appreciate it, it is only necessary to imagine the piston of the starboard engine, for example, to be near the outboard end of its stroke, in which case nearly the whole of the cylinder of that engine will be filled with steam. At this moment the piston of the port engine is near the centre of its stroke, and about one-half of the port cylinder adjacent to the starboard cylinder will be open to the condenser and exposed to its refrigerating influence; consequently, the boiler-steam in the starboard cylinder has been exposed for about one-half of the stroke of its piston to this refrigerating influence from the port cylinder, transmitted through the iron partition of the two cylinders, which, as their diameter is great in proportion to the stroke of their piston, forms a large proportion of the surface in contact with the steam. Nor does the evil end here; for, as the sides of both cylinders are the same piece of iron—those of the one being merely an extension of those of the other—the conduction of heat is very rapid from one cylinder to the other, and the heat imparted by the steam to the sides of the starboard cylinder quickly passes along by conduction to the sides of the port cylinder, whose interior is in communication with the condenser, and whose exterior is exposed to the atmosphere. The inevitable result, it is manifest, must be a largely-increased steam-condensation in cylinders of this type of engine over that in the cylinders of the usual type—how much larger, is a question which experiment alone can answer. There is still to be added to the already-described peculiar causes of steam-condensation in cylinders of the *Monitor* type of engine that of the half-trunk, the effect of which is, for a given capacity of cylinder, to increase both the interior and exterior cylinder surfaces; while the thin, unprotected metal of the half-trunk—one side of which is always in contact with the atmosphere, while the other side is, too, for half the time, and not only in contact with, but in rapid movement through, it—makes it a regenerator of maximum power.'

"Before analyzing this extraordinary reasoning, let us examine closely the section of the cylinder in the annexed diagram.

"It will be seen that, although the two cylinders are combined in one casting, each has a separate bottom, with a considerable space between the two; also that the heat to be transmitted through the metal of the cylinder, as Mr. Isherwood states, must travel a distance of 6 ins. from *a* to *b*, or from *b* to *a*, in less than half a second, in order to produce the baneful effect pointed out by the author of 'Experimental Researches.' It will not be necessary to demonstrate that heat cannot be transmitted through 6 ins. of metal in half a second, and it would be an insult to the intelligence of your readers to detain them by disproving Mr. Isherwood's assertion that a considerable amount of the motive force is lost by thus transmitting heat back and forwards through the substance of the cylinder.



" With regard to the supposed rapid transmission of heat through the 'iron partition of the two cylinders,' you will find on referring to the section that no transmission of heat can take place, since the two bottoms are separated by a stationary body of air or vapor. In the ordinary cylinder-bottom, the outside of the metal acquires, during regular working of the engine, a permanent temperature, attended by a constant loss of heat radiated into, and continually absorbed by, the atmosphere. In the case of the bottom-plates of the *Monitor's* cylinder, a permanent temperature is also acquired, but there is no loss of heat by radiation after the intervening small body of air or vapor has attained maximum temperature. It may be truly said that the *Monitor* engine, with its cylinders combined in one casting, furnishes the only instance in which no heat is lost by radiation through the cylinder bottom. Having thus disposed of the absurd notion that a vast quantity of heat is transmitted from cylinder to cylinder, we now come to the question of increased internal cylinder surface consequent on the application of the trunk. Mr. Isherwood treats this question as one of such great importance that I have taken the trouble to ascertain the exact amount of increase. Area of 40-inch cylinder, 1,256 square inches; area of 13½-inch trunk, 143 square inches. Deducting from this 20 square inches for a 5-in. piston-rod, which the ordinary engine would require, we have a difference of 123 square inches occupied by the trunk. But the trunk only affects the outboard end of the cylinder, and hence the mean area taken up is only 61½ square inches. To make up for this loss of area, the diameter of the cylinder, it will be found by calculation, has only to be increased $\frac{15}{16}$ of an inch. I should be trifling with the patience of your readers were I to enter on a calculation to show the amount of loss attending such small increase of the diameter of the cylinder. Only one more point, urged by Mr. Isherwood against the *Monitor* engine in explanation of the asserted 27 per cent. loss of motive force, remains to be considered, viz., the effect of the trunk, which he calls a 'refrigerator of maximum power.' Mr. Isherwood devotes so much time to the theoretical consideration of the steam-engine that I can well understand that he has no time left for practice; otherwise I should feel surprised at his ignorance of the fact that the great difficulty with trunk engines is that of keeping the packing steam-tight without causing overheating. Experience shows that the best that can be done in practice is to prevent the trunk from exceeding the initial temperature of the steam; and hence the trunk, in place of being a 'refrigerator of maximum power,' is actually a super-heater.

"It will be asked by what process did Mr. Isherwood ascertain the amount of the assumed loss of power for which he accounts by this extraordinary reasoning? He placed, according to his statement in 'Experimental Researches,' a tank on a wharf, to which the *Monitor* was made fast. From this tank he supplied the boilers of the vessel by means of temporary feed-pipes. Steam having been raised, the engines were started and kept in motion for seventy-two hours in succession. Indicator-cards were taken every hour, by means of which the mean indicated horse-power exerted by the engines was ascertained. This was compared with the quantity of water measured into the tank and supposed to have been converted into steam. The utmost precision was practised; the water run into the tank was ascertained to the third decimal of a pound; the barometer and direction of the wind carefully noted. The difference between the indicated power and that which ought to have been produced according to the quantity of water used, supposed to have been converted into steam, was set down as 'loss occasioned by cylinder-condensation.' I observe that Mr. Isherwood's tables and calculations make no allowance for condensation in the steam-pipes and valve-chests. Loss by leaks through the pistons, valves, and glands; leaks and waste of water and steam in the boilers—all these sources of loss appear to be ignored by the experimentalist, and every pound of water measured into the tanks is debited to the engine. A balance is then struck by deducting the indicated horse-power, and the difference put down as 'loss caused by cylinder-condensation.' I abstain from criticising this rough and unsatisfactory mode of deciding the nice point of cylinder-condensation; but I cannot omit adverting to the fact that, while the pressure in the boilers, during the trial of seventy-two hours, was kept at 17 lbs. above the atmosphere, the pressure admitted into the cylinders was only 1¾ lbs. above the atmosphere. The tables show that, in order to maintain this low working-pressure in the engines, the throttle-valve was set permanently at an opening of four square inches. In view of the magnitude of the engine—two double-acting cylinders of 40 ins. diameter—the admitting the steam through a single opening of such small area was certainly a most singular expedient. Had the object of the trial been to exhibit a minimum indicated horse-power, a more effective expedient could not have been devised. As the mean area of the piston, according to the tables, was 1,185 square inches—about three hundred times greater than the area of the throttle-valve—the speed of the pistons being at the same time upwards of 2.5 feet per second, some idea may be formed of the amount of dynamic force exerted and heat extinguished in passing the steam from the boilers to the engines. Yet this waste of force was ignored by the experimentalist, and the indicated piston-power alone was set against the water measured into the tank.

"Apart from these facts, the most critical examination of the sectional plan of the cylinders of the *Monitor* before referred to (see page 487) fails to discover any error of construction productive of cylinder-condensation to a greater extent than in the screw-engines of the most celebrated makers."

CHAPTER XXXV.

THE MONITOR DICTATOR.

(SEE PLATES 52, 53, 54, AND 55.)

THE *Dictator* is the most powerful and efficient fighting-ship possessed by the United States. Like the *Monadnock* class of monitors, she is also a good cruising vessel. The hull, engines, turret, and gun-carriages of this ship were designed and furnished by the writer, under a contract with the United States Navy Department, 1862. Her length on deck is 314 ft., the overhang aft being 31 ft., and the forward overhang 13 ft., leaving a length of 270 ft. between perpendiculars (see side elevation, Pl. 52). Her breadth over the sides is 41 ft. 8 ins., and her total beam 50 ft., whilst her draught is 20 ft., the sides midships projecting only 1 ft. 6 ins. above the water-line. The sides are protected at and near the water-line by 11 ins. of wrought iron, this thickness consisting of inner bars 5 ins. thick, and six plates each 1 in. thick (see transverse section, Pl. 53). The plates are placed upon massive timber backing, as shown by the illustration on the plate referred to. Her tonnage is 3,000 tons.

The engines of the *Dictator* (see illustrations on Plates 53 and 54) are 4,500 indicated horse-power, consisting of a pair of vertical cylinders 100 ins. in diameter, with a stroke of 4 ft. The pistons have small trunks on their upper side, and are connected by links with the ends of curved horizontal arms attached to the forward end of rock-shafts placed outside the cylinders slightly above the latter. Straight arms nearly vertical are attached to the after-ends of the rock-shafts. These arms are coupled by means of diagonal connecting-rods to a common crank-pin fixed near the circumference of a fly-wheel upon the screw-shaft. The engines drive a propeller 21 ft. 6 ins. in diameter, provided with four blades set at a pitch of 34 ft. The propeller weighs 39,000 lbs., and its shaft 36 tons. The engines are supplied with steam by six boilers having altogether 56 furnaces; the total grate-surface is 1,128 square feet, and the heating surface over 32,000 square feet. The coal-bunkers accommodate 600 tons of coal.

The *Dictator* has a single revolving turret, essentially the same as that delineated on Plate 49; it is 24 ft. in diameter inside, by 9 ft. high, and contains two fifteen-inch guns. The sides of the turret are built up of two separate concentric cylinders, composed of plates 1 inch thick firmly riveted together, a space of five inches being formed between the said cylinders. This space is filled with segmental wrought-iron slabs 5 ins. thick and 12 ins. broad; hence the total thickness of the turret wall is 1 ft. 3 ins. The turret has a bell-mouthed top formed of iron plates ½ in. thick, curved outwards, as shown on Plate 52, for the purpose of throwing off the water which, during heavy weather, is dashed up the sides of the turret. Around the bell-mouthed top mentioned is carried a wooden grating provided with a hand-rail, and appropriate stanchions for supporting an awning. The grating referred to forms a convenient balcony for promenade. Over the centre of the turret is placed the pilot-house, which is 8 ft. in diameter in the inside, and 7 ft. high, its sides being formed of twelve thicknesses of 1-in. plates. This structure is supported by a strong cross-beam which rests upon a collar formed on a strong central wrought-iron shaft passing down through the turret; this shaft being stationary, the turret revolving round it. Excepting the bell-mouthed plate-iron extension at the top, the *Dictator* turret is constructed precisely as the turrets of the *Passaic* class of monitors delineated on Plate 49. Referring to this delineation, it will be seen that the weight of the turret wall is suspended by diagonal rods in such a manner that the entire weight of the turret and armament, as well as the pilot-house, is sustained by the stationary central shaft. The latter rests on a casting bolted to the transverse bulkheads of the ship, as shown in Plate 47. The pilot-house is provided with sight-holes placed at a convenient height, and, like the central shaft, is stationary. The diagonal rods before referred to, it should be observed, are furnished with screw-ends and nuts, in order to admit of their being tightened in case the turret wall should sag. The cross-beam before mentioned, which extends across the top of the turret, supports rafters carrying iron bars 4 ins. deep by 3 ins. wide, and 2½ ins. apart, these bars being covered with perforated plates 1 in. thick. The base of the turret wall rests on a flat ring composed of bronze, the under-side of which is accurately faced. It is supported by another flat ring faced on the top and secured to the deck. By this means a watertight joint is formed between the base of the turret wall and the deck. It is obvious that considerable power would be required to cause the turret to revolve if its weight rested on the rings described. Accordingly, a taper key is inserted under the stationary central shaft, by which the weight of the turret and appendages may be raised so as to rest wholly on the shaft. During the war this key was invariably tightened before going into action, hence the turrets revolved with perfect freedom while the gunners pointed the pieces. A circular channel is formed in the deck near the inside of the turret, in order to carry off water that may leak under the base. It is conducted to the bilge by small scupper-pipes. The machinery for turning the turret consists of a pair of donkey-engines, which work gearing connected with a large cog-wheel secured by strong lugs to the under-side of the gun-slides, which are in their turn firmly attached to the sides of the turret. It should be observed that all the turning gear is below the deck-line. The floor of the pilot-house consists of a wooden grating fitted with hinged hatches, through which the captain and steersman enter from the turret. The steering-wheel is contained in the pilot-house, and its motion is transferred, by gearing and by a rack sliding in a groove formed in the central shaft, to a pinion fixed upon the axle of the steering barrel below. From this barrel chains extend to the rudder, which is of the balanced kind. The vessel is strengthened beneath the turret by transverse and longitudinal bulkheads.

The gun-carriages are run out upon their slides by means of winch-handles moving wheel-work geared into racks, the friction-gear being tightened as soon as the pieces are full out, and of course relieved immediately after the recoil. Each gun has a radial bar placed above it, upon which runs a wheel supporting a block and tackle, provided with a small dished platform upon which the shot is placed. By this contrivance the shot can be rapidly raised from the shot-locker to the muzzle of the gun.

In the *Dictator* the air required for ventilation and for supplying the boiler-furnaces is drawn in by several large fan-blowers, partly through the top of the turret and partly through shot-proof trunks carried high above the decks, as shown in the side-elevation, Plate 52. The vessel is provided with a spacious platform or promenade deck, placed at nearly the same height as the top of the turret (see plate referred to). This deck is supported on vertical iron stanchions, the ship's boats being suspended below the same. The cabins are lighted by means of bull's-eyes fitted into brass frames let into the deck, these frames being replaced by solid wrought-iron covers when the ship is going into action.

The *Engineer*, in an article published 1866, states with reference to the *Dictator :*

"It may be laid down as a general axiom that when the introduction of fresh elements into any mechanical problem has effected a revolution in its first conditions, originality is at great advantage over hesitating and long-pondering judgment. Though without the advantages which our great command over iron in large masses has given in the modern substitution of iron for wood in naval warfare, the Americans have certainly shown much originality and boldness in their designs for war-ships. A good deal of this is due to Captain Ericsson—an original thinker and constructor, whose very originality would have led him to be distrusted in this conservative country. Broadly stating the matter, it may be said that in France and in England we have pretty much confined ourselves to bolting massive iron slabs, with an intermediate packing, to the skins of our iron vessels of war; but Ericsson has taken a much more comprehensive view of the capabilities of engineering in its application to the eternal war-problem of doing as much damage as possible to your adversary with as little as possible harm to yourself."

CHAPTER XXXVI.

THE MONITOR TURRET AND THE CASEMATE.

(SEE PLATE 56.)

An opportunity of instituting a direct comparison between the monitor turret and the fixed casemate was furnished by the completion of the Turkish armor-clad vessel *Moyini Zaffer*, launched on the Thames in June, 1869. The building and arming of this iron-clad being the result of the joint efforts of Sir William Armstrong, Samuda, and Ravenhill, we have a guarantee that whatever merits the fixed casemate system possesses have been fairly developed in this attempt to supersede the monitor.

It cannot fail to be noticed, on careful examination of the illustrations on the plate referred to, that the planning of the casemate of the *Moyini Zaffer* shows much thought and elaboration; also that the complication which characterizes its form is evidence that the planner was dealing with a difficult subject. Nor can the attentive observer fail to see at a glance how imperfectly the disadvantages attending the elongation and immobility of the battery—viz., the limited horizontal range of the guns—have been overcome by the combination of curvature and angles resorted to by the constructor of this substitute for the monitor turret.

Our illustrations, besides representing a top view of the *Moyini Zaffer*, accurately drawn to scale, also represent a top view of a monitor provided with two turrets of the same diameter as those of the *Passaic* class—viz., 21 feet internally. The length of the Turkish vessel is 230 feet, with 35 feet 6 inches beam. The monitor, for the sake of exact comparison, has the same dimensions; but the thickness of its armor is greater than that of the former, and so proportioned that the *weight* of armor of both vessels is alike. The freeboard of the *Moyini Zaffer*, as in all iron-clads built by English engineers, is several times higher than that of the monitor, and consequently deeper armor below water must be applied to afford protection, increased rolling being the inevitable result of high freeboard. Referring to the batteries, it will be seen that the circumference of the fixed battery is greater than that of the two turrets in the ratio of 25 to 15.

The English mechanical journals, in describing the *Moyini Zaffer*, point with apparent satisfaction to the circumstance that this casemate ship, which is intended for the defence of the Bosporus, has armor-plates "generally six inches in thickness, the whole of the battery (backed with wood) being cased with 5-inch plates." The battery, though pierced for eight guns, will only carry four of Armstrong's 12-ton rifles. The intention being to transfer the pieces from one side of the battery to the other during action, it is evident that Sir William has reached the limit of weight. The difficulty of changing sides with the rapidity called for during contest with screw-propelled assailants needs no explanation. But the constructor of the monitor turret, which, as our illustration shows, commands 340 deg. of the horizon, is not hampered by considerations of weight of metal, a 24-ton gun, or even one weighing forty-eight tons, being pointed as readily by turning the turret as the lightest field-piece. Accordingly, the monitor which our illustration represents is mounted with four 24-ton guns.

Making proper allowance for the greater area of side-armor and battery-plating of the *Moyini Zaffer*, it will be found that our double-turreted monitor will, on the same draught of water, support 10-inch thick side-armor, 15-inch thick turret-plating, and carry four 24-ton guns. The greater security—we might say the impregnability—thus attained by the monitor form is, however, only a part of the advantage of this system over that which is represented by the Turkish iron-clad—the latest endeavor of some naval constructors to demonstrate that the conflict at Hampton Roads was not, after all, so decisive as supposed.

Impregnability and calibre, although very important, by no means decide the superiority of armored vessels; horizontal range is in many cases of equal importance. A monitor hull provided with a fixed battery may be made as impregnable as a complete monitor, but at least two-thirds of the guns of such a vessel will be ineffective in battle. Samuda, evidently, was fully aware of the impotency of his artillery, owing to limited horizontal range, when he adopted the complicated form of the battery of the *Moyini Zaffer.*

Let us now consider in detail this question of horizontal range, and inspect closely the extent of ranges marked on our illustration for each gun separately. The ranges obtained by the fixed battery of Samuda's construction first claim our attention. To avoid confusion, the ports have been lettered *a*, *b*, *c*, and *d*, the first letter denoting the forward port of the battery, and also the muzzle of the piece belonging thereto. Beginning with the first-mentioned port, it will be seen that each gun respectively ranges over a field of 96, 98, 98, and 92 deg. Referring to the monitor, it will be seen that each of the four guns sweeps a field of 170 deg. It should be observed that the ranges marked on the illustration have reference only to the starboard side of the line of keel.

It will be proper, before assigning a numerical value to the efficiency of each of the systems under consideration, to remember that the real power of naval artillery is determined by multiplying the weight of shot by the horizontal range, the position of the vessel remaining constant. Modern target practice having demonstrated that a 24-ton gun is capable of throwing a projectile of 600 pounds with adequate force, and that a 12-ton gun is about the proper size for 300-pound projectiles, we are enabled, by applying the rule before mentioned, to determine with exactness the relative efficiency of the monitor turret and the fixed battery or casemate. The power of the forward gun *a* of the casemate will accordingly be represented by 300 × 96 = 28,800. In like manner, by multiplying the weight of the projectiles of the remaining three guns by their respective ranges in degrees, we obtain a sum total of 115,200. Applying the same mode of computation to the monitor—viz., multiplying 600 × 170 × 4—we establish the important fact that the actual efficiency of the monitor is to that of the casemate vessel as 408 to 115. Apart from this superiority as regards the artillery of the monitor over that of the Turkish iron-clad, the armor of both battery and hull of the latter is wholly insufficient to compete with the former. The inference, therefore, is obvious and irresistible that the monitor represented by our illustration could readily destroy Samuda's casemate vessel. But it is not my intention to prove the worthlessness of the *Moyini Zaffer* as a war vessel, the object of discussing the subject being simply that of instituting a comparison between the two systems represented by the illustrations on Plate 56.

It merits special attention that, apart from the limited horizontal range of all the guns of the *Moyini Zaffer*, only *one* of the four—viz., *a*—can be pointed forward parallel with the ship's course; and that *c*, the only other gun capable of firing ahead, cannot point nearer than 11 deg. of the line of keel. At a distance of a mile ahead, there is, consequently, a field of 1,200 feet which an assailant may occupy, exposed to only one 12-ton gun. Chased by an enemy, the Turkish war-ship, with the Samuda-Armstrong battery, will be equally impotent; the gun marked *d* being her only defensive weapon. It will be found, on inspection, that the piece marked *b*, like that marked *c*, cannot be pointed nearer than 11 deg. of the line of keel.

Let us now turn to the monitor. It will be seen that four 24-ton guns, two forward and two aft, fire in a direct line with the keel; there being no safe position, as in the case of the fixed battery, for the enemy's vessel to occupy. The entire field, viewed from stem to stern, as the plan shows, is swept by all the guns of the monitor. Bearing in mind that these powerful guns are protected by 15-inch thickness of iron, which, if applied in *two* thicknesses, is proof against any artillery yet produced, while the 12-ton guns of the Samuda-Armstrong battery are protected by armor which a 7-inch rifle will pierce through and through, the argument in favor of the monitor turret becomes overwhelming.

It will be asked, in view of these incontrovertible facts, why do constructors advocate the fixed battery? I know of no other reason than the assumption that the joint between the rotating turret and the deck cannot be made secure. English engineers, relying on the accounts of the performances of the monitors published by the enemies of the Union during the war, apparently do not take the trouble to investigate the matter; while American experts who have written about turrets appear to be ignorant of the leading facts connected with the turret system.

For instance, Mr. Eads, in a report to the Navy Department, informs the Secretary that "the band round the base of the turret on the *Dictator* weighs over 20,000 pounds," and points out how much better this great weight of iron might be applied for other purposes. Now, this turret has no band round its base, nor was it ever intended to have one. Mr. E. also tells the Secretary that any downward swelling of the plating, produced by the impact of projectiles striking low, will stop the rotation of the turret by friction under its base. This assertion proves ignorance of the fact that the *Dictator* turret rests wholly on the four inner courses of plating (which cannot be swelled), and that the intermediate wrought slabs and outer plating (together 11 inches in thickness) *do not reach the deck*, and therefore can, by no possibility, cause the predicted stoppage. Again, the apprehensions expressed in several reports, with reference to the base of the pilot-house in connection with the rotation of the turret, prove that another very important circumstance has been overlooked—viz., that the turret projects considerably *above* said base, thereby effectually protecting it.

CHAPTER XXXVII.

CARRIAGES FOR HEAVY ORDNANCE.

(SEE PLATE 57.)

THE *Engineer*, in discussing the subject of gun-carriages (in 1868), says: "Americans mount their big guns in turrets, and France has no peculiarly big guns to mount. In the matter of carriages, as in almost everything else connected with recent improvements in ordnance, England must be content to act as schoolmistress to the rest of the world." This assertion is preposterous, in view of the fact that England had not mounted a single heavy gun on shipboard at the time when we had a large fleet of iron-clads armed with 11 and 15 inch guns. Not only that: we had effectually used those guns in numerous engagements, and fully established the reliable character of our system of mounting the same, before English artillerists believed it possible to dispense with breeching. But our contest was watched by attentive eyes, and hence our success did not long remain a secret. An enterprising English captain speedily procured drawings of the *Monitor* gun-carriages and their friction-gear. How faithfully he copied our system the reader will see by comparing the several devices for producing friction represented on Plate 57. Sir William Armstrong, too, becoming convinced that the *Monitor* friction-gear was the best for checking the recoil of naval ordnance of heavy calibre, also followed our lead. An amusing contest arose between Sir William and the enterprising naval officer alluded to, whose indignation knew no bounds on finding that the great gunmaker had adopted the same plan as himself for checking the recoil. But Mr. Scott Russell having in the meantime published accurate drawings of the *Monitor* gun-carriages and friction-gear, Sir William was in a position to silence the complaints of his rival by simply pointing to Plate No. 139 of Scott Russell's great work on naval architecture.

By referring to the illustration mentioned, the reader will see at a glance that Captain Scott's friction-gear is identical with that applied to the gun-carriages of the American iron-clad fleet. The principle is very peculiar, and involves the apparent paradox of obtaining increased friction to any desirable extent without adding to the force employed. A brief explanation will show how this singular result is effected. A series of vertical plates are secured to the lower part of the gun-carriage in such a manner as to admit of a slight transverse movement. These plates slide freely between longitudinal friction-timbers, or planks composed of hard wood, which in broadside vessels are attached to the "slides," and in the monitors secured to the base of the turrets. It will be readily understood that, by applying lateral force to the two outside vertical plates from without, friction will be established between all the plates and the intervening planks; and it will be evident that the amount of friction between the surfaces in contact will depend on the force thus applied, wholly independent of their *number*. Thus, by merely doubling the number of plates and planks, the friction will be doubled without calling for the application of any additional force. It rarely happens in mechanical contrivances that the effect to be produced is so completely independent of the force applied as in this instance. The practical advantage of obtaining requisite friction without employing great manual power is obvious; and that it is fully appreciated may be inferred from the alacrity with which the system has been copied in Europe.

The difficulty of handling the modern monster guns on board ship in bad weather, which at one time was deemed impracticable by experienced sailors, vanished with the introduction of my multiplex friction apparatus thus briefly described. The reader will observe how closely even the *detail* of the original has been followed by the plagiarists; the mode of producing the lateral pressure, for instance, has been carefully copied by Captain Scott. He employs the transverse screw and vertical levers by which the outside friction-plates are forced inwards, precisely as in the *Monitor* carriages. Sir William Armstrong also employs the transverse screw and vertical levers, but he divides the screw in the middle—an ill-considered modification, as it calls for the application of force on *both* sides of the carriage, increases the friction, and tends to pull the sides together. Sir William Armstrong also introduces the modification of employing iron bars in place of the wooden friction-planks—a most objectionable expedient, as the needed friction is greatly diminished by presenting metal against metal. Moreover, the friction becomes so irregular as to baffle any attempt at systematic tightening with reference to the charge of powder employed, rendering accidents inevitable. It is evident that if the metallic plates are kept dry, abrasion follows, and that their surfaces are liable to cut and stick. If oiled, the least excess of lubrication will reduce the friction to such an extent as to permit the gun to recoil without check, as experience during experimental practice has shown. Apart from these objections, the want of that indispensable elasticity which the wooden friction-plank affords is fatal to Sir William Armstrong's substitution of metal for wood.

With such facts before it, the *Engineer* tells its readers that, in the matter of *carriages* and other improvements connected with naval ordnance, England must be content to act as "schoolmistress" to the rest of the world.

Alas for the schoolmistress! She has been endeavoring to teach the world for a long time that our system of naval defence was all wrong, until at last she has discovered that her boasted broadside iron-clads, on which millions have been spent, are hopelessly vulnerable.

The leading journal of England, February 12, 1868, frankly admits that "the final blow" has been given to the "already tottering theory of broadside iron-clads," and adds: "Why do we obstinately refuse to build small iron-clad, single-turret vessels, with low freeboard, and one or two guns of the heaviest calibre? The American and Russian officers who have actually tried them report with enthusiasm of their sea-going properties." It would have been well for the "schoolmistress" if she had not listened to the advice which prejudiced naval constructors have persistently tendered; it might have spared the naval administration of England the severe censure called forth at the time for having neglected to adopt the monitor system. "It seems to us," says the *Times* of the date before mentioned, "that the Admiralty have in nothing so neglected their duty as in failing to provide us with a large supply of these formidable little vessels."

Can the *Engineer*, moreover, point to a single invention connected with our turret iron-clads, naval ordnance, or gun-carriages which has originated in England? Those best acquainted with the matter know that every mechanical device relating to the system which so successfully vindicated itself during the late war was contrived on this side of the Atlantic—a success the more remarkable since the exigency of the time did not admit of previous experiments, everything being despatched directly from the foundry and workshop to the scene of conflict.

CHAPTER XXXVIII.

PIVOT-CARRIAGES OF THE THIRTY SPANISH GUNBOATS.

(SEE PLATE 58.)

The gun-carriages and slides constructed for the Spanish gunboats present two important features which distinguish the same from other pivot systems—viz., the slide is made to rotate round a *permanent* central fighting-bolt secured in the middle of the deck near the bow; consequently, as the bulwarks of the Spanish gunboats are low enough to admit of firing *en barbette*, a horizontal range of 240 deg. is obtained.

The other important feature of the new system is that of enabling the gunner to apply and relieve the compressor instantaneously.

Naval artillerists are well aware of the advantage of rotating slides, but, owing to the circumstance that such an arrangement unavoidably carries the fighting-bolt in the rear of the trunnion when the gun is run out, such slides have been deemed impracticable. Evidently, if the fighting-bolt be placed far in the rear of the trunnion, the slide will be lifted upwards with great violence at the instant of discharge. This apparently insuperable difficulty is completely overcome in the arrangement now under consideration, by the expedient of raising the circular ring on which the slide turns about one inch above the deck. By this expedient an efficient abutment will be obtained for restraining the longitudinal movement of the slide in *all positions*. A plate attached to the front transom of the slide, as represented by the illustration on Plate 58, extending down as far as the bottom of the ring, thus takes the place of the ordinary fighting-bolt. The central pivot, round which the slide revolves, fits so loosely in the socket of the cross-plate that the whole force of the recoil is received by the descending transom-plate and the edge of the deck-ring. The latter is sustained by a circular platform of boards 1 in. thick, secured to the deck, and flush with the top of the ring. The front transom and outside circumference of the deck-ring being in advance of the centre of the trunnion of the gun when run out, the force of the recoil, in place of lifting, will evidently tend to *depress*, the slide. Ample experience in working the slides of the Spanish gunboats has fully demonstrated this fact, and established the superiority of the rotating slide in point of easy handling as well as extensive lateral range.

It will be evident on reflection that a very slight modification will adapt the rotating slide thus described to broadside firing. Such a modification was made in December, 1869, and the slide thus modified, together with its carriage, was presented to the Ordnance Bureau for trial. A 100-pounder Parrott rifle-gun having been mounted on the carriage, Commander E. Simpson was ordered by the Chief of the Bureau to conduct the trial on board the U. S. steamer *Tallapoosa*, during a run from New York to Washington. Commander Simpson's report of this trial and his description of the new arrangement are so lucid that I adopt the same in preference to any description I could pen:

"The carriage consists of a slide and top-carriage, constructed of wrought iron. The slide is composed of two rails, with four bolts connecting them at intervals of two feet. The heurters consist each of two plates of half-inch iron, between which are placed the rollers for lateral train. They are each strengthened by two castings placed between the plates near the rails, those at the rear end being continued up nine inches above the rails, to which are secured the *buffers* of india-rubber, designed to receive the recoil when the carriage is permitted to recoil the whole length of the slide.

"The middle of the slide rests on a rail on the deck designed to support it at that point, and on which it slides when training.

"The slide has one transom half way of its length riveted to the inner sides of the rails, and on a plane six inches below their upper surface.

"To an angle-iron turned up from the rear of the transom, and rising to the level of the rails, is bolted the rear end of the *friction-bar*, six inches wide and one and a quarter inches thick, which is continued horizontally to the forward heurter, where it is bolted to a casting, after passing which it inclines downwards gradually to the pivot, where it is secured to the pivot-bolt through a hole in its end.

"A composition rack is bolted on the inside of the right rail, the teeth extending above the level of the rails.

"The carriage rests on four rollers front and rear, the former of 18 inches diameter, the latter of 7 inches. To the inner face of the right forward roller is bolted a working-wheel of composition, with its cogs gearing below into the rack on the slide, while above it gears into a pinion on a shaft which has its bearings in the brackets of the carriage. A crank is attached to the end of this shaft on the right side of the carriage, and by it the carriage is run in and out on the slide. This shaft has a longitudinal motion, which allows the pinion to be geared or ungeared at pleasure. It is always desirable to ungear before firing, in order to prevent motion of the crank, which might prove dangerous to the gun's crew.

"A conveniently-arranged clutch holds the shaft in either position.

"The carriage has one transom, from the forward part of which project two arms, one-third the width of the transom apart, extending to a length of 20 inches, and terminating in eyes, through which the compression-shaft passes, which has bearings in the lower part of the brackets and well forward of the forward axle of the carriage.

"Under the friction-bar is a clamp 17 inches long and 6 and 10 inches wide, which binds against the under face of the bar. The compression is produced through the eccentric motion of a third piece resting on the upper clamp, a side-elevation of which represents a half-circle, and which is fitted over the compression-shaft. This eccentric piece is connected with the friction-clamps by two iron straps, with nuts screwed on the lower ends of them. It will be perceived that the friction-clamps occupy a position in the centre line of the carriage and between the ends of the two arms projecting from the transom. The friction-clamps are lined with hard wood, which forms the surfaces binding on the friction-bar. The compression-shaft has its bearings on the brackets of the carriage, and projects far enough outside the left bracket to receive a long lever which is shipped on its end, and which has a vertical motion, limited by the adjustment of the screw-nuts on the ends of the iron straps which connect the friction-clamps. This lever is held in position by a rack on the outside of the left bracket when the required compression is attained. A steel spring at the lower end of the lever binds it against the bracket, and a very convenient eccentric arrangement at the handle of the lever enables this pressure to be overcome when desiring to move the lever."

Having prefixed this very clear and precise description to his report, Commander Simpson proceeds: "During the firing thus tabulated, the running-out gear was but seldom used, the carriage being allowed to move obedient to the roll of the vessel, and its motion was found to be perfectly under the control of one man at the compression-lever, who could check it at any point. The compression being found to work well in deliberate fire, thirty rounds were fired to test the point whether rapid fire would cause the heating of the friction-bar. The thirty rounds consumed nearly thirty minutes in firing, at the end of which time the temperature of the bar was slightly raised, but in no way interfered with a continuance of firing. Very rapid firing may be done with this carriage; the time consumed in firing the thirty rounds above mentioned was in consequence of the crew not being accustomed to gun-exercise.

"The most prominent advantage—in fact, the essential characteristic—of this carriage is its system of compression, which is complete and instantaneous.

"The compression in use with our pivot-guns and with our turrèt-guns involves the use of a screw, which requires time to work; the substitute provided in this carriage is a simple motion in a vertical plane of a lever, which is instantaneous in action, and quite as effective in its result.

"The tardiness of action in the compression of our turret-guns may often cause hesitancy in casting them loose in a sea-way, when, with a more speedy means of compression, they might be made of service. The slow and imperfect action of the compressors fitted to our pivot-guns renders necessary eccentric rollers to the axles, so that the carriage may be let down on the slide, to increase, by the increased surface in contact, the friction that the compressors do not supply.

"The system of compression now under consideration admits of keeping the carriage always on its rollers, thus simplifying the mechanism of the carriage, and dispensing with the levers which are now necessary to bring the rollers in and out of action. The four men now devoted to this duty could be dispensed with.

"During the experiments here recorded the carriage has fulfilled the advantages claimed for it by its inventor, and, unless subsequent experiments or the experience of actual service should develop defects not now apparent, its claim for preference over any carriages now in use in the navy must be allowed.

"During the firing, the shortest distance at which the recoil was checked was 2 feet 5 inches, which was only half the recoil that would be required in service so as to have the gun in position for loading. If less recoil were required at any time, it can be obtained by a change in the adjustment of the screw-nuts on the strap binding the friction-clamp." *

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* It will be proper to notice that the new system has proved so successful in practice that the Spanish Government, in addition to the thirty carriages and slides mounted on board of the new gunboats, have recently ordered several sets of similar carriages and slides for other vessels.

CHAPTER XXXIX.

ROTARY GUN-CARRIAGE AND TRANSIT PLATFORM.

APPLIED TO THE SPANISH GUNBOAT TORNADO.*

(SEE PLATE 59.)

The illustration on the plate referred to represents a new system of transferring the battery from side to side, without resorting to the complicated method of pivoting practised in our vessels of war. In addition to the advantage of rapidly transferring the guns from side to side, an all-round fire is also secured by this system, as will be seen by the following description :

The leading feature of the device is that of placing the gun-carriage and its rotary slide on a circular platform, supported on four cylindrical rollers (partially shown at *ff*) provided with flanges like those of the wheels of railway

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* It will be remembered that in 1873 this gunboat, after a spirited chase, captured the American steamer *Virginia*, having on board a company of "Cuban patriots" and war material intended for the Cuban insurgents. The capture of this vessel, it will also be remembered, very nearly led to a war between the United States and Spain.

carriages. These rollers, the axles of which turn in appropriate bearings under the platform, move on two flat parallel bronze rails, *l* and *m*, secured to the deck at right angles to the line of keel. One of these rails, *m*, is provided with cogs on the outside, thus forming a toothed rack. A small horizontal cog-wheel under the platform is geared into the said rack, and actuated by a set of cog-wheels arranged as in ordinary lifting-jacks. The gear is put in motion by a vertical spindle having a hand-wheel attached to its upper end, the lower end being made to fit a square socket, *n*, formed in the axle of the actuating pinion of the gear. It is hardly necessary to observe that after having transferred the platform to the desired position, the vertical spindle should be lifted out of its socket and removed, in order not to interfere with the free rotation of the slide. It may be mentioned that in addition to the gear referred to, suitable eyebolts are applied to admit of employing ordinary tackle in transferring the platform from side to side. Having been rolled into position on the fighting side of the vessel—say starboard—the platform must, of course, be secured by *two* fighting-bolts. One of these is seen at *k*, the second of the pair being concealed by the slide. On rolling the platform to port, after having removed the fighting-bolts, the latter will be inserted through the bolt-holes of the lugs *g* on the opposite side of the platform. It should be observed that in housing the gun the fighting-bolts will occupy diagonal positions—plates, as shown at *k*, being inserted in the deck accordingly.

It was pointed out in the previous chapter that if the force of the recoil were brought to bear on the central pivot round which the slide revolves, the latter would be lifted up violently, or seriously jarred at the instant of discharging the gun, since the vertical line, passing through the centre of the trunnion, is far in advance of the central pivot when the gun is rolled out. To prevent such lifting or jarring, a very effective expedient has been resorted to—viz., that of attaching a bracket *d* at the forward end of the slide, extending about two inches below its base, and bearing firmly against the circumference *p* of the platform. It will be readily seen that if the bracket referred to, which acts as a hook, be placed at a proper distance, while the pivot round which the slide turns fits loosely in its socket, the force of the recoil will be received wholly by the edge *p* of the platform, at the point where the bracket *d* bears. The professional reader cannot fail to perceive the advantage of transferring the strain from the central pivot in rear of the trunnion to a point in *advance* of the same. Obviously, the practical result will be that of causing the carriage and slide to bear down against the platform, instead of being violently jarred or lifted up, as it would be if the force of the recoil were brought to bear on the central pivot. Regarding the proper position of the fighting-bolts for securing the platform during firing, it will be evident that if inserted at *k*, as shown (for the sake of ready explanation) in the illustration, the platform would be lifted or jarred at the moment of discharging the gun; while by inserting the fighting-bolt at *g* the tendency will be to depress the platform, thereby securing perfect repose throughout the entire structure.

The gun-carriage itself having been minutely described in Chap. XXXVIII., it will only be necessary to observe that the friction-bar *c*, which in the carriage referred to was made of *iron*, has been made of bronze in all the recent carriages constructed under my patents. It was found in practice that the application of oil or grease to this bar, indispensable to prevent its corrosion, considerably diminished the friction—a circumstance of no importance if the diminution had been constant in amount; but the lubricating medium, varying in quantity, obviously causes irregularity in the intensity of the required friction. Bronze being now substituted for iron, renders the application of grease unnecessary; hence the friction between the wooden lining of the clamp *b* and the bar *c* becomes uniform. Accordingly, by pushing the hand-lever *a* to a given notch of the circular tooth-rack *s*, it has been found that the length of the recoil may be regulated with remarkable accuracy.

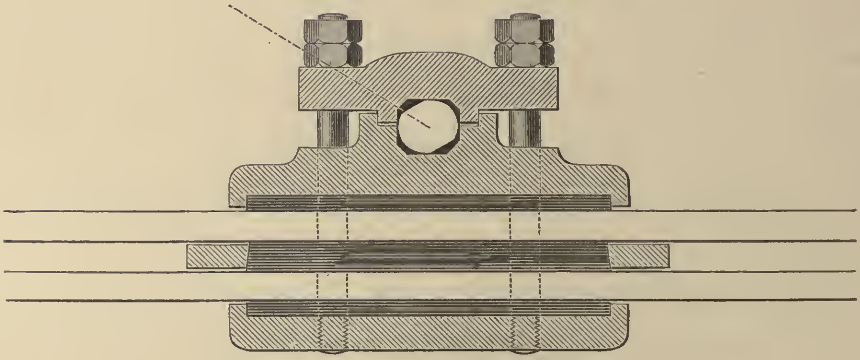
CHAPTER XL.

GUN-CARRIAGE FOR COAST DEFENCE.

(SEE PLATE 60.)

Engineering of March 20, 1872, published the following article, headed "Coast Defence":

"The problem of how best to defend our coasts has of late attracted so much attention that the illustration which we publish, representing a gun-carriage forming part of a new system of coast defence planned by Captain Ericsson, will possess special interest. The gun is mounted behind an inclined movable shield of solid plate iron, 4 ft. high above the parapet, so arranged that the muzzle is unmasked at the moment of firing, the shield affording protection against projectiles striking above the parapet. It is asserted that this plan is more efficient than that of Moncrieff; but, as it is not our intention at present to institute a comparison between the rival systems, we proceed at once to describe the illustrated carriage (see Plate 60). The recoil is checked by friction produced by clamping two longitudinal bars secured in the middle of the slide, the compression being effected by a transverse axle, on the principle adopted in the *Princeton* carriage. The longitudinal bars, however, are composed of bronze in place of wood. The friction-clamp (a longitudinal section of which, through the vertical plane, will be found represented in the accompanying delineation is firmly attached to the front of the carriage. The faces of the friction-bars being smooth and true, and the wooden linings of the clamp accurately fitted, it will be perceived that a very slight movement of the upper and lower parts towards each other, after contact with the bars, will at once cause friction, provided that the set-nuts of the clamp-cap have been properly tightened. In order to comprehend correctly this peculiar system of compression, let us suppose that the clamp, as well as the bolts which hold the same together, are perfectly rigid, and that the transverse axle is flattened so as to make it but slightly oval. Turning the latter through an arc of 90 deg.



will, under these conditions, obviously produce an enormous pressure. It has been objected that, if the axle is but slightly oval, the wear of the wooden linings and the faces of the friction-bars will soon destroy the efficacy of the compression. To meet this objection the constructor has placed the clamp conveniently in front of the carriage, in order that the set-nuts may readily be screwed down whenever required. Practice, it appears, has shown that the wear is insignificant with friction-bars composed of bronze. Iron bars, on the other hand, owing to corrosion and consequent abrasion, tend to cut the wooden lining unless grease be applied—an expedient inadmissible, as it greatly diminishes the desired adhesion, besides rendering the same very irregular. It will be seen in the illustration on Plate 60 that the hand-lever by means of which the compression is applied or relieved is held in position by a segment (provided with notches) attached to the side of the carriage; while a spring secured to the end of the transverse axle presses against the outside of the lever, thereby preventing the same from leaving the notches during the recoil of the gun.

"Captain Ericsson's plan of employing a series of friction-bars one above the other, or placed side by side, as in the monitors, appropriately termed the 'multiplex system,' copied by Captain Scott, Sir William Armstrong, and others, involves a paradox which merits special notice—viz., that without employing additional force, any amount of friction may be produced. It will be evident on reflection that whatever number of bars be employed, the friction between the face of each and the face of the clamp will depend solely on the pressure applied. Hence, if four bars, presenting eight surfaces, be employed, the retarding force opposing the recoil of the gun will be quadruple that of one bar presenting two surfaces. With reference to running out the gun, the following explanation will suffice: The forward trucks, situated somewhat in advance of the trunnion, are keyed to an axle supported by bearings in the side frames of the carriage. A cog-wheel is attached to the said axle, into which a small pinion, operated by an ordinary crank-handle, is geared.

"Before adverting to the mechanism of the slide, it will be well to observe that light gear of small multiplying power will answer for training, since the movement is always in the horizontal plane. It will be noticed that the exterior segment is provided with a projecting rack in the middle—an expedient which overcomes the difficulty so frequently experienced on the old plan of employing separate racks, that settlement of the segment on which the rollers run occasions binding between the cogs of the driving-pinion and those of the rack. It is scarcely necessary to remark that the rollers applied on the opposite sides of the toothed projection of the exterior segment turn freely on the axle to which the driving-pinion and the vertical conical wheel are attached. The action of the small conical pinion geared into the wheel mentioned, operated by means of the horizontal hand-wheel, requires no explanation."

CHAPTER XLI.

THE THIRTY SPANISH GUNBOATS AND THEIR ENGINES.

(SEE PLATE 61.)

THE material aid which the Cuban insurrection derived from outside sources compelled the Spanish Government in 1869 to build a fleet of swift gunboats to form a cordon round the island as the only means of preventing blockade-runners from conveying men and warlike stores to the insurgents. Admiral Malcampo, naval commander in Cuba, was accordingly instructed by his Government to procure the needed vessels in the United States. The Admiral succeeded in carrying out his instructions with extraordinary promptness, as will be seen from the following concise statement, copied from the *Army and Navy Journal* of November 20, 1869:

"The annals of naval construction probably furnish no instance of greater diligence than that displayed in the production of the thirty Spanish gunboats now floating on the

Hudson. The planning having been entrusted to Captain Ericsson, the contract for building the fleet was entered into with the Delamater Iron-Works, in this city, on the 3d of May, 1869. On the 19th of May the first keel was laid, and on the 23d of June the first vessel was launched from Pouillon's ship-yard—thirty-four working days after laying the keel. September 3—just four months from the signing of the contract, and three months and sixteen days after laying the first keel—the last vessel of this fleet was launched, at which time fifteen of the vessels previously launched had engines and boilers on board!

"The Spanish gunboats are sea-going twin-screw vessels, 107 feet long on the water-line, 22 feet 6 inches extreme beam, 8 feet depth of hold, and draw 4 feet 11 inches when fully equipped for service, with coal, stores, and ammunition for 100 rounds on board. The lines at the bow are somewhat full, in order to sustain a heavy bow gun, the breadth of the deck being carried well forward for the purpose of facilitating the manipulation of this gun, of which we will speak presently. The run is very clean, the lines being deemed faultless for a twin-screw vessel. The construction of the hull presents two novelties worthy of special mention. The apparently insoluble character of the problem—a gunboat of this class drawing only 59 inches of water when fully equipped for service—compelled the designer to dispense with the keel. Shipbuilders, it appears, at first objected to this innovation, but now admit that these gunboats may take ground with far less risk of straining and leaking than ordinary light-draught vessels with their weak keels. The other novelty alluded to is the cutting down the rail and substituting a low, heavy timber bulwark at the bow, provided with substantial water-ways and lined with sheet-iron to admit of firing the gun *en barbette.*

"In addition to their ample steam-power, the Spanish gunboats carry full amount of canvas, being schooner-rigged, with yard and square-sail on the foremast. Wire-rigging having been adopted, and the masts and smoke-pipe raked more than usual, the appearance of these twin-screw vessels is peculiarly light and saucy. Considering their great number, swiftness, light draught, and the long range of their guns, it is evident that the Spaniards will be enabled for the future to prevent effectually incursions on the Cuban coast.

"As might be expected, the *steam machinery* of these novel war-vessels presents features of special interest (see illustration on Plate 61). It has frequently been urged as an objection against the twin-screw system that the double set of engines, four steam-cylinders, with duplicates of all their working parts, called for in this system, render the whole too complicated and heavy for small vessels; preventing at the same time the application of *surface-condensation.* The designer has overcome these objections by introducing a surface-condenser which, while it performs the function of condensing the steam to be returned to the boiler in the form of fresh water, serves as the principal support of the engines, dispensing entirely with the usual frame-work. Besides this expedient, each pair of cylinders have their slide frames for guiding the movement of the piston-rods cast in one piece. Altogether, the combination is such that the total weight and the space occupied by these novel twin-screw engines do not exceed the ordinary single-screw engines of equal power. Several improvements connected with the working-gear have also been introduced. The outer bearings of the propeller-shafts, always difficult to regulate and keep in order on the twin-screw system, are self-adjusting, and accommodate themselves to every change of the direction of the shafts. This is effected by their being spherical externally, and resting in corresponding cavities in the stern braces or hangers. The 'spring-bearings,' for supporting the middle of the shafts, are also arranged on a similar self-adjusting principle. The thrust-bearing, which receives the pressure of the propeller, is a peculiar construction, the arrangement being such that the bearing surfaces remain in perfect contact, however much the shaft may be out of line. The reversing-gear, likewise, is quite peculiar, insuring complete control over the movement of the two propellers under all circumstances. It is claimed that these engines are the lightest and most compact yet constructed for twin-screw vessels.

"The internal arrangements and fittings show thorough knowledge and experience on the part of the superintending officer. Our friends on the Baltic, who pride themselves on knowing more about gunboats than other nations, will be astonished when they learn how the Spaniards fit out such vessels. Indeed, the equipment more resembles that of a yacht than that needed for a plain gunboat. We cannot afford space for a specification, and therefore proceed to notice only that which is essential. The coal-bunkers are placed on each side of the boiler, extending equally forward and aft of the centre of displacement of the vessel, in order to preserve perfect trim, whether the bunkers are full or empty. The magazine, located in the centre of the vessel between the engine-room and the officers' quarters aft, is lined with lead on the inside, with the unusual precaution of having the outside protected by sheet-iron. There are three distinct modes of flooding this magazine—viz., from the sea, by a powerful hand-pump, and by the donkey-engine pump. In addition to the ordinary water-tanks, a 'fresh-water maker' of ample capacity is provided, in which the condensation of the steam is effected by the current of sea-water which passes through the surface-condenser; the fresh water being drawn off through a bent pipe on deck. A combined capstan and windlass of novel construction, sufficiently low to fire over, is bolted to the deck over the chain-locker at the bow, the combination being such that the capstan may be used alone, or one or both anchors raised at the same time.

"Respecting the armament, the following brief notice must suffice for the present: It consists of a 100-pound rifle-gun placed at the bow—a Parrott rifle—but a very different weapon from that represented by the photographed fragments which embellish so many pages of General Gillmore's famous book. Briefly, it is an improved Parrott 100-pound rifle, with wrought-iron hoops round the chamber, carried to within three inches of the trunnion, the chase being increased to correspond with the increased strength attained by the extension of the re-enforce. The severe ordeal through which the improved gun has passed during recent trials at Cold Spring, conducted by the Spanish officers, promises so well that no doubt this improved Parrott gun has a future.

"Of Captain Ericsson's new gun-carriage—on which the improved gun is mounted—one of the leading features of the Spanish gunboats, we have space for only a cursory notice. It will be inferred from what has already been stated that the intention is to fire over the bow and in line with the keel. For this purpose, and in order to command a wide horizontal range, a circular platform of wood, surrounded by a brass ring of 12 feet 6 inches diameter, is bolted to the deck at the bow. The gun-slide, composed of wrought iron, provided with friction-rollers at both ends, rotates round a pivot secured to the deck, in the centre of the said brass ring. The carriage is made of light wrought-iron plates and angle-iron, riveted together in such a manner as to ensure great strength longitudinally as well as transversely." (See illustration of gun-carriage on Plate 59.)

Having described the internal arrangements of the Spanish gunboats somewhat minutely, the *Army and Navy Journal* concludes its notice of these vessels by saying:

"A fleet of thirty war-vessels precisely alike being by no means an ordinary sight, a visit to Delamater's works on the Hudson where the saucy-looking craft are now stationed, ten abreast, cannot fail to be very interesting to naval men. It is a significant fact that this great display of offensive and defensive force is the result of the efforts of a single establishment, directed by individual skill. Evidence more conclusive could not be furnished that the progress of the country and its resources are equal to any future emergency."

CHAPTER XLII.

A NEW SYSTEM OF NAVAL ATTACK.

(SEE PLATE 62.)

A HEAVY body of regular form, whose density is greater than that of atmospheric air, moving laterally through the atmosphere, is inexorably under the influence of the earth's attraction, and therefore describes a foreshortened parabolic curve during its flight; while a submerged body, the weight of which is equal to the weight of the water it displaces, is not affected by the earth's attraction; and that consequently, if put in motion under the surface of a quiescent fluid of unlimited extent, such a body will continue to move in a *straight* line until the motive energy which propels it becomes less than the resisting force of the surrounding medium.

In virtue of the first part of this general proposition, a heavy body may be projected in such a manner that the termination of its trajectory shall make any desirable angle, less than 45 deg., with the horizontal line, independently of the length of the chord of the trajectory. In other words, the body may be projected at *variable* distances over water, and yet strike its surface at any desirable angle. This important result is effected simply by varying the relative proportion between elevation and strength of charge. The second part of the stated general proposition is of equal importance. It points to the fact that the trajectory may be extended in a straight line under water, to any desirable distance, irrespective of the *speed* of the submerged projectile. Accordingly, a shot may be projected from one vessel towards another within moderate ranges in such a manner that it shall dip into the water at a considerable distance from, or close to, the vessel assailed, independently of the distance between the two vessels. Also, that the shot may be projected at such an angle that the prolongation of its trajectory in a straight line, after contact with the water, shall strike the hull of the vessel assailed at any desirable depth below the surface.

That a certain relation between charge and elevation enables us to project a *spherical* shot in such a manner as to strike the water at any desirable distance from an opponent's vessel, at angles within 45 deg., needs no further demonstration. Hence, if the trajectory be such that its extension in a straight line from the point of contact with the water leads to the hull of the vessel assailed, the latter will be hit—on condition, however, that the shot is not diverted from its course on entering the water, and provided its *vis viva* be sufficient to overcome the resistance encountered during its passage through the water. These indispensable conditions, especially the first-named, which apparently cannot be complied with, show the difficulty of hitting a vessel below the water-line. And if we suppose that the projectile is not spherical, another serious difficulty presents itself. An *elongated* body will not bend to the curvature of the trajectory during the flight through the air, but retain during its course the same inclination as the gun from which it has been projected; hence it will fall nearly flat on the surface of the water when striking.

Agreeably to our general proposition, a regular body, weighing as much as the water it displaces, is independent of the earth's attraction; but there is another force which, notwithstanding the absence of any gravitating tendency, will cause a body of regular form moving under water to deviate from a straight line and rise to the surface. A cone moving in the direction of its apex and in the line of its axis horizontally, or on an incline, will, owing to the inertia and the nearly incompressible nature of water, more readily displace the column which rests upon and depresses its upper half than the column from below with its lifting tendency. Consequently, the course of the conical body will be diverted from the straight line upwards, describing a curve nearly elliptical, and quite sudden, if the speed be great. A cylinder with semi-spherical ends will, from the same cause, ascend to the surface if moved in the line of its axis; while a cylinder with flat ends will take a downward course, gradually increasing its inclination, until at last the axis assumes a vertical position. Obviously, the lower part of the forward flat end encounters a greater resistance than the upper part; hence the lower half of the transverse section of the cylinder suffers an excess of retardation, which occasions the downward course described.

The question whether the apparently insuperable difficulties thus pointed out can be overcome by mechanical expedients, has occupied my attention for a long time; and numerous experiments have been made to test the efficacy of certain forms suggested by theoretical considerations. These forms being correct, the direction of the projectile during its flight through the air will be parallel with the trajectory, and on entering the water it will not be diverted, but continue to move under the surface with the same inclination it had on coming in contact with the dense medium.

The illustrations on Plate 62 present the main features of the system under consideration so distinctly that it will be superfluous to enter on a general explanation of the nature of the scheme. It should be stated, however, that the elongated projectile is charged with dynamite or guncotton, and provided with a percussion-lock at the forward end, which explodes the charge by contact. It may be mentioned that numerous plans have been suggested during the last few years for projecting solid shot under water, for the purpose of sinking ships. In several instances these plans have been carried into practice, with the invariable result that the resistance of the water has been found so great, even at short distances, that an ordinary wooden hull has proved to be impenetrable. The plan now under consideration bears no resemblance to these projects, since the force of the projectile on reaching its destination need only be sufficient to actuate the trigger which causes the ignition of the explosive charge.

Apart from the theoretical considerations relating to the course of elongated projectiles under water, the practical question of *motive power* to propel the same claims our attention. It is hardly necessary to state that the force relied upon is the *vis viva* possessed by the projectile on coming in contact with the water. Before estimating this force, it will be proper to call attention to the fact that the new system, to be successful, does not call for attack at a great distance, provided the vessel from which the missile is projected has greater speed than the opponent, and at the same time adequate protection against his artillery. Hence the destruction of the vessel assailed would be as certain if the distance of 500 ft. were the limit as if a range of 5,000 ft. better suited the new system. It will be inferred from this explanation that, although there is no special limit within ordinary ranges, the plan is to attack at distances not much exceeding 500 feet, unless the sea be very smooth.

The *vis viva* of a projectile 15 in. in diameter, of such a length that it displaces 500 lbs. of water, may be readily estimated if we suppose the charge of powder in the gun to be so regulated that the speed on entering the water will be 400 ft. per second, necessary to furnish sufficient motive power; thus $\frac{400^2}{64} = 2500 \times 500 = 1{,}250{,}000$ ft.-lbs. A cylindrical body, 15 in. in diameter, with semi-spherical ends, moving at a rate of 100 ft. per second under water, requires a constant motive force of somewhat less than 1,500 lbs. Assuming, then, that the projectile passes through 150 ft. of water—the mean distance represented by the diagram—we have a resistance of 150 × 1500 = 225,000 ft.-lbs. to overcome. The motive force, it will thus be seen, is more than five times greater than the resistance; consequently, no doubt can be raised as to the adequacy of the motive power furnished by the *vis viva* of the projectile. It should be observed that the resistance is very great at first, and that the speed diminishes in a very rapid ratio; but it would be futile to present a formula expressing the ratio of speed and resistance, since the *form* of the body (withheld for obvious reasons) is the chief element in the calculation. Let us bear in mind that, while the resistance against a blunt body is exceedingly great, one provided with a sharp point readily enters the water, even at the rate of 400 ft. per second.

With reference to the gun, it should be mentioned that the very low speed of the projectile, and the consequent small charge of powder needed, render heavy metal unnecessary. Besides, slow-burning cake-powder, contained in cellular cartridges, will be employed, in order to check rapid ignition, and in order to sustain a uniform pressure during the discharge. By reference to our illustration, it will be seen that the guns are loaded from below, and for that purpose so arranged as to admit of being depressed 60 deg.

Gun-carriages are dispensed with, the trunnions being suspended by adjustable pendulum-links secured under the turret-roof. The recoil is checked by buffers attached to the turret wall in rear of the breach.

It is proper to state that the method of loading guns from below deck, as shown in our illustration, was planned by me, and drawings of the same exhibited in New York several years before it was claimed by certain American engineers as their invention.

Respecting the safety of the charge in the shell from ignition during the discharge, it should be observed that recent improvements in torpedo practice effectually prevent such accidents. With reference to the *calibre*, it is evident that this system of attack calls for dimensions that will admit a projectile of sufficient capacity to contain a charge which, by its explosion, will destroy a first-class ship of war built on the cellular plan. Nothing short of 15-in. calibre will answer for this purpose. The American and Swedish 15-in. guns are admirably calculated for the purpose, although they are unnecessarily heavy.

European savants, especially certain Swedish naval artillerists, who have criticised my advocacy of the 15-in. guns, will understand, on looking into this matter, why I have persisted in advising the Scandinavians to carry this large calibre in their monitor turrets as the most effective weapon against their powerful neighbors. Assuredly the Danes will have no cause to fear the Prussian *König Wilhelm* or *Friedrich der Grosse*, should their ports be defended by vessels armed with guns, by means of which several hundred pounds of dynamite or gun-cotton could be exploded under the hulls of the intruders.

The important question of hitting the intended object will be best answered by a careful examination of the illustration, which cannot fail to convince experts that, in moderate weather, the proposed projectile may be made to dip at the proper distance from the opponent's vessel. The different parabolic curves marked on the delineations on Plate 62 clearly show that no great accuracy is called for, and that the projectile may dip at various distances from the vessel assailed, and yet strike the hull. It should be observed that the vertical scale is different from that of the horizontal, in order not to place the vessels too far apart for the limited size of the plate; consequently, the trajectory shown is considerably foreshortened.

The turret represented on the illustration, in which the light 15-in. shell-guns are mounted, is composed of wrought-iron plates of great thickness, the size of the structure being sufficient to accommodate the two pieces, suspended, as already stated, by pendulum-links secured under the roof. A massive central shaft of wrought iron supports the turret, on the plan adopted in the monitors. The vessel designed to carry the battery is a mere iron hull, crammed with motive power, in order to ensure high speed. The midship section is triangular and the bow raking, as shown by the illustration. The overhanging sides and deck are heavily armored.

CHAPTER XLIII.

SUBMARINE WARFARE—THE MOVABLE TORPEDO.

(SEE PLATE 63.)

It was stated as a general proposition, in the preceding chapter, that a heavy body, of regular form, projected laterally through the air, commences to fall from the instant of leaving the muzzle of the gun, describing during its progress a parabolic curve considerably foreshortened owing to atmospheric resistance. But a body of regular form, projected under the surface of water or other fluid, in a horizontal or inclined direction, will move in a *straight* line, provided its specific gravity be equal to that of the fluid. In other words, a heavy body moving through the atmosphere is under the influence of the gravitating force of the earth; while a submerged body, the weight of which is equal to its displacement, is not affected by gravitation. If put in motion under the surface of a quiescent fluid of unlimited extent, such a body will continue to move in a straight line until the motive energy which propels it becomes less than the resisting force of the surrounding medium.

Starting with these cardinal propositions, I entered, some thirty years ago, on the task of solving the problem of submarine attack—viz., the propelling or projecting below the surface of the water of an elongated body containing explosive substances to be ignited when reaching some point under the bottom or bilge of an opponent's vessel. The best method of carrying out the idea is that of projecting the elongated body by means of a tube or chamber with parallel sides applied near the bottom of the aggressive vessel. Such a method I proposed to the Emperor of France in the month of September, 1854, as mentioned in Chap. XXVIII.

At close quarters the stated plan of attack will unquestionably be found very effective—indeed; infallible; but, unless the opponent's vessel can be approached very near, it will prove abortive. Obviously, if the projectile be pushed out in any direction not parallel with the line of keel while the aggressive vessel is in motion, a side resistance will be offered by the stationary water of the sea, which will divert the course of the missile the instant it is deprived of the guiding power of the tube from which it is ejected. Currents will, from the same cause, change the intended course. It need scarcely be observed that, in addition to the difficulty of controlling the direction of the projectile, the force imparted to the same, whether steam or compressed air, will be insufficient to propel it to any considerable distance. In order to meet these serious practical objections—viz., that the projectile cannot be propelled far enough, and that its course cannot be controlled—I have resorted to a device by which any desirable amount of propulsive force may be imparted, irrespective of the distance traversed, and by which the course of the missile is under perfect control during its progress to the intended point. Persons of a mechanical turn of mind in almost every country have for a long time been engaged in contriving torpedoes to be propelled under water by independent motive power of various kinds, for the purpose of blowing up vessels. The Austrian torpedo, urged through the water by means of compressed air, may be classed as one of this numerous tribe, the reported terrible nature of which has from time to time frightened naval constructors, and amazed some unmechanical sailors who have witnessed the trials, and found that the mysterious body actually can move under water. Proper investigation of the subject, however, exposes imperfections of the Austrian torpedo which render its final success problematical.

It should be borne in mind that atmospheric air compressed, so as to exert a pressure of 300 lbs. to the sq. in., weighs nearly 2 lbs. to the cubic ft. Consequently, the amount of motive force which the torpedo is capable of containing will be found wholly insufficient for its effective propulsion unless an impracticable or, at any rate, dangerous pressure be employed, accompanied by great weight, seriously interfering with buoyancy, while the want of means for directing the torpedo to the desired point presents an insuperable objection. As before stated, I have contrived a torpedo that may be propelled with any requisite amount of force, irrespective of distance, the course of which is under perfect control, notwithstanding currents, and which may be directed with perfect certainty to an object in motion. In contradistinction to the term projectile, applied to the structure of 1854, which was propelled alone by its *vis viva* on leaving the guiding-tube, I propose to apply the term *torpedo* to the contrivance now to be considered.

It should be observed that some attempts to propel bodies under water have been successful as regards maintaining a given depth. The self-evident device of applying a fin or horizontal rudder, operated by a piston or elastic bag actuated by hydrostatic pressure, has suggested itself to inventors. It will be readily perceived that an increase or diminution of draught, attended as it is with a corresponding variation of pressure, may be made subservient in changing the inclination, thereby establishing a tendency of the horizontal rudder either to elevate or depress the torpedo during its forward motion. Thus, by a proper adjustment and application of the hydrostatic pressure, the torpedo may be made to move at any desirable depth below the surface of the sea. Nor has any difficulty been experienced as regards the instrument of propulsion in the experiments made since the introduction of the screw propeller. But the difficulty of procuring the requisite amount of motive force for actuating the propeller, and the absence of means for directing the torpedo, have in each instance defeated the object in view.

Before proceeding to consider the important question of *guiding* the torpedo, I will now briefly describe my method of obtaining the required power for actuating the propellers. A reel, of suitable diameter, revolving on a horizontal axle, is applied near the chamber from which the torpedo is ejected, one end of the axle being supported by a suitable bearing, while the other enters an air-vessel through a stuffing-box. The end thus inserted in the air-vessel is perforated longitudinally for a short distance, and provided with an opening in the side at the point where the perforation terminates. A tubular rope, the bore of which is about one inch in diameter, composed of hemp and vulcanized rubber, is connected with this opening, and then coiled around the reel a certain number of times, and, lastly, connected with the rear end of the torpedo. The air-vessel into which the perforated axle of the reel enters, being charged with compressed air (by means of force-pumps worked by steam-power), it will be readily understood that the compressed air will pass through the axle, then through the several coils of tubular rope wound round the reel, and ultimately reach the rear end of the torpedo, where the rope is attached to the engine which actuates the propellers. Accordingly, the propulsion of the torpedo may be regulated by simply opening or closing the aperture of the perforated shaft within the air vessel. The rotation of the reel, consequent on the onward movement of the torpedo, obviously cannot interrupt the passage of the compressed air through the coils of the tubular rope; hence the supply of motive force will continue undiminished during the onward movement. The tubular rope being about one inch diameter in the bore, it will be found by calculation that a quantity of compressed air, sufficient to develop any desirable amount of power, may be transmitted through it during the progress of the torpedo, whether far off or near the aggressive vessel. The arrangement thus described being sufficiently simple to be comprehended without entering into detail, it will only be necessary to state that the tubular rope, after leaving the reel under the deck, is made to descend through a vertical tube into the torpedo chamber, in order to prevent an entrance of water at the point where the rope passes out. Also, that *two* propellers are employed, revolving in opposite directions round a common centre—indispensable to prevent the torpedo itself from rotating when subjected to the powerful torsion produced by a *single* propeller actuated by the motive force which may be transmitted through a tubular rope of one-inch bore.

I will now proceed to describe my method of guiding the torpedo, premising that the external casing which contains the mechanism and explosive compound is heavier at the bottom than at the top, in order to preserve a vertical position, and that, in addition to the horizontal rudders for regulating the immersion, the torpedo is provided with a vertical balance-rudder for directing the lateral course. The reel having a mean circumference of 10 ft., it will be seen that the tubular rope need only be coiled round it 100 times to admit of attack at a distance of 1,000 ft., probably far enough, since the position of the aggressive vessel which carries the torpedo may be changed at all times with desirable rapidity.

The apparently absurd proposition to direct and change the course of the torpedo at will, on board of the aggressive vessel, without external aid, is solved by the following simple expedient: A small elastic bag, connecting the tubular rope with the induction-pipe of the rotary engine, is attached to the side of the tiller of the torpedo's balance-rudder. As the compressed air during its passage to the motor must pass through the elastic bag, the latter will expand and contract with every change of internal pressure; and, as such change will depend on the quantity of compressed air admitted into the tubular rope, the expansion and contraction of the bag is evidently under perfect control. Now, the power of this bag, or the power of a loaded piston in an open cylinder, to resist internal pressure, may be so proportioned that when maximum pressure is admitted the swelling of the bag, or the motion of the piston, will cause the tiller to move about 20 deg. to port; and when the pressure is reduced 25 per cent., the accompanying contraction of the bag, or corresponding motion of the loaded piston in the open cylinder, will move the tiller 20 deg. to starboard. Thus, by admitting more or less compressed air into the tubular rope, thereby changing the dimensions of the bag or moving the piston referred to, the tiller will assume any desirable angle within 20 deg. on either side of the torpedo's centre line.

Accordingly, the direction of the torpedo will be as completely under the control of the hand which admits the compressed air to the tubular rope as if an intelligent directing power resided within the torpedo itself. Probably no greater mechanical feat than this can be instanced. The position of the torpedo is indicated by a circular disc, four inches in diameter, attached to the upper end of a perpendicular steel wire, or mast, secured to the top of the torpedo. The said disc is painted sea-green on the forward side and white on the opposite side. It need scarcely be observed that the explosion of the torpedo will sever the connection with the tubular rope, which thus may be hauled in by turning the reel. Should the intended object not be reached, the admission of compressed air to the tubular rope will be shut off, and the torpedo hauled in, or sent out on a new errand.

The scope of the device thus described is, of course, more limited than the scope of the method illustrated on Pl. 62; yet, had the Italians possessed it, the result at Lissa would unquestionably have been reversed. No harbor can be entered which is protected by it; nor would any amount of vigilance save vessels from destruction if approaching an enemy's coast defended by it.

With reference to the reel on which the tubular rope is coiled, it will be well to mention that it may be applied within the torpedo itself; in which case the tubular rope, instead of being *towed*, will be paid out during the onward motion towards the object intended to be struck.

The illustrations on Pl. 63, Figs. 1 and 2, represent top view and side elevation of the actuating steam-engine, air-compressing pump, air-vessel, and reel; while Figs. 3 and 4 show the side elevation and top view of the torpedo. It may be briefly mentioned that the torpedo thus represented, after having been tested during a series of trials in open water, has been purchased by the Navy Department at Washington. Negotiations are now pending for the purchase of the invention by the United States Government, on conditions of secrecy, as in the case of the Austrian torpedo; hence detailed information respecting the internal mechanism cannot be presented in this work.

CHAPTER XLIV.

TRANSMISSION OF MECHANICAL POWER BY COMPRESSED AIR.

(SEE PLATES 64 AND 65.)

Professor Barnard, in his admirable report of the Paris Universal Exposition, observes "that, next in importance to the creation of a new motive power, may be placed any material improvement in the methods of making available the powers which we have. Nature often furnishes us with such powers in abundance in situations where they cannot be conveniently converted to use. The positions of waterfalls are determined by geographical accidents. These do not always conspire with the causes which promote the growth of towns and development of industries. If it were possible to transfer the immense forces which are thus unprofitably expending themselves to points where there are hands to direct them, and materials on which to employ them, they might be productive of incalculable wealth, and of immeasurable benefit to mankind."

The foregoing views, so well expressed, are quite correct; but there is another power running to waste which the engineer, ere long, will be called upon to utilize—viz., the power of the tides. Already a prominent association has been formed in France for erecting tidal motors on a very large scale. Thus, while engineering skill has nearly exhausted itself in endeavors to improve the steam-engine, a new field opens, boundless in extent, which will demand far greater abilities than those called for within the narrow bounds hitherto limiting the energies of the mechanical engineer. The grand scheme of utilizing the natural forces now running to waste divides itself into two distinct branches: 1st. The requisite mechanism for receiving the force exerted by nature. 2d. The means for transmitting that force to desirable localities. It is the latter branch which I propose to discuss. But, before entering on the subject, it will be proper to point out that it is not the natural forces alone which the engineer is called upon to devise means for transmitting. Indeed, with our present abundant supply of coal, the transmission of force developed by steam will be most frequently called for; since the steam-engine, however portable in its character, cannot be applied in all places where power is required. The experience of late years has shown that the substitution of mechanical power for manual labor in driving tunnels and for mining operations has reduced the cost and greatly increased the amount of work done in a given time. But the presence of steam in tunnels and in the galleries of mines is wholly inadmissible; hence small motive engines, operated by compressed air, have been introduced for operating the rock-drills and other cutting tools. Not only has the work by these means been greatly accelerated, but the escape of the exhaust air from the motors has in a material degree tended to purify the atmosphere within the mines, rendering the work healthful which formerly proved destructive to the miners.

The first question which presents itself in treating of the transmission of force by compressed air is the size of the tube necessary to convey a certain amount of energy in a given time—*pressure* and *velocity* being the elements which determine the question. Fortunately, we are not without practical data on the subject, the engineers of the Mont Cenis tunnel having, some time ago, thoroughly investigated it. The result of their labors has been recorded in the Report of the United States Commissioners at the Paris Universal Exposition of 1867. The Commissioners state that, at the date of the report on the progress of the work in the tunnel during the year 1863, the operation was carried on at a distance of nearly two thousand metres from the reservoirs of compressed air, and that nine borers were in operation with a force of two and a half horse-power each. The tube conveying the air was very nearly eight inches in diameter, the air being under a pressure of six atmospheres, and its velocity in the tube three feet per second. The transmission of the power under these very favorable conditions was attended with no sensible loss, the pressure not being perceptibly less at the working extremity of the tube when all the perforations were in operation than when the machinery was entirely at rest.

The Report of the Commissioners furnishes a very full account of the result of the experiments conducted at Corsica, in 1837, by order of the Italian Government, on the resistance of tubes to the flow of air through them. These experiments were made previously to the commencement of the work on the tunnel, the employment of compressed atmospheric air as a motive power to actuate the boring apparatus being at the time considered a doubtful expedient. The Report states that it was the aim of the investigation not only to ascertain the absolute loss of force attending the transmission of air through tubes of certain dimensions at certain velocities, but also to determine what are the *laws* which govern the resistance when the velocities of the air and the diameter of the tube are varied. The following conclusions were deduced from the experiments: 1. The resistance is directly as the length of the tube. 2. It is directly as the square of the velocity of flow. 3. It is inversely as the diameter of the tube.

The fact before adverted to—that in the actual working of the machines in the tunnel no perceptible loss of power was experienced at a distance of two thousand metres from the reservoirs—must be attributed to the want of delicacy of the manometer or pressure-gauge employed. Although insignificant at moderate distances and low velocities, the experiments at Corsica proved that the loss becomes serious when the velocity and distance are considerably increased since, agreeably to the law before cited, the resistance varies as the square of the velocity. Consequently, when the velocity is six times greater than the moderate rate of six feet, or thirty-six feet per second, the resistance will be thirty-six times greater, the power developed increasing in the ratio of the volume of air delivered—viz., six times. It will be perceived, therefore, that while the length and diameter of a tube remain unaltered, and while the absolute resistance opposed to the flow of a current of air through it varies as the square of the velocity, the relative resistance is only as the simple velocity. It follows from the foregoing facts that the power of compressed air varies as the product of its pressure and its volume; hence, when the pressure is constant, as the volume simply. But the volume delivered varies as the velocity multiplied by the square of the diameter of the tube. Now, as the resistance is inversely as the diameter, and the volume directly as the square of the diameter when the velocity remains constant, it follows also that under a given pressure and velocity the relative resistance (namely, the resistance divided by the power) will vary inversely as the cube of the diameter. Obviously, therefore, by enlarging the diameter of the tube, we may increase the power transmitted, and at the same time diminish both the absolute and relative resistance. In conclusion, I strongly recommend engineers who may be called upon to transmit mechanical power by compressed air not to aim at economy by employing tubes of small diameter.

Having thus disposed of the first branch of the subject under consideration, let us now consider the mechanism needed to compress the air to be transmitted. At first sight the solution of the problem appears to be very simple, but due reflection at once suggests to the practical mind numerous difficulties. Considerations of weight, space, and first cost, of course, demand the adoption of a double-acting compressing-cylinder; hence the practicability of employing double action is the very first question that presents itself. Now, in double-acting cylinders both ends must be closed, consequently lubrication of the compressing piston must be effected from without. Supposing that means for effecting such lubrication have been devised (by no means easy), will the packing of the piston be preserved and abrasion prevented? In answering this question, we must bear in mind that even at moderate pressure the compression of the air generates a degree of heat which precludes the employment of oil, as it quickly dries up and ultimately burns. Water, if continually replenished, so as to make good the loss caused by the formation of steam, may answer for a short time. The dust drawn into the cylinder from the surrounding atmosphere will, however, mix with the water, and soon form a paste, resembling mud, on the piston, productive of friction and abrasion of the cylinder incompatible with the functions of a piston. The objectionable plan of compressing air by rising and falling columns of water I do not propose to discuss in this place.

The illustrations on Plate 64 represent a perspective view, while Plate 65 shows a longitudinal section of a machine for compressing air, in which the difficulties before referred to have been effectually overcome; the leading features being that the compressing cylinders, open at the top, are immersed in a cistern through which a continuous circulation is kept up by a current of water which flows over the compressing pistons before entering the cistern. A glance at the sectional drawing on Plate 65 will give a clear idea of the nature of the device and the mode of operation, which may be thus briefly described: A small pipe communicating with a reservoir or other supply of water is applied behind the machine, provided with a branch for each compressing cylinder. These branch-pipes are bent downwards vertically in such a manner that a stream of water flowing through each will fall on the top of the compressing-piston, near its circumference. The compressing-cylinders, as already stated, are suspended within a water-cistern, and supported by their upper flanges, which rest on the top of the cistern. Referring to the perspective view of the machine, shown on Plate 64, it will be seen that the water-cistern forms a pedestal supporting the side frames on which the pillow-blocks of the crank-journal rest. It will also be seen that the side frames form slides which guide the cross-head of the piston-rods. A band-wheel, provided with a very heavy rim, to be driven by steam or other motive power, is attached to the crank-shaft between the pillow-blocks formed at the top of the side frames. It scarcely needs explanation that the object of making the rim of the band-wheel very heavy is that of equalizing the irregular resistance offered by the compressing-pistons. The inlet-valves which supply the atmospheric air to be compressed are inserted in the pistons, while the outlet-valves are placed at the bottom of the cylinder, the valve-chambers of the latter communicating directly with an air-conductor which leads to an ordinary air-reservoir. Referring again to the sectional representation of the machine, it will be seen that the sides of the compressing-cylinder are perforated near the top, the position of these perforations being such that when the piston reaches the full up-stroke its upper face will not quite reach the under side of the perforations. It will be readily understood that by this arrangement a certain body of water will always remain on the top of the piston, while at the same time the perforations effectually prevent an overflow within the cylinder. The connecting-rod is very short compared with the length of throw of the crank; hence the piston will remain for a considerable interval of time near the top of the cylinder, during which time the necessary discharge of the water lodged on the top of the piston takes place. To prevent undue accumulation of water in the cistern, an overflow-pipe is introduced at the side, as shown in the sectional illustration. It should be particularly noticed that the air, while undergoing compression in the cylinder, is completely surrounded by metallic surfaces cooled by the circulating water. But this is not all. During the reciprocating action of the piston, the body of water lodged on its top washes the inside of the cylinder both during the upward and downward movement. Now, the speed of the piston is fully one hundred and fifty feet per minute; hence an internal refrigeration is established far more efficient than the external circulation. The metal composing the cylinder, it will thus be seen, is actually cooled on *both* sides, a very remarkable and almost paradoxical achievement. Again, it will be perceived that the circulating cold water continually washes the top of the piston before entering the cistern. Accordingly, the entire quantity of water required for cooling during the compression passes over the piston at the initial low temperature, thereby subjecting the part of the machine that most needs cooling to the greatest amount of refrigeration. As regards lubrication, it is self-evident that no conceivable plan can be more efficient than that of actually washing the inside of the cylinder with the lubricating medium, both during the up and down movement of the piston.

Regarding the utility of cooling the compressed air, it needs no demonstration to show that refrigeration *after* the air has left the compressing-cylinder, recommended by some engineers, is not only useless, but tends to reduce the efficiency of the compressed air as a motive agent. Obviously, if the air during its transmission from the compressor to the motor intended to be actuated loses in temperature, it also loses in bulk. On the other hand, refrigeration *within the cylinder* during the down-stroke is useful, as it tends to check the swelling of the volume of air under the piston caused by the heat generated by compression, consequently diminishing the necessary motive power.

CHAPTER XLV.

SUN POWER—THE SOLAR ENGINE.

(SEE PLATES 66 AND 67.)

The illustration on Plate 66 derives its chief interest from the fact that it represents the first motor actuated by the direct agency of the sun's radiant heat. It was constructed at New York, 1870, and intended as a present to the French Academy of Sciences. Apart from being a motor, this engine was designed to operate as a meter for registering the volume of steam generated by the concentrated heat of a pencil of solar rays of a given section. Regarded as a steam-meter, it proved important, as it verified the results of previous experiments and previous calculations, based on the number of thermal units developed by the evaporation of a certain weight of water in a given time. Engineers will not fail to notice the unusual proportions of the working parts, nor will they fail to appreciate the object in view, that of reducing the friction to a minimum—an indispensable condition in a meter. The entire mechanism being shown with perfect distinctness in the perspective view of the engine on the plate referred to, it is only necessary to mention that the square pedestal which supports the steam-cylinder (4½ ins. in diameter), the beam-centre, and the crank-shaft, conceals a surface-condenser.

Under a clear sun the engine performed its functions with perfect uniformity, at a velocity of 240 revolutions per minute. It consumed, at the stated rate, only part of the steam furnished by a solar steam-generator, temporarily employed, belonging to an engine of greater dimensions then in the course of construction. With reference to ascertaining correctly the amount of mechanical power developed by the concentrated radiant heat applied to this engine, experts need scarcely be reminded that, by dispensing with a vacuum, the atmospheric resistance and back pressure exerted against the piston furnish elements for measuring, with critical nicety, the dynamic force transmitted by pencils of solar rays of definite sections.

Drawings and descriptions of the mechanism by which the sun's radiant heat has been concentrated in my experimental engines will not be presented in this work, nor will the form of the steam-generator which receives the concentrated heat be delineated or described. Experienced professional men will appreciate the motive—viz., that of preventing enterprising persons from procuring patents for *modifications.* With reference to the course thus adopted, it will be proper to mention that I have in several instances, notably in the case of the screw-propeller and the caloric engine, been prevented from perfecting my invention in consequence of conflicting privileges having in the meantime been granted to others.

Regarding the solar engine, it may be well to state that I shall not apply for any patent rights, excepting for the purpose of protecting the community, and that it is my intention to devote sufficient time and means to ensure its completion. Hence my anxiety to guard against legal obstructions being interposed before perfection of detail shall have been measurably attained. In the meantime, let us hope that no exclusive privilege will be granted tending to throw obstacles in the way of an unrestricted manufacture and introduction of the solar engine in countries where a continuously clear sky warrants its adoption, especially in Upper Egypt and on the coast of Peru.

The experiments instituted show that the mechanism which I have adopted for concentrating the sun's radiant heat abstracts, on an average, during nine hours a day, for all latitudes between the equator and 45 deg., fully 3.5 units of heat per minute for each square foot of area presented perpendicularly to the sun's rays. A unit of heat being equivalent to 772 foot-pounds, it will be perceived that, theoretically, a dynamic energy of 2,702 foot-pounds is transmitted by the radiant heat, per minute, for each square foot; hence, 270,200 foot-pounds for an area of 10 feet square. If we divide this sum by the adopted standard, 33,000, we ascertain that 100 square feet of surface exposed to the solar rays develop continuously 8.2 horsepower during nine hours a day, within the limits of latitude before mentioned. But engineers are well aware that the whole dynamic energy of heat cannot be utilized in practice by any engine or mechanical combination whatever, nor at all approached; hence I have assumed, in order not to overrate the capability of the new system, that a solar engine of one horse-power demands the concentration of solar heat from an area of 10 feet square. On this basis, I will show presently that those regions of the earth which suffer from an excess of solar heat will ultimately derive benefits resulting from an unlimited command of motive power which will, to a great extent, compensate for disadvantages hitherto supposed not to be counterbalanced by any good. But before estimating the magnitude of mechanical power which we may produce by availing ourselves of the fuel contained in that great storehouse from whence it may be obtained free of cost and transportation, let us consider the leading feature of the device resorted to, especially that by which I have succeeded in augmenting the comparatively low temperature developed by direct solar radiation sufficiently for the production of useful work.

The solar engine, when steam is employed as the medium for transmitting the radiant energy, is composed of three distinct parts—the engine, the steam-generator, and the mechanism by means of which the inadequate energy of the sun's rays adverted to is increased to such a degree that the resulting temperature will exceed that corresponding with the steam-pressure necessary in an efficient engine. The motor itself, when the acting medium under consideration is employed, resembles in all essential points a modern steam-engine, utilizing to the fullest extent the mechanical energy of the steam admitted to the working-cylinder. But when atmospheric air is employed as the medium for transmitting the solar energy to the motor, an entirely different combination of mechanism is called for, as will be seen hereafter. Regarding the steam-generator, it will be superfluous to point out the advantages resulting from its not being exposed to the action of fire or soot; hence that it can only suffer from the slow action of ordinary oxidation. As the motor itself resembles a steam-engine, we have of course merely to consider the nature of the mechanism by means of which the solar heat is concentrated and the temperature raised above that of the water in the steam-generator. Regarding this mechanism—viz., the *concentration apparatus*—it has been asked, Is it costly? Is it heavy and bulky, so as to render transportation difficult? And, finally, the question has frequently been put, Is it liable to derangement and expensive to keep in order? The cost is moderate. The weight is small; indeed, lightness is the most notable peculiarity of the concentration apparatus. As to bulk, it may be observed that this apparatus is composed of small parts readily put together. With reference to durability, the fact need only be pointed out that certain metals, however thin, if kept dry, may be exposed to the sun's rays during an indefinite length of time without appreciable deterioration; hence, unlike the furnaces of steam-boilers, which soon become unserviceable, the concentration apparatus, as it consists of thin metallic plates, composed of durable materials, cannot be damaged by the mere action of the sun's rays. Another question has been asked, Whether the solar engine will answer as well on a large as it does on a small scale? The following reply disposes of this pregnant query: It is not necessary, nor intended, to enlarge considerably the size of the apparatus by means of which the comparatively feeble intensity of the sun's rays has been successfully concentrated, and the temperature sufficiently elevated to generate steam for actuating the solar engine. The maximum size adopted has been adequate to utilize the radiant heat of a pencil of rays (sunbeam) of 35 square feet section. The employment of an increased number of such structures will, therefore, in most cases be resorted to when greater power is wanted, as we increase the number of hands when we desire to perform an additional amount of work. The motor itself—viz., the steam-cylinder and the working parts—will obviously be proportioned, as at present, in accordance with the pressure of steam employed and the work to be done.

It should be clearly understood that I do not recommend the erection of solar engines in places where there is not steady sunshine, until proper means shall have been devised for storing up the radiant energy in such a manner that regular power may be obtained from irregular solar radiation. Experienced engineers need not be told that formidable difficulties present themselves in storing up mechanical energy of any kind; yet when coal can no longer be obtained, necessity, ingenuity, and increased experience will find means of overcoming obstacles which now appear insurmountable.

Before considering further the nature and capabilities of my solar engine, it will be proper to notice the result of the labors of Professor Mouchot of Tours, formerly of the Lycée of Alençon, who claims to have anticipated me in employing solar heat for the production of motive power. Mouchot bases his claim on some experiments, made in 1866, intended to show that by the accumulation of heat which takes place when a blackened surface is surrounded by glass bells, steam may be generated for actuating machinery. Sir John Herschel, it is well known, elaborated the old idea of concentrating solar radiation, and conducted a series of experiments at Cape Town, in 1838, showing that not only was it possible to produce boiling heat by accumulating solar heat as described, but he succeeded in elevating the temperature sufficiently for roasting meat. Some time previous to 1870, Mouchot made a small model engine, a mere toy, actuated by steam generated on the plan of accumulation by glass bells; but finding the heat insufficient, he added a polished metallic reflector. The increase of temperature resulting from this expedient rendered his steam-generator more effective, and it was found that under favorable circumstances sufficient steam could be produced to actuate his small model. The Conseil-Général of Indre-et-Loire having subsequently provided Professor Mouchot with necessary means, he put up a steam-generator at Tours in 1872, which he deems a perfect machine, its action being based on the results of his previous experiments. The accompanying diagram, Fig. 1, represents a vertical section of the said steam-generator, thus described by M. L. Simonin in *Revue des Deux Mondes:*

"The traveller who visits the library of Tours sees in the court-yard in front a strange-looking apparatus. Imagine an immense truncated cone, a mammoth lamp-shade, with its concavity directed skyward. This apparatus is of copper, coated on the inside with very thin silver-leaf. On the small base of the truncated cone rests a copper cylinder, blackened on the outside, its vertical axis being identical with that of the cone. This cylinder, surrounded as it were by a great collar, terminates above in a hemispherical cap, so that it looks like an enormous thimble, and is covered with a bell-glass of the same shape.

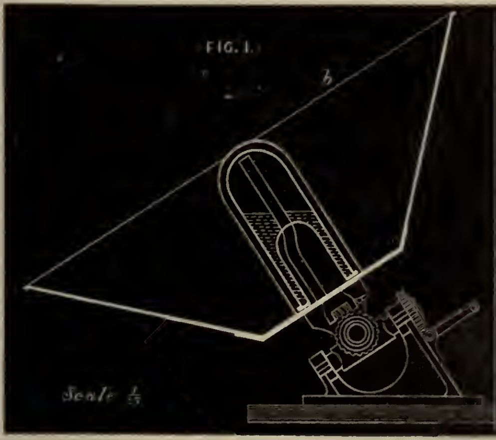


FIG. 1.

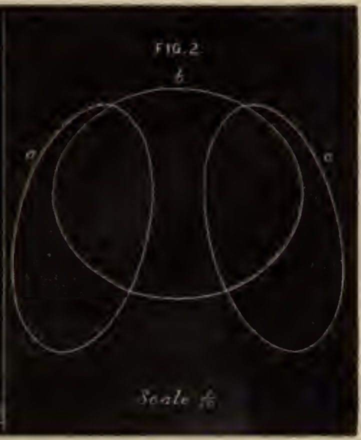


FIG. 2.

"This curious apparatus is nothing else but a solar receiver, or, in other words, a boiler, in which water is made to boil by the heat-rays of the sun. This steam-generator is designed to raise water to the boiling point and beyond by means of the solar rays, which are thrown upon the cylinder by the silvered inner surface of the conical reflector. The boiler receives water up to two-thirds of its capacity through a feed-pipe. A glass tube and a steam-gauge communicating with the inside of the generator, and attached to the outside of the reflector, indicate both the level of the water and the pressure of the steam. Finally, there is a safety-valve to let off the steam when the pressure is greater than desired. Thus the engine offers all desirable safety, and may be provided with all the accessories of a steam-boiler.

"The reflector, which is the main portion of the generator, has a diameter of 2.60 metres at its large, and one metre at its small, base, and is eighty centimetres in height, giving four square metres of reflecting surface, or of insolation. The interior walls are lined with burnished silver, because that metal is the best reflector of the heat-rays; still, brass with a light coating of silver would also serve the purpose. The inclination of the walls of the apparatus to its axis measures 45 deg. Even the ancients were aware that this is the best form for this kind of metallic mirrors with linear focus, inasmuch as the incident rays parallel to the axis are reflected perpendicularly to the same, and thus give a focus of maximum intensity.

"The boiler is of copper, which of all the common metals is the best conductor of heat; it is blackened on the outside, because black possesses the property of absorbing all the heat-rays, just as white reflects them; and it is enclosed in a glass envelope, glass being the most diathermanous of all bodies—that is to say, the most permeable by the rays of luminous heat. Glass further possesses the property of resisting the exit of these same rays after they have been transformed into dark rays on the blackened surface of the boiler. None of these applications of physical laws present any novelty; people reduced them to practice instinctively, as it were, before men of science could assign the reasons. Here the arts of cookery and of gardening, and the processes for warming our rooms, did not wait for the experiments of the physicist. Saussure himself started from these data in his researches; but the inventor needed the discoveries of modern physics in order to give to these applications a rigorous formula.

"The boiler proper of the Tours solar engine consists of two concentric bells of copper, the larger one, which alone is visible, having the same height as the mirror—*i.e.*, eighty centimetres—and the smaller or inner one fifty centimetres; their respective diameters are twenty-eight and twenty-two centimetres. The thickness of the metal is only three millimetres. The feed-water lies between the two envelopes, forming an annular envelope three centimetres in thickness. Thus the volume of liquid is twenty litres, and the steam-chamber has a capacity of ten litres. The inner envelope is empty. Into it pass the steam-pipe and the feed-pipe of the boiler. To the steam-pipe are attached the gauge and the safety-valve. The bell-glass covering the boiler is eighty-five centimetres high, forty centimetres in diameter, and five millimetres in thickness. There is everywhere a space of five centimetres between its walls and those of the boiler, and this space is filled with a layer of very hot air.

"The earth, owing to its diurnal and annual revolution, does not occupy the same position with regard to the sun at all hours of the day, or in all seasons of the year. This being the case, the generator is so contrived as to revolve 15 deg., or one twenty-fourth of its circumference, hourly around an axis parallel to the earth's axis—*i.e.*, so as to follow the apparent diurnal motion of the sun, and to incline gradually on its axis in proportion to the solar declination. Hence the intensity of the utilized heat is always nearly the same, whatever the hour of the day or the season of the year, inasmuch as the apparatus is always so arranged as to reflect with the least possible loss all the rays emitted by the sun. This double motion of the generator is effected by a very simple contrivance."

The foregoing description of the Solar Steam-Generator of Mouchot is so lucid that it requires no explanation. Mr. Simonin, however, erroneously supposes that the power developed by the apparatus is nearly the same at all hours of the day, the fact being that the energy developed by the concentrated solar heat varies with the depth of atmosphere penetrated by the rays. The latter evidently depends on the sun's zenith distance; hence at Paris, where the maximum solar intensity during the summer solstice is 65°.0

Fah. at noon (see diagram on Plate 9), it scarcely reaches 52°.0 F. at five o'clock in the afternoon, owing to the increased zenith distance, and consequent increase of the depth of atmosphere to be penetrated by the sun's rays. Obviously, the efficiency of the solar generator will be diminished in the same ratio as the stated intensities. Mr. Simonin states that on some occasions, when the sun has been exceptionally clear, the solar generator at Tours has evaporated five litres of water per hour, which he assumes equivalent to half a horse-power. The reflector producing this result—a truncated cone—being 2.6 metres (8 feet 6 inches) in diameter, it will be found that in order to double the reflective area necessary to generate steam for an engine of *one* horse-power, a truncated cone of 3.6 metres (11 feet 9 inches) aperture will be required. Practical engineers are aware that an inverted conical body whose base is nearly 12 feet in diameter, swinging round an inclined axle at least 60 deg. on each side of the vertical line, presents a structure so formidable, even if counterpoised, that it would not be prudent to increase its size. Accordingly, *one hundred* of Mouchot's solar generators would be needed to furnish steam for an engine of 100 horse—a very moderate power, if employed for manufacturing or other industrial purposes. Referring to the diagram on page 565, Fig. 2, representing a bird's-eye view of the aperture of the conical reflector at Tours in three different positions—viz., *a* in the morning, *b* at midday, and *c* during the afternoon—it will be seen that each instrument, owing to the necessary change of position, demands a front space of nearly twenty feet. If placed side by side, the conical solar generators required for an engine of 100 horse-power would therefore occupy a front of 2,000 feet from east to west. If arranged in four lines, with sufficient space north and south to prevent interference, a distance of 500 feet by 200 feet would be required.

Now, let us consider that the scheme calls for 100 separate boilers, to be continually fed with water, the height of which can only be known by the indication of outside gauges, while the steam from the scattered boilers must be conveyed by a series of flexible tubes to the motive engine. The hundred glass bells can, no doubt, be dusted and kept clean with moderate exertion; but the hundred silver-plated reflectors, which Mr. Simonin says must be exposed to the vicissitudes of the atmosphere, cannot be kept bright without herculean labor, since silver tarnishes in a few hours. In view of the foregoing statement, which embraces only the chief difficulties attending Mouchot's system, the most sanguine might well despair of rendering sun-power available for practical purposes.

The Professor of the Lycée of Alençon, in claiming to have anticipated me, has done so ignorant of the fact that sun-power has been the study of my whole professional life —a life the early part of which was chiefly devoted to the production of a cheaper motive power than steam. The industrious scientist, if he had been correctly informed on the subject, would no doubt have perceived the advantages resulting from such antecedents, with reference to a successful practical solution of the problem of utilizing solar heat.

On grounds already fully explained, minute plans of my new system of rendering sun-power available for mechanical purposes will not be presented in this work. The occasion, however, demands that I should present an outline of the *concentration apparatus* before referred to. It consists of a series of polished parabolic troughs, in combination with a system of metallic tubes charged with water under pressure, exposed to the influence of converging solar rays, the augmented molecular action produced by the concentration being transferred to a central receiver, from which the accumulated energy is communicated to a single motor. Thus the mechanical power developed by concentrated solar heat is imparted to the solar steam-engine without the intervention of a multitude of boilers, glass bells, gauges, feeders, etc. Moreover, the concentration apparatus, unlike the instrument of Mouchot, requires no parallactic motion, nor does its management call for any knowledge of the sun's declination from day to day. Its position is regulated by simply turning a handle, until a certain index coincides with a certain bright line produced by the reflection of the sun's rays.

Plate 67 represents a perspective view of a solar engine, in which the concentrated energy of the sun's rays is communicated to the motor by means of heated atmospheric air, instead of being communicated by water heated under pressure and expanded into steam. A glance at the illustration shows that the upper end of the working-cylinder is heated by the sun's rays reflected by a curved mirror. It will be seen by careful examination that the solar rays converge at a point *beyond* the axis of the reflector; hence that the form of the latter is not parabolic, but composed of an irregular curve. The object is that of spreading the converging rays over a greater length of the cylinder than possible with the divergence which would result from employing a reflector of true parabolic curvature. It will be perceived on inspection that the upper end of the cylinder will be subjected to a concentration of heat many times greater than the concentration at the lower end. Referring to the accompanying diagram representing a vertical section of the machine, it will be seen that the working-cylinder, open at the lower end, contains two pistons, a working-piston *a* and an exchange-piston *b*. The working-piston is

connected with the crank-shaft *d* by the beam *c* and the connecting-rod *g*. The exchange-piston *b* is connected with the crank-shaft by the bell-crank *f f* and connecting-rod *h*. An annular space is formed round the exchange-piston, admitting of a free passage of the air from end to end of the cylinder during the motion of this piston. It will be readily understood that during the downward motion of the exchange-piston the cold air from the lower end of the cylinder will be transferred to the upper end, heated by the concentrated solar rays; hence internal pressure will be produced tending to force the working-piston down. By a careful examination of the combination of the several working parts, it will be easily comprehended how the working-piston is actuated by the confined air, heated and cooled alternately by the peculiar motion of the exchange-piston. It will be evident that the large surface presented by the outside of the exchange-piston, and inside of the cylinder, will cause a rapid change of temperature of the air while circulating from end to end of the latter. The upper end of the cylinder being heated by the concentrated solar rays, the cold air from the lower end will, during its transfer to the upper end caused by the downward motion of the exchange-piston, become heated and expanded; while during the upward motion of the said piston the air, in being transferred to the lower end of the cylinder, becomes cooled and contracted. It will be found on due consideration that the exchange-piston thus performs the office of a *regenerator*. The engine, therefore, is capable of operating for a considerable time by exposing the upper end of the cylinder to the reflected solar heat during a few minutes at starting. By continuous exposure to the concentrated solar rays, the engine performs fully 400 turns per minute. It should be observed that concentrated solar radiation supplies heat with such extraordinary rapidity that the apparently insufficient amount of heating surface presented by the cylinder has proved adequate, notwithstanding the great speed of the engine. It only remains to be stated that the body *m m* represents a radiator carrying off the heat which is not taken up by the circulating air during the motion of the exchange-piston. Of course, the amount of heat carried off by the radiator furnishes a nearly correct measure of the solar energy not converted into mechanical work. Engineers need not be reminded that the form of the solar engine thus described is applicable only for purposes requiring moderate power. In the largest class of solar engines actuated by atmospheric air, in which the radiator is incapable of abstracting the superfluous heat, I employ valves, and take in fresh air at each stroke of the machine, precisely as in the caloric engine delineated on Plate 46.

Having thus cursorily examined the construction of the solar engine actuated by the intervention of atmospheric air, and briefly adverted to the steam solar engine and the mode adopted in concentrating the molecular motion imparted by solar radiation, and also pointed out the nature of the expedient resorted to in transferring the said concentrated molecular motion to mechanical motors, let us now consider the stupendous amount of the energy at our command.

It has already been stated that the result of repeated experiments with the concentration apparatus shows that it abstracts on an average, during nine hours a day, for all latitudes between the equator and 45 deg., fully 3.5 units of heat per minute for each square foot of area presented perpendicularly to the sun's rays. Theoretically, this indicates the development of an energy equal to 8.2 horsepower for an area of 100 square feet. On grounds before explained, our calculations of the capabilities of sun power to actuate machinery will, however, be based on one horsepower developed for 100 square feet exposed to solar radiation. The isolated districts of the earth's surface suffering from an excess of solar heat being very numerous, our space only admits of a glance at the sunburnt continents.

There is a rainless region extending from the northwest coast of Africa to Mongolia, 9,000 miles in length and nearly 1,000 miles wide. Besides the North African deserts, this region includes the southern coast of the Mediterranean east of the Gulf of Cabes, Upper Egypt, the eastern and part of the western coast of the Red Sea, part of Syria, the eastern part of the countries watered by the Euphrates and Tigris, Eastern Arabia, the greater part of Persia, the extreme western part of China, Tibet, and, lastly, Mongolia. In the western hemisphere, Lower California, the table-land of Mexico and Guatemala, and the west coast of South America, for a distance of more than 2,000 miles, suffer from continuous intense radiant heat.

Computations of the solar energy wasted on the vast areas thus specified would present an inconceivably great amount of dynamic force. Let us, therefore, merely estimate the mechanical power that would result from utilizing the solar heat on a strip of land a single mile in width, along the rainless western coast of America; the southern coast of the Mediterranean before alluded to; both sides of the alluvial plain of the Nile in Upper Egypt; both sides of the Euphrates and Tigris for a distance of 400 miles above the Persian Gulf; and, finally, a strip one mile wide along the rainless portions of the shores of the Red Sea, before pointed out. The aggregate length of these strips of land, selected on account of being accessible by water communication, far exceeds 8,000 miles. Adopting the stated length and a width of *one* mile as a basis for computation, it will be seen that this very narrow belt covers 223,000 millions of square feet. Dividing the latter amount by the area of 100 square feet necessary to produce one horse-power, we learn that 22,300,000 solar engines, each of 100 horse-power, could be kept in constant operation, nine hours a day, by utilizing only that heat which is now wasted on the assumed small fraction of land extending along some of the water-fronts of the sunburnt regions of the earth. Due consideration cannot fail to convince us that the rapid exhaustion of the European coal-fields will soon cause great changes with reference to international relations, in favor of those countries which are in possession of continuous sun-power. Upper Egypt, for instance, will, in the course of a few centuries, derive signal advantage and attain a high political position on account of her perpetual sunshine and the consequent command of unlimited motive force. The time will come when Europe must stop her mills for want of coal. Upper Egypt, then, with her never-ceasing sun-power, will invite the European manufacturer to remove his machinery and erect his mills on the firm ground along the sides of the alluvial plain of the Nile, where an amount of motive power may be obtained many times greater than that now employed by all the manufactories of Europe.

APPARATUS FOR MEASURING RADIANT HEAT. DESIGNED BY JOHN ERICSSON.

CONSTRUCTED AT NEW YORK, 1873.

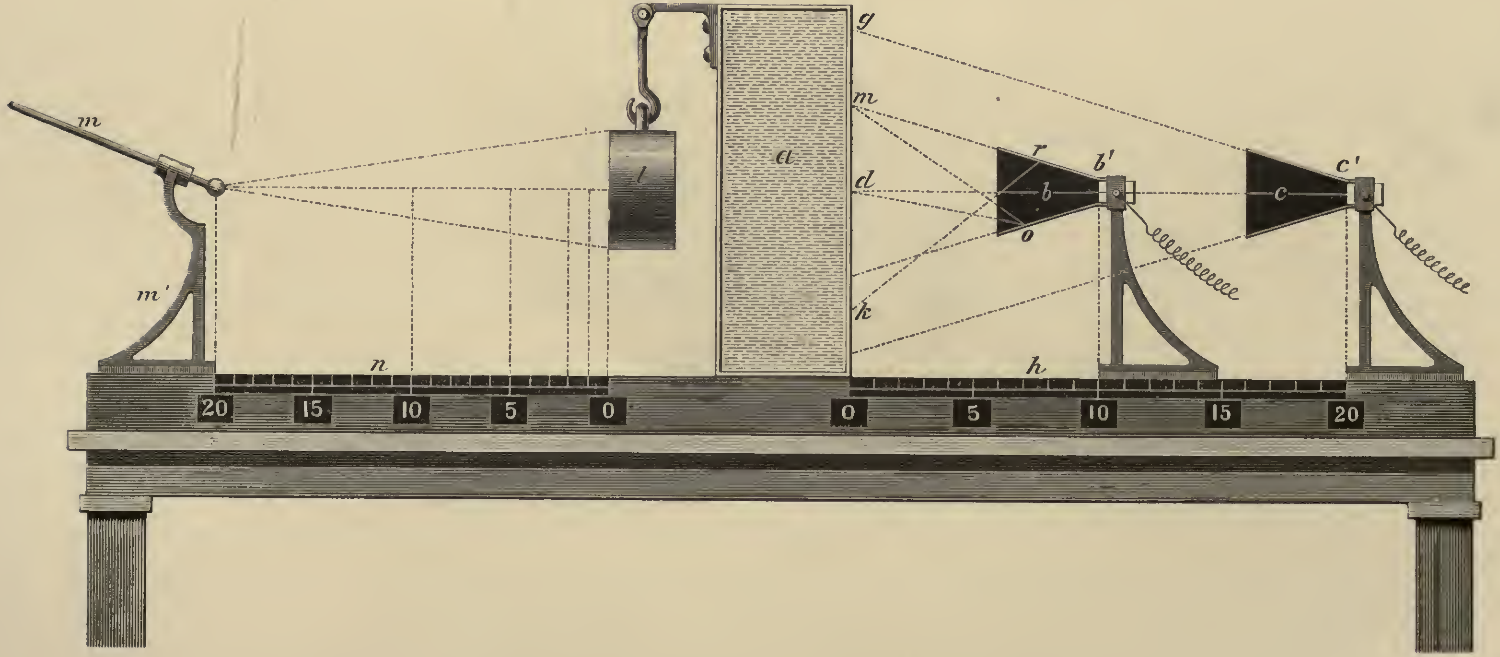


PLATE 1. SEE CHAP. I.

Instrument for measuring the Intensity of Radiation from Enclosed Concave Radiators.

Designed by John Ericsson. Manufactured at New York, 1873.

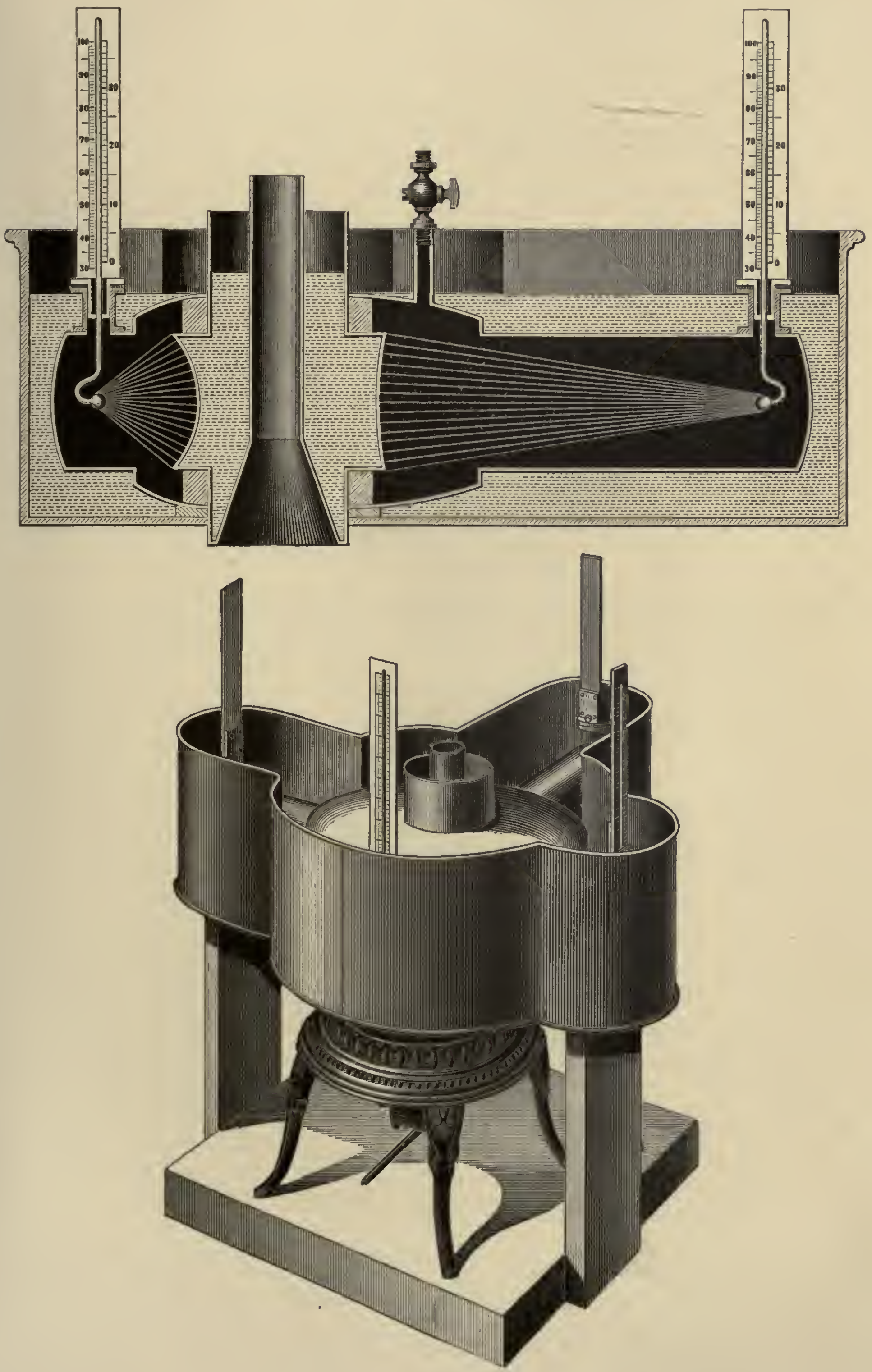


Plate 2. See Chap. I.

DIAGRAMS SHOWING THE PROPAGATION OF RADIANT HEAT THROUGH SPACE.

FIG. 4

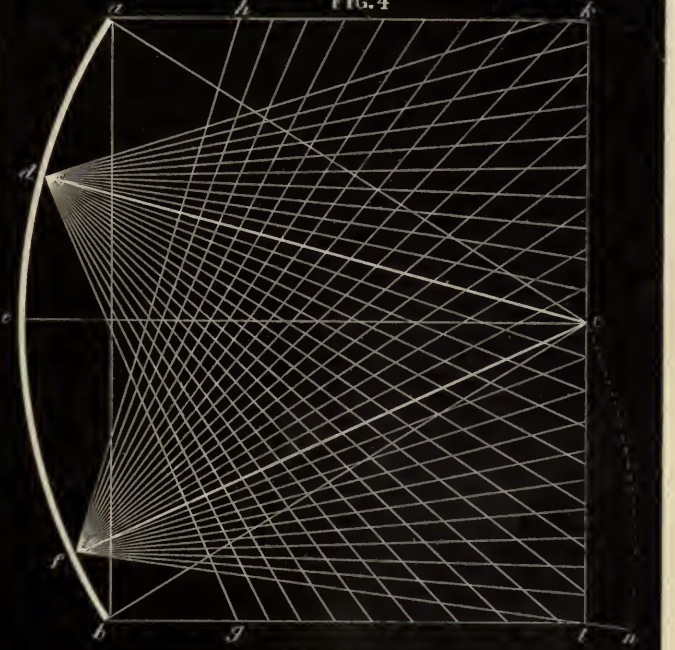


FIG. 5

PLATE 3. SEE CHAP. I.

Instrument showing the Rate of Cooling of a Heated Body within an Exhausted Cold Enclosure.

Designed by John Ericsson. Manufactured at New York, 1872.

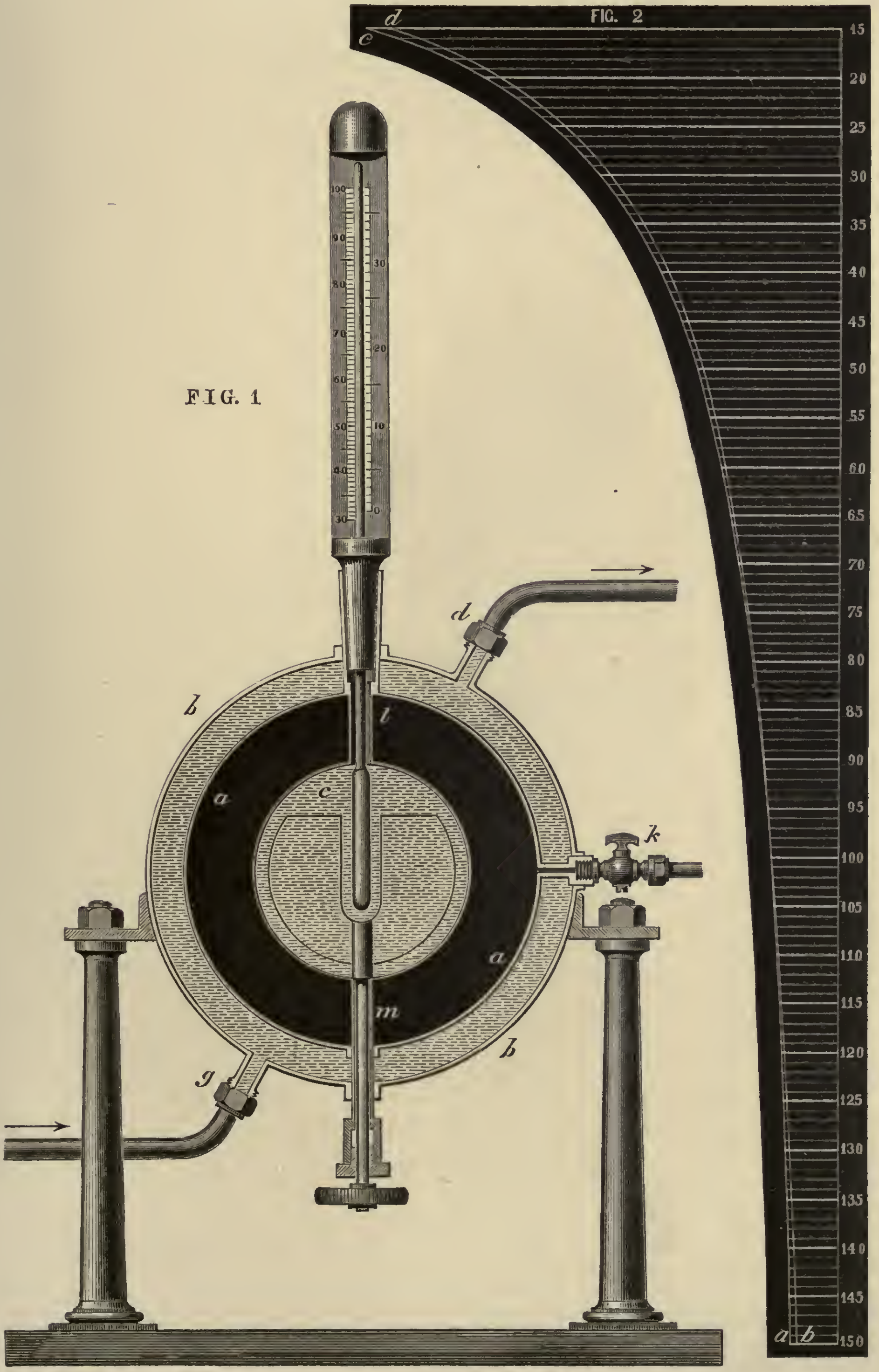


FIG. 1

FIG. 2

Plate 4. See Chap. II.

INSTRUMENT SHOWING THE RATE OF HEATING OF A COLD BODY WITHIN AN EXHAUSTED HEATED ENCLOSURE.

DESIGNED BY JOHN ERICSSON. MANUFACTURED AT NEW YORK, 1874.

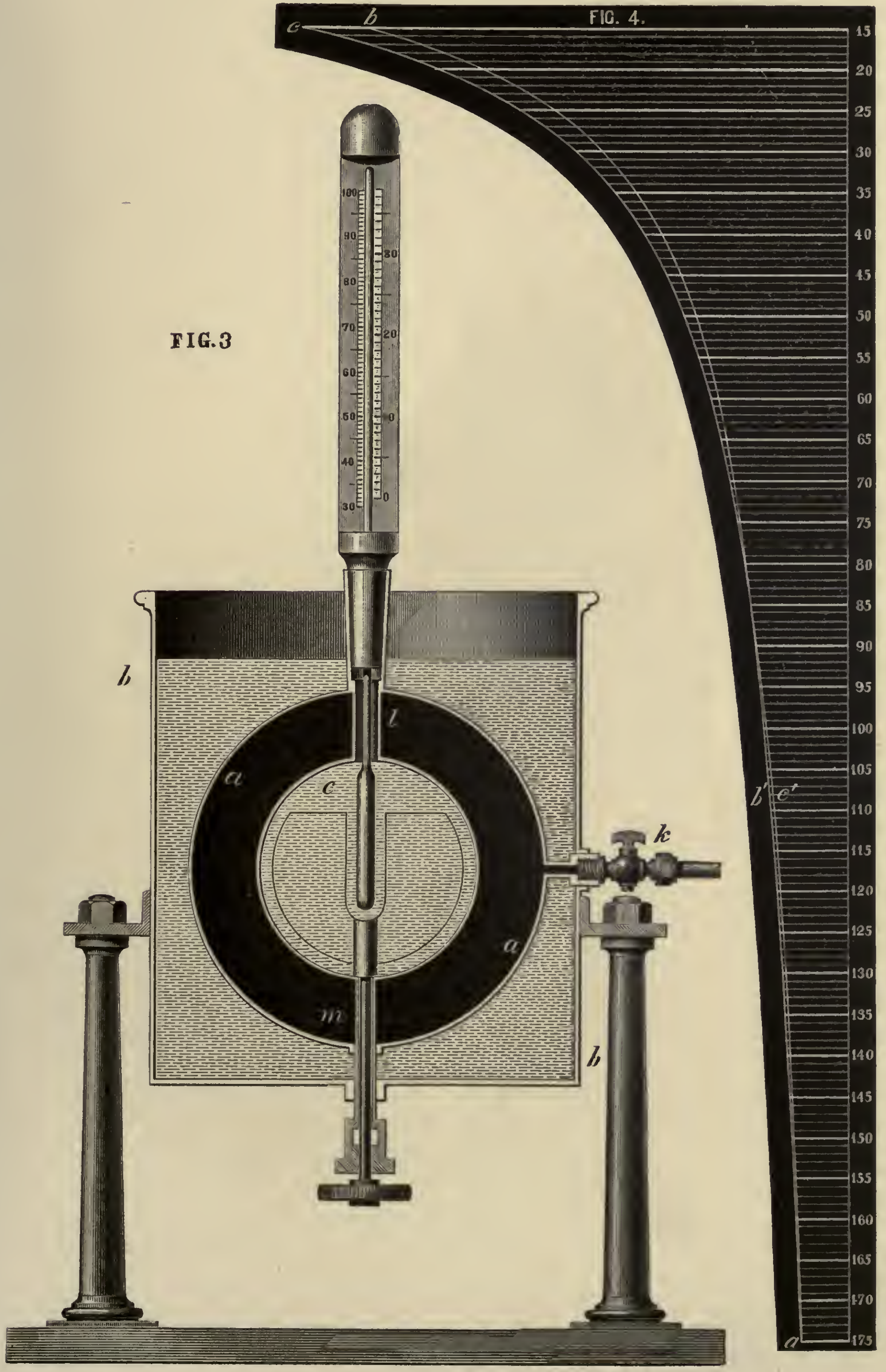
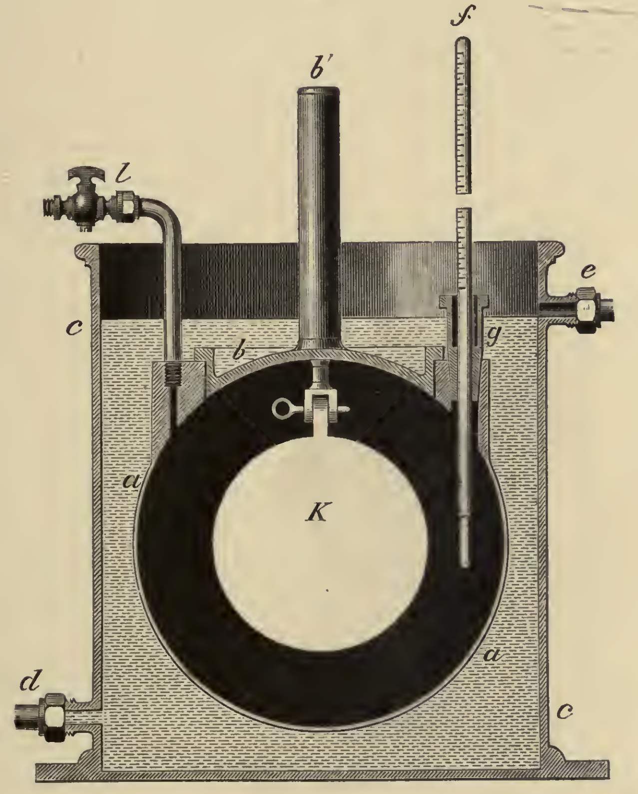


PLATE 5. SEE CHAP. II.

Instrument showing the Rate of Cooling of an Incandescent
Sphere within an Exhausted Cold Enclosure.
Designed by John Ericsson. Manufactured at New York, 1874.

FIG. 5.



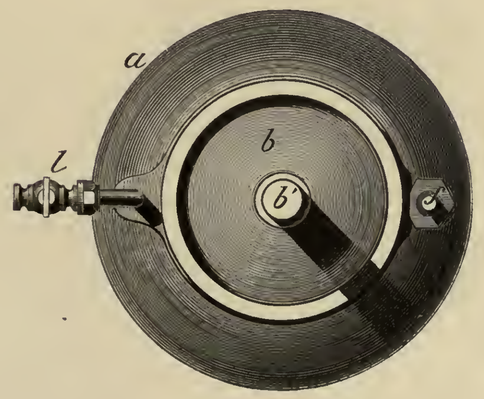


Plate 6. See Chap. II.

INSTRUMENT FOR MEASURING THE DYNAMIC ENERGY DEVELOPED BY RADIANT HEAT.

DESIGNED BY JOHN ERICSSON. MANUFACTURED AT NEW YORK, 1870.

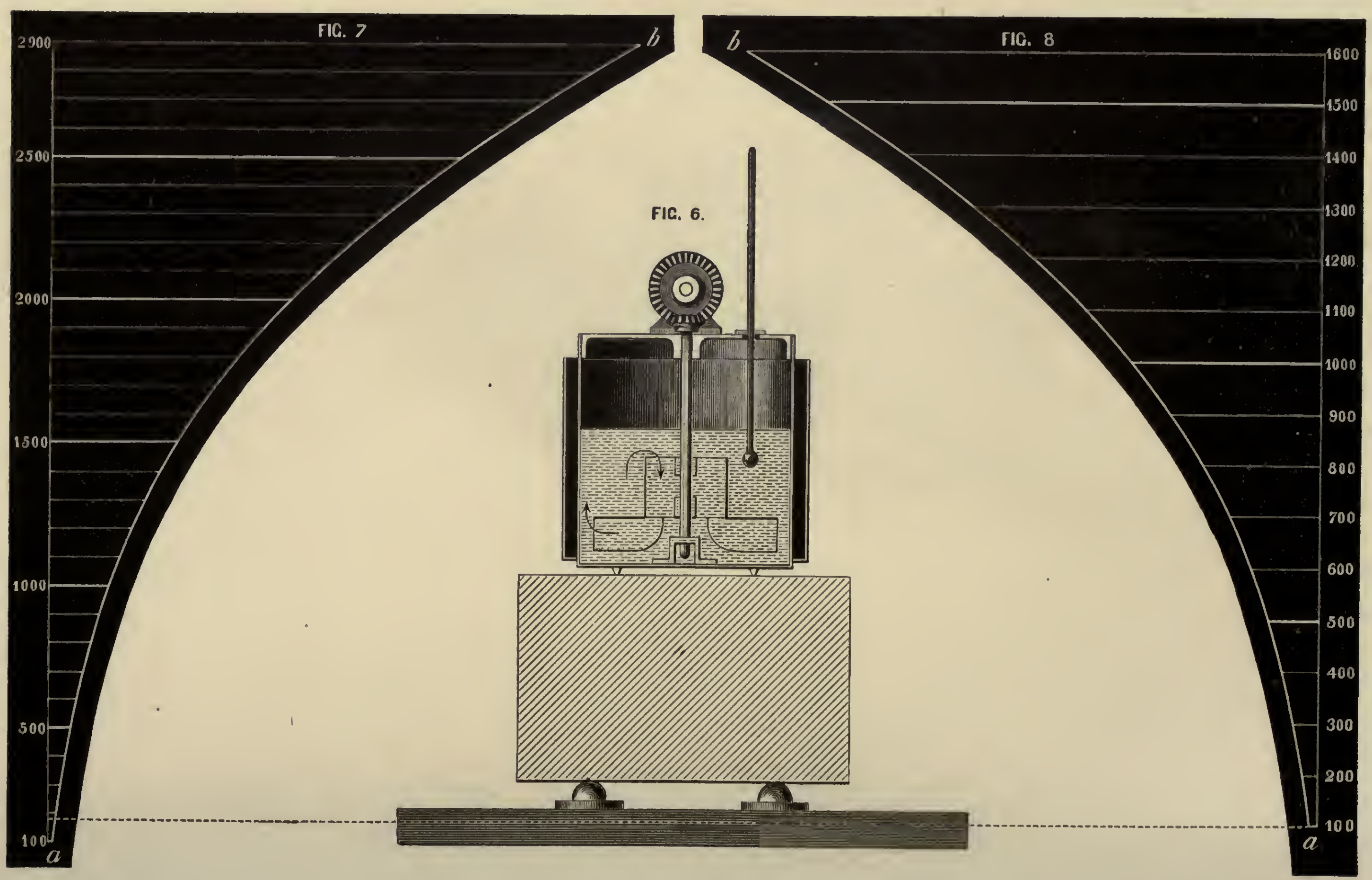


PLATE 7. SEE CHAP. II.

ACTINOMETER, FOR MEASURING THE INTENSITY OF SOLAR RADIATION.

DESIGNED BY JOHN ERICSSON. MANUFACTURED AT NEW YORK, 1870.

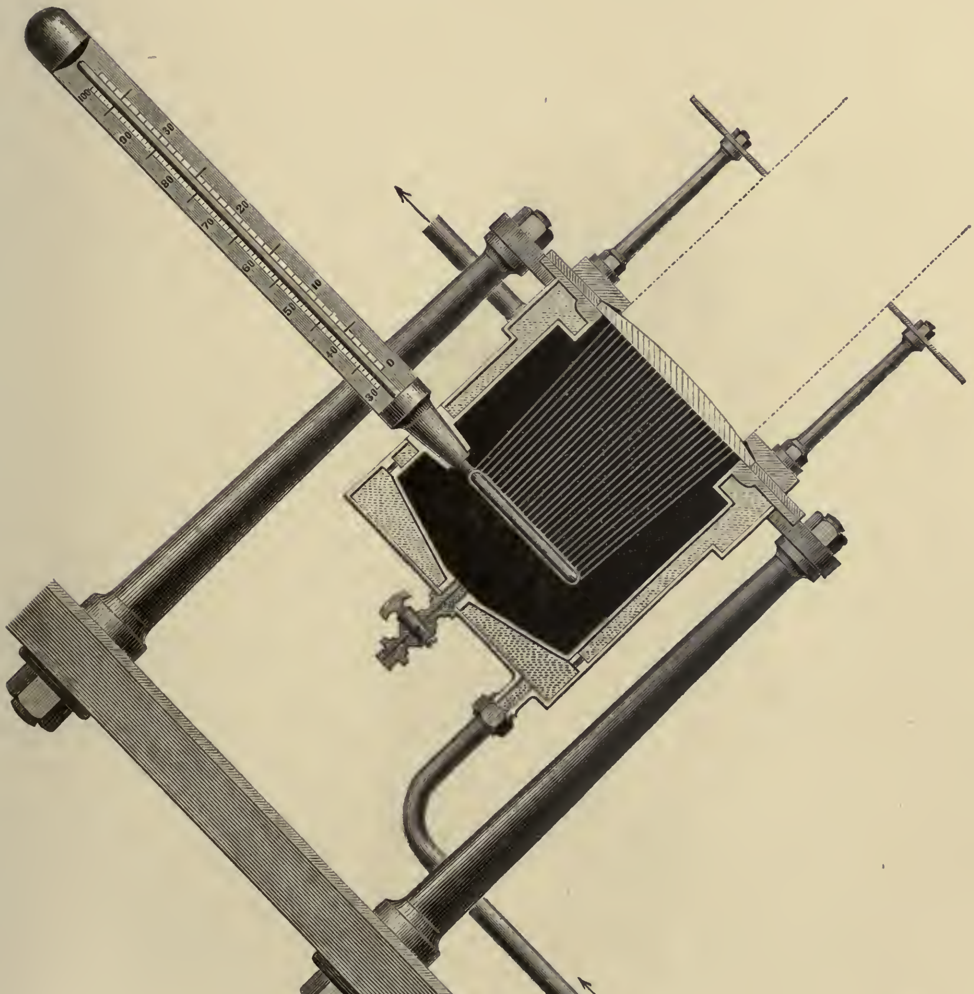


PLATE 8. SEE CHAP. III.

DIAGRAMS SHOWING THE INTENSITY OF SOLAR RADIATION AT DIFFERENT ZENITH DISTANCES.

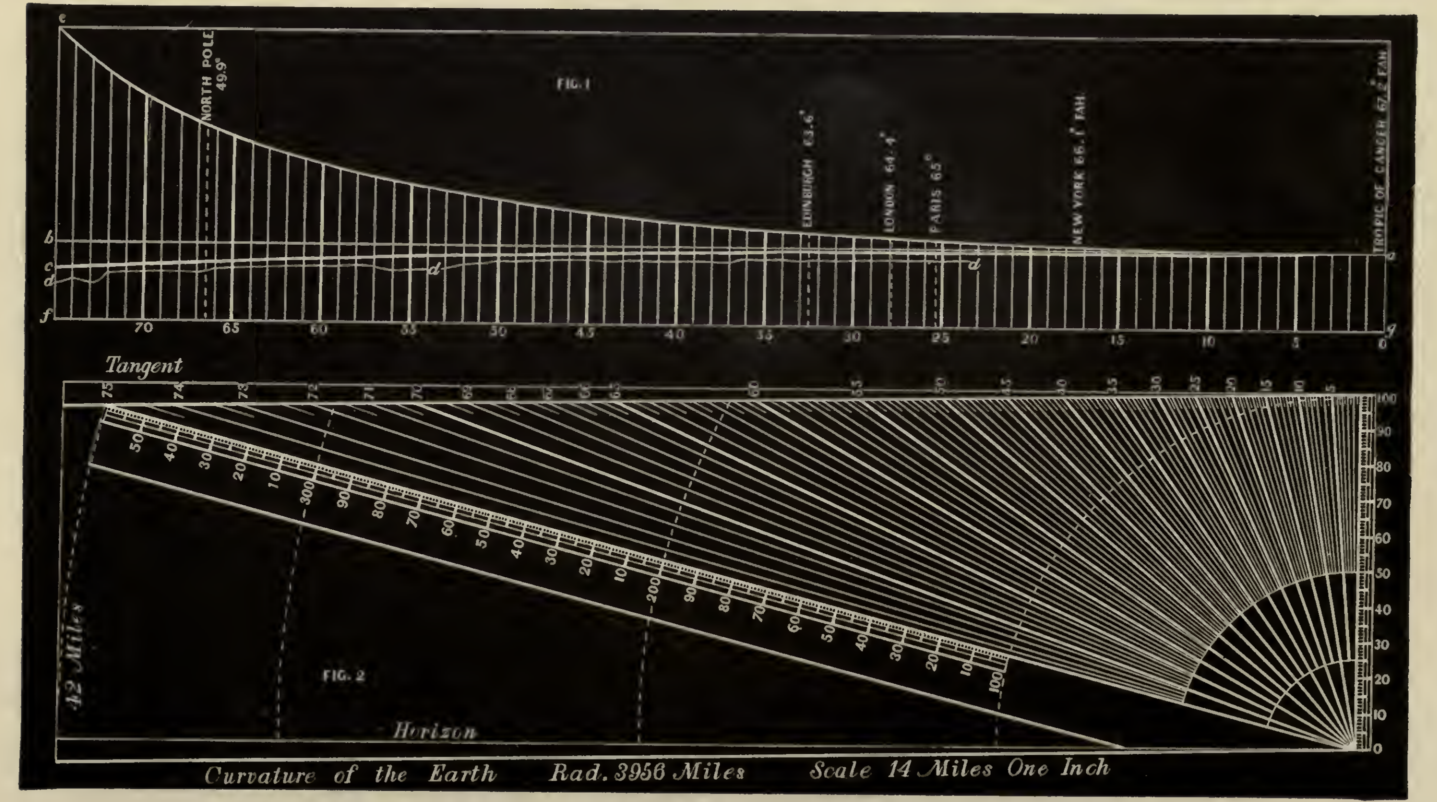


PLATE 9. SEE CHAP. III.

Solar Calorimeter, for measuring the Mechanical Energy of
Solar Radiation. Designed by John Ericsson.
Manufactured at New York, 1870.

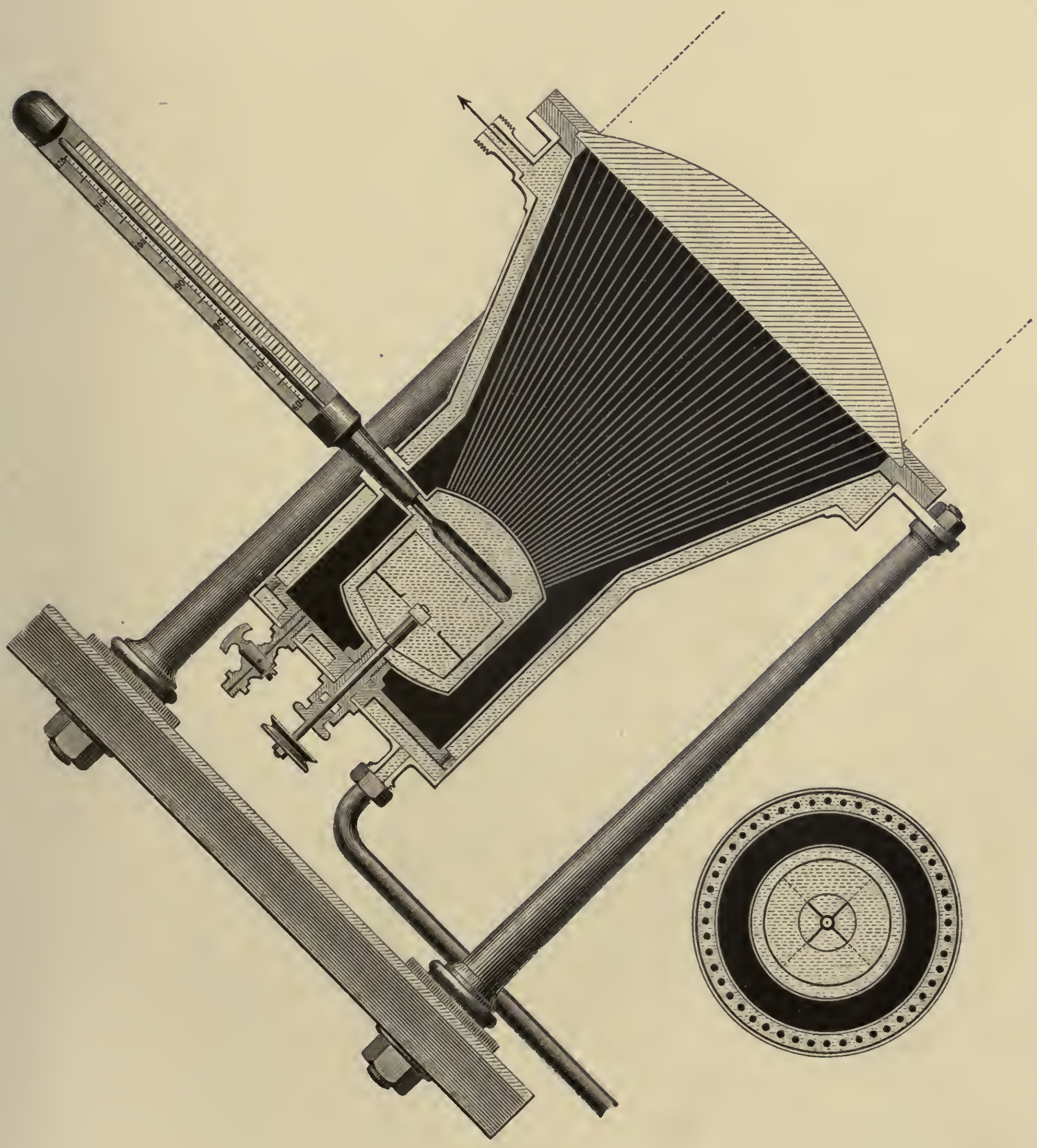


Plate 10. See Chap. V.

Portable Solar Calorimeter, for measuring the Mechanical Energy
of Solar Radiation. Designed by John Ericsson.
Manufactured at New York, 1874.

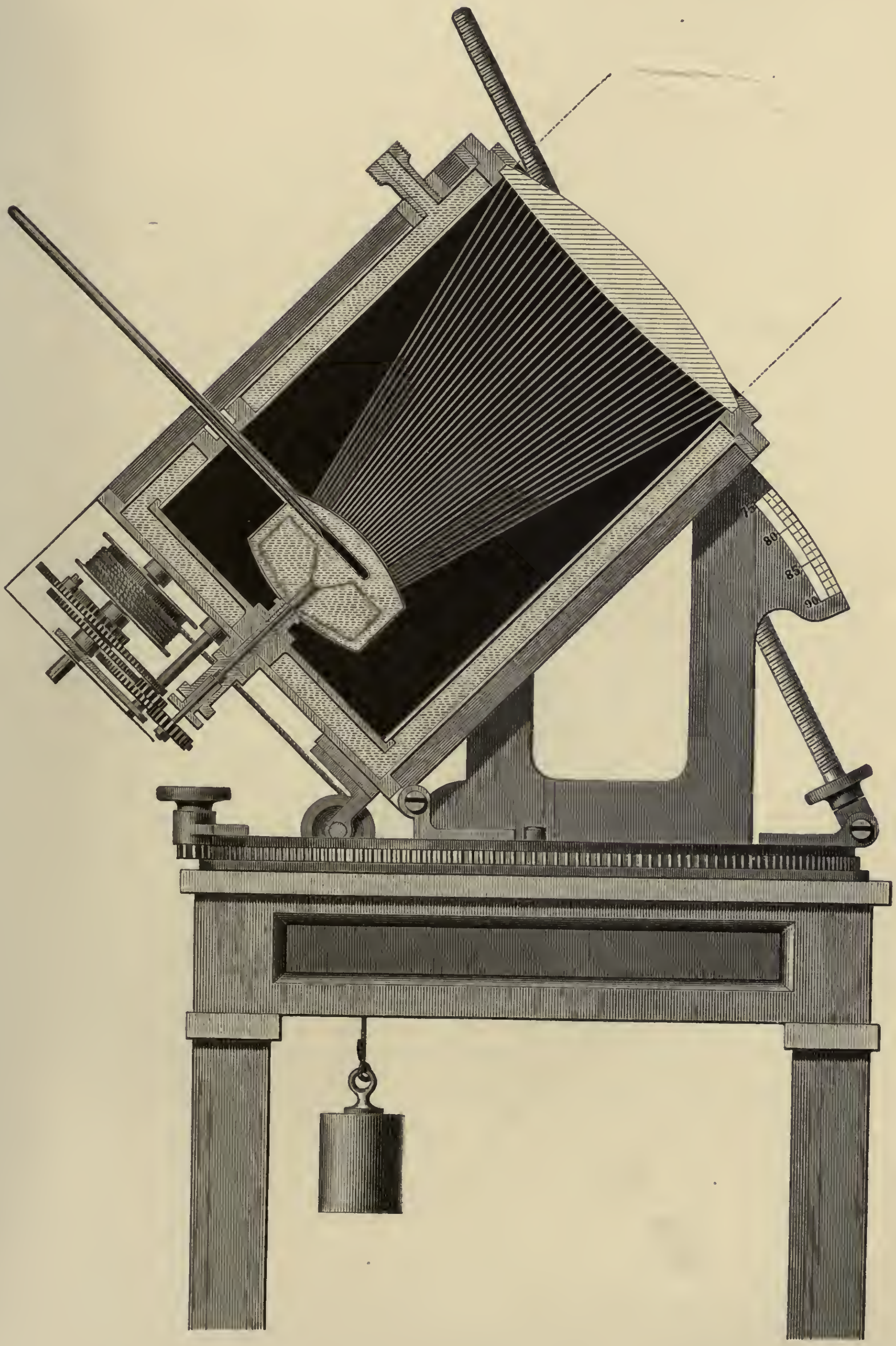


Plate 11. See Chap. V.

DIAGRAMS SHOWING THE RADIATION FROM DIFFERENT PARTS OF THE SOLAR DISC.

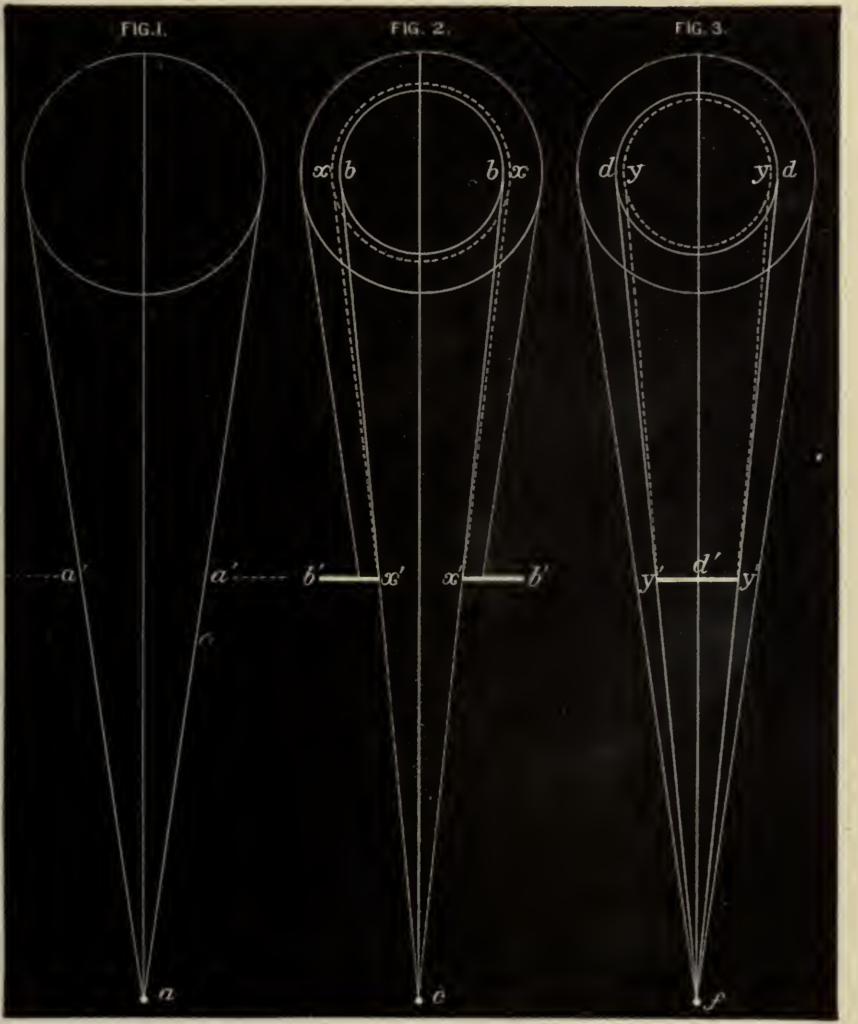


PLATE 12. SEE CHAP. VI.

PARALLACTIC MECHANISM FOR MEASURING THE INTENSITY OF RADIATION FROM DIFFERENT PARTS OF THE SOLAR DISC.

DESIGNED BY JOHN ERICSSON. CONSTRUCTED AT NEW YORK, 1875.

FIG. 17.

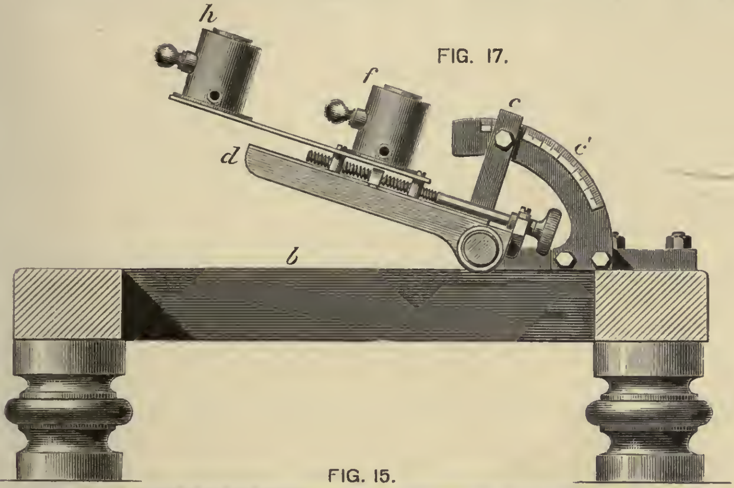


FIG. 15.

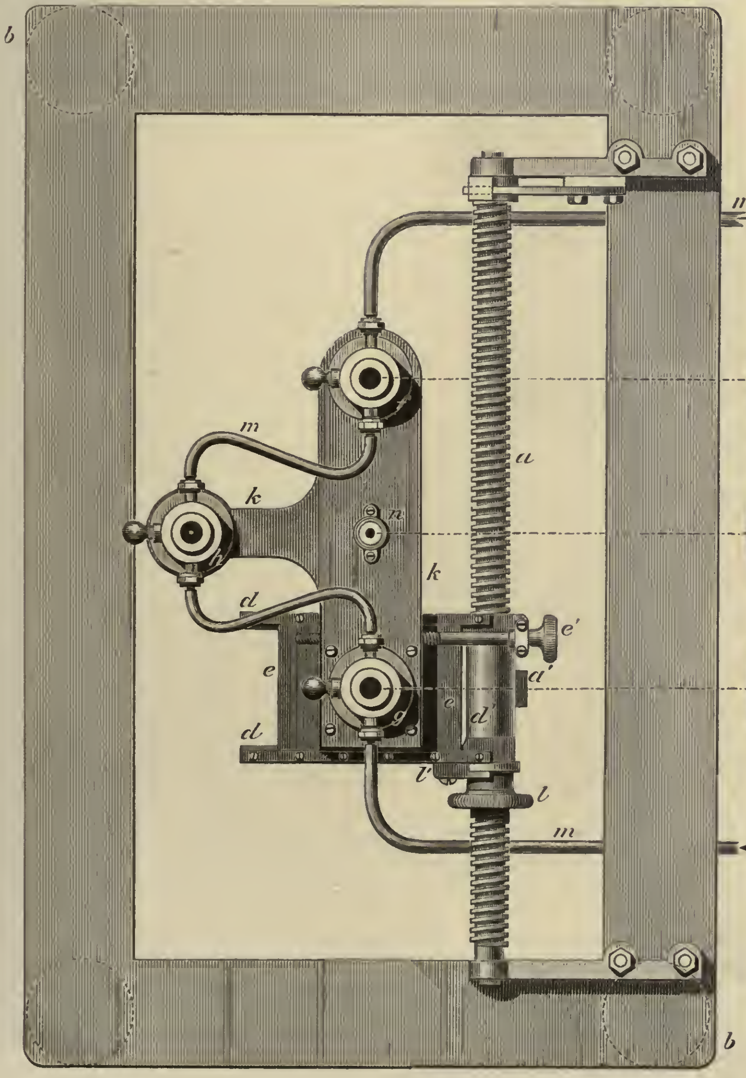


FIG. 16.

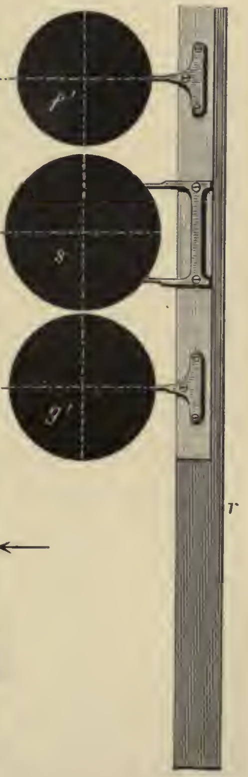


PLATE 13. SEE CHAP. VI.

Diagram showing the Attraction within the Solar Mass at Different Distances from its Centre.

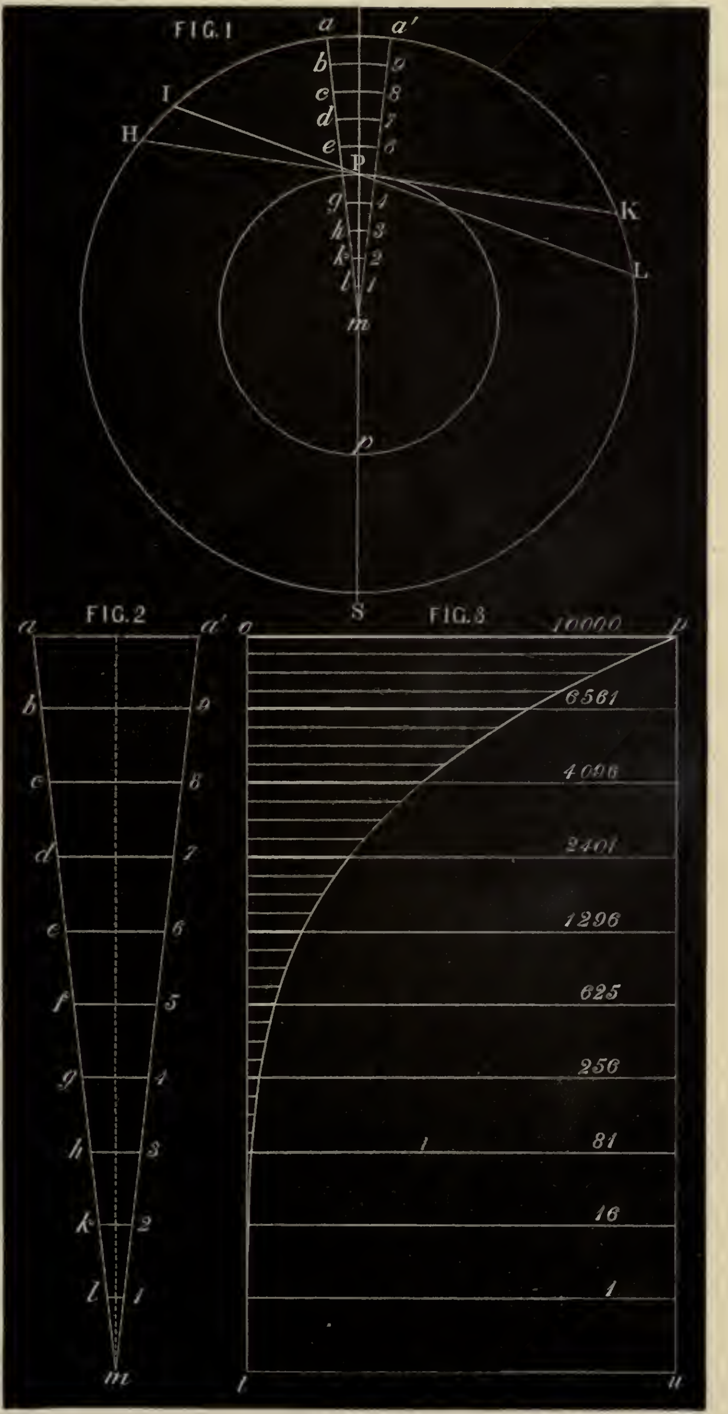


Plate 14. See Chap. VII.

INSTRUMENT FOR MEASURING THE RADIANT POWER OF THE SOLAR ATMOSPHERE. DESIGNED BY JOHN ERICSSON.

MANUFACTURED AT NEW YORK, 1872.

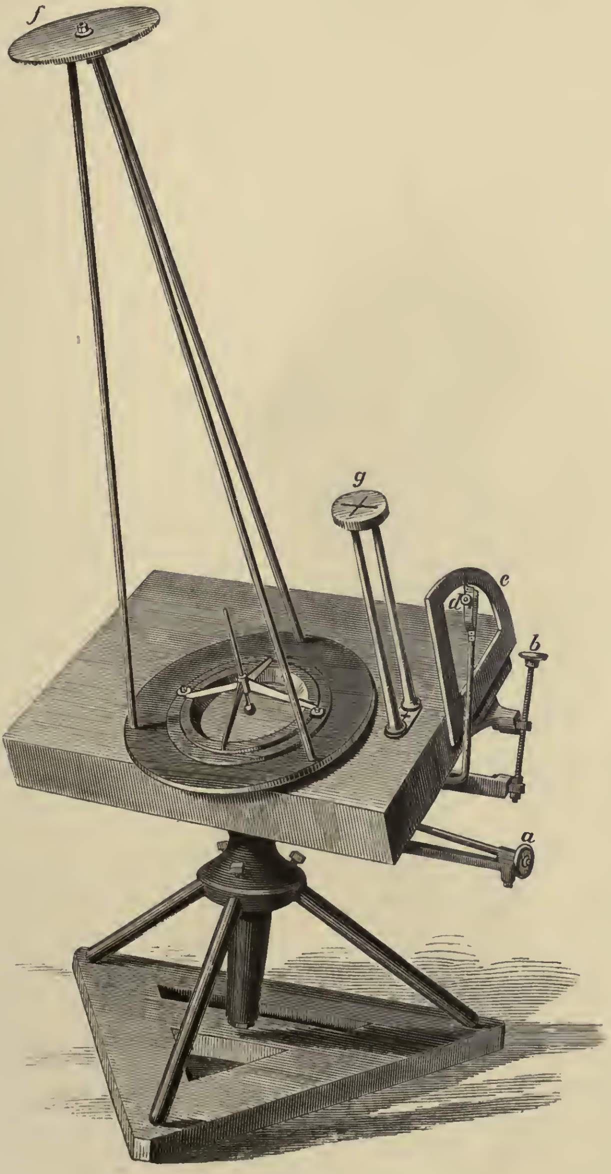


PLATE 15. SEE CHAP. VIII.

Diagrams showing the Radiant Power of the Solar Atmosphere.

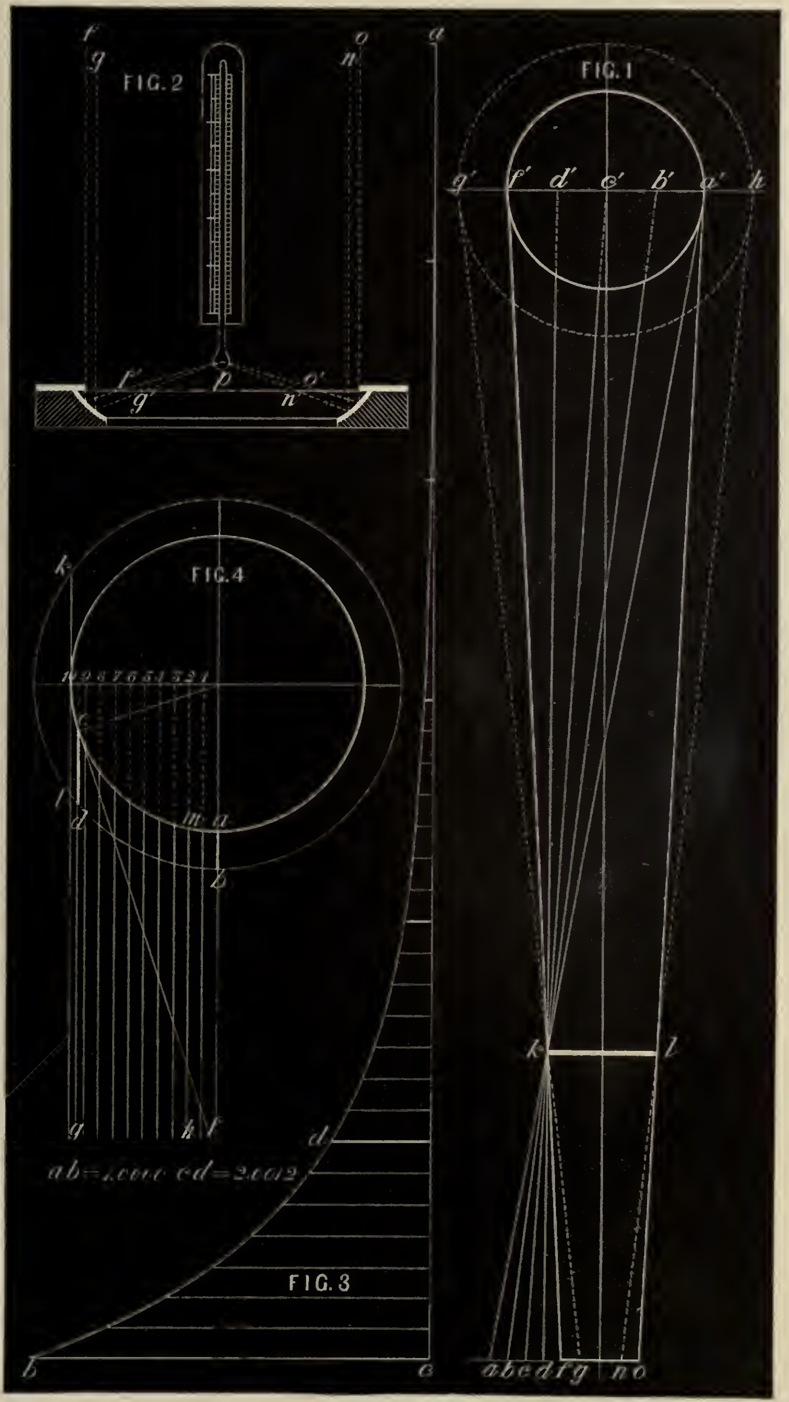


Plate 16. See Chap. VIII.

INSTRUMENT FOR MEASURING THE ACTUAL INTENSITY OF THE SUN'S RAYS.

DESIGNED BY JOHN ERICSSON. MANUFACTURED AT NEW YORK, 1871.

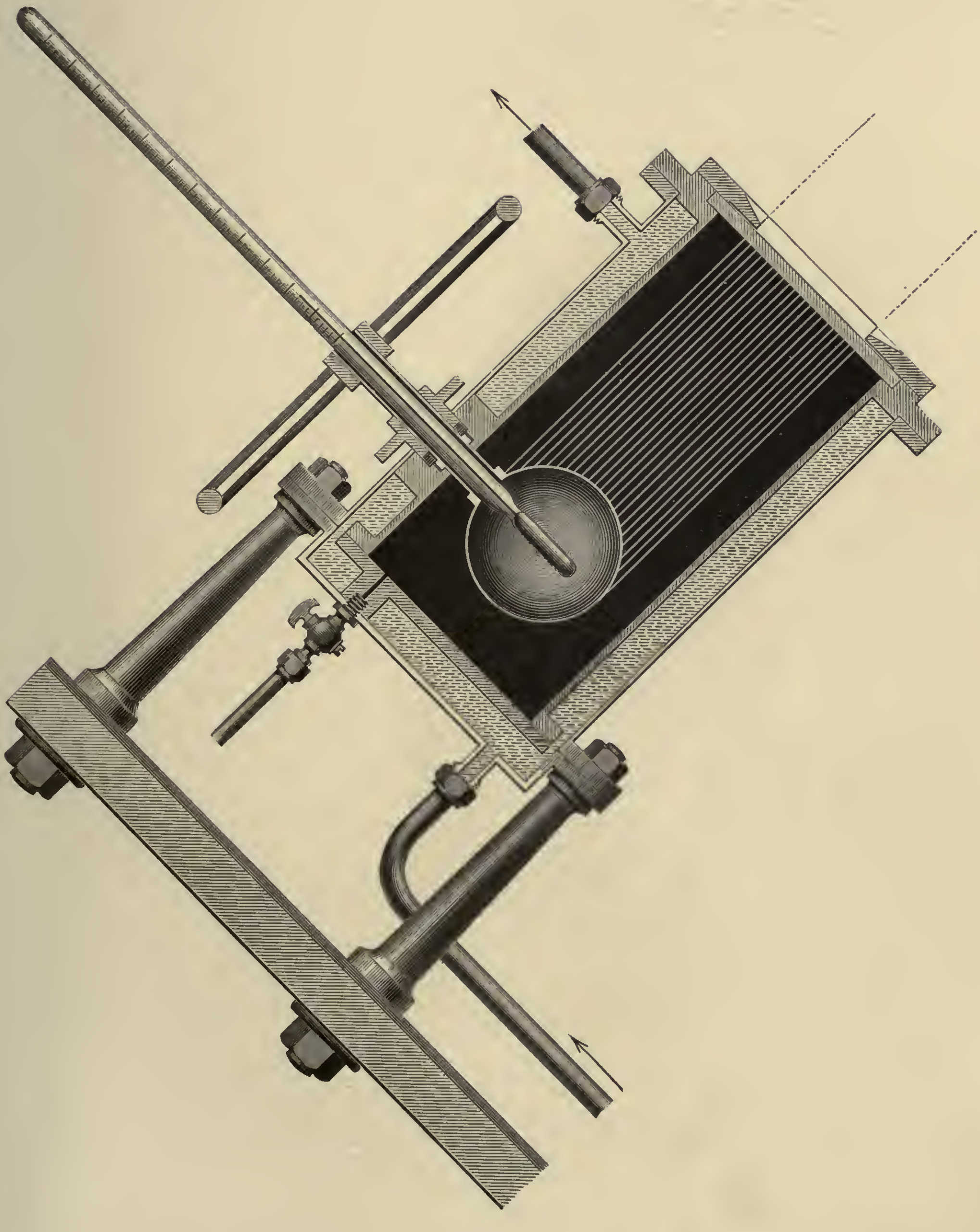


PLATE 17. SEE CHAP. IX.

INSTRUMENT FOR SHOWING THE FEEBLENESS OF SOLAR RADIATION.

DESIGNED BY JOHN ERICSSON. CONSTRUCTED AT NEW YORK, 1872.

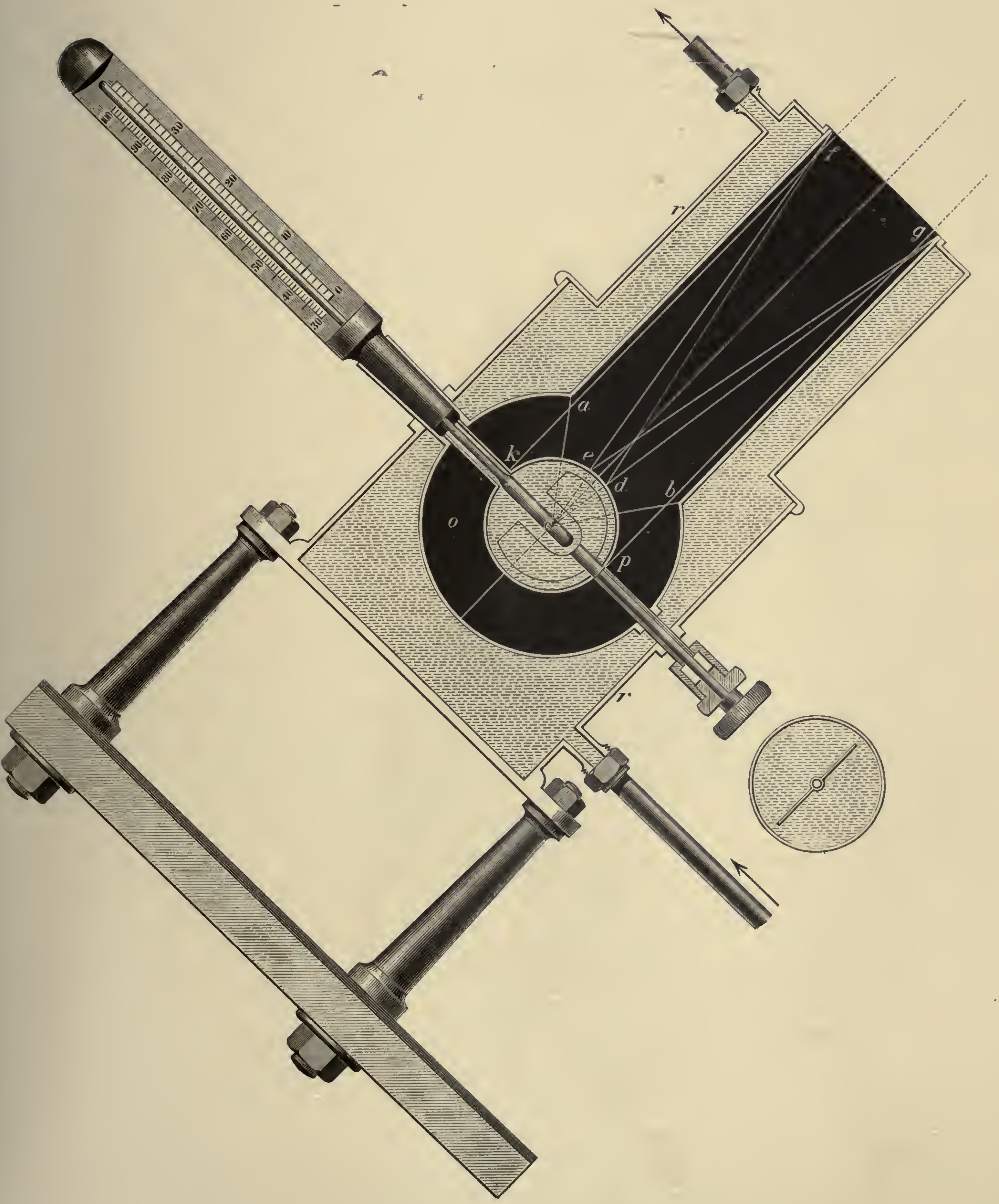


PLATE 18. SEE CHAP. IX.

SOLAR PYROMETER, FOR ASCERTAINING THE TEMPERATURE OF THE SOLAR SURFACE. DESIGNED BY JOHN ERICSSON.
CONSTRUCTED AT NEW YORK, 1870.

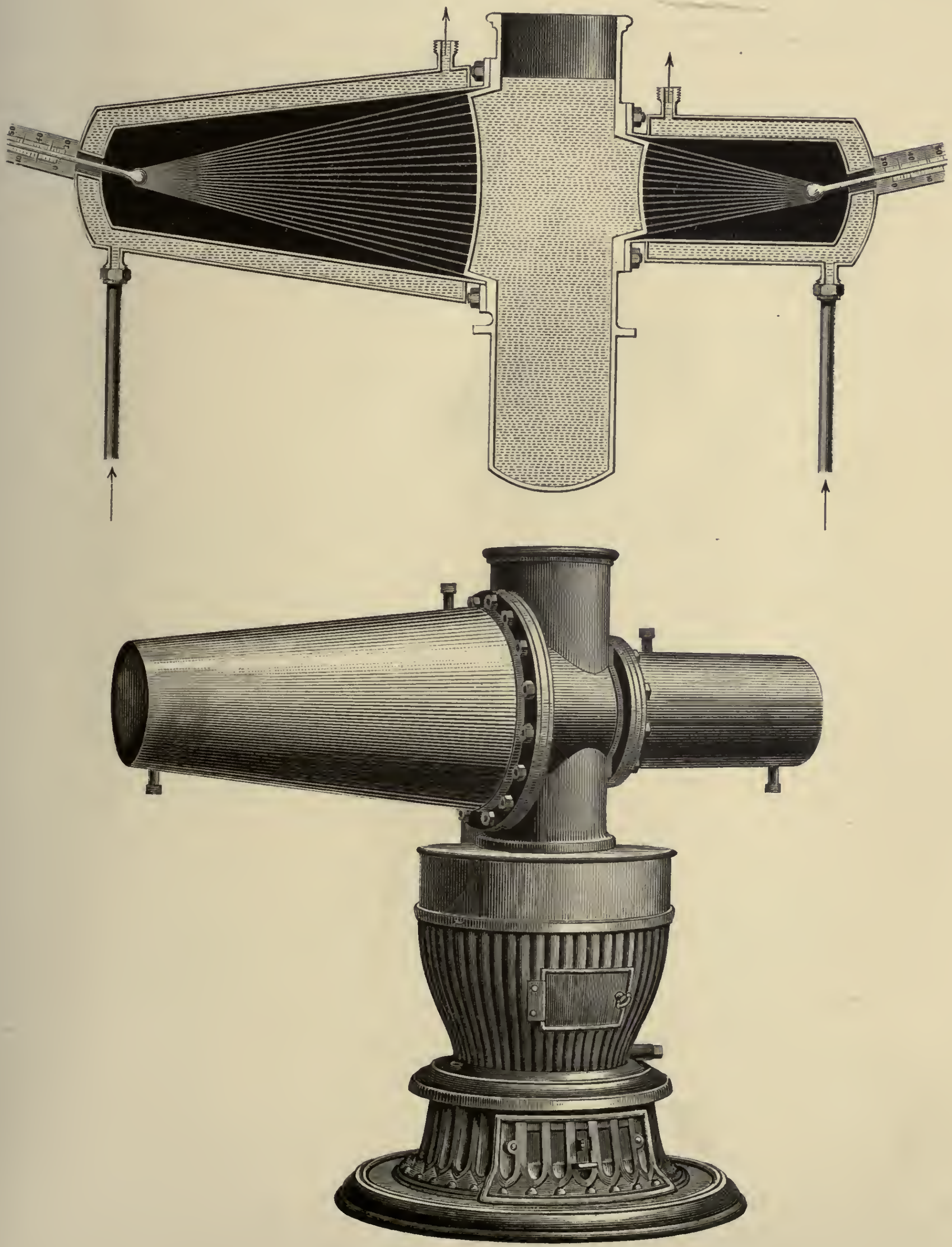


PLATE 19. SEE CHAP. X.

Apparatus for measuring the Radiant Intensity of Flames.

Designed by John Ericsson. Constructed at New York, 1871.

FIG. I.

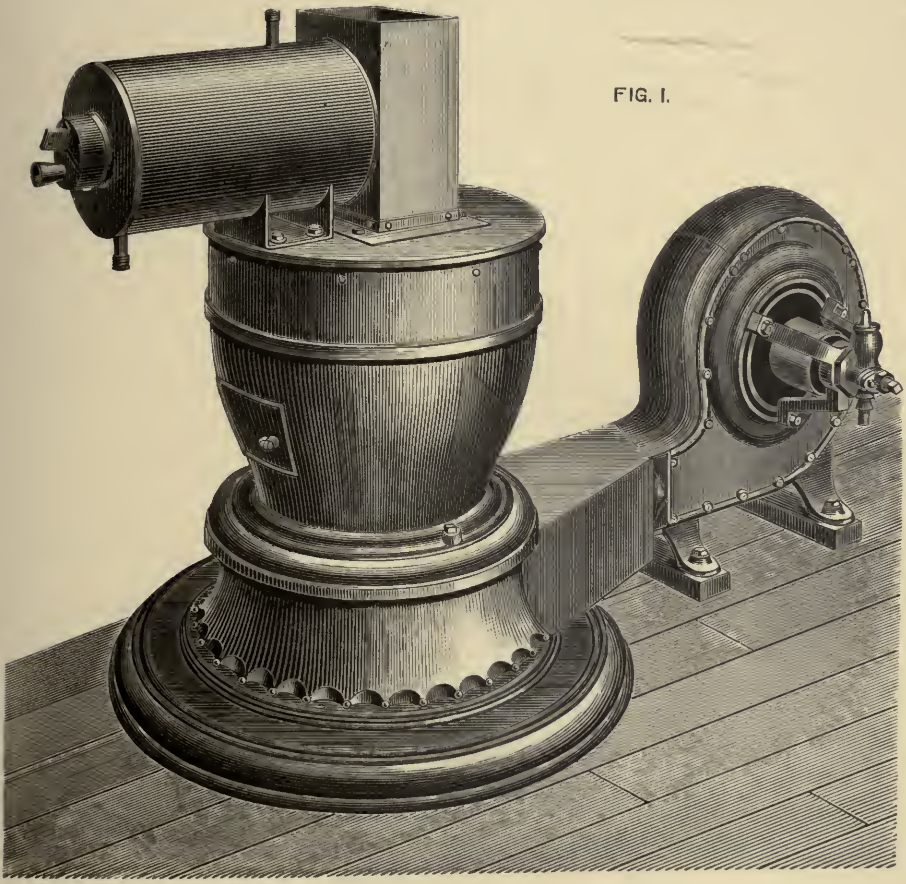


FIG. 2.

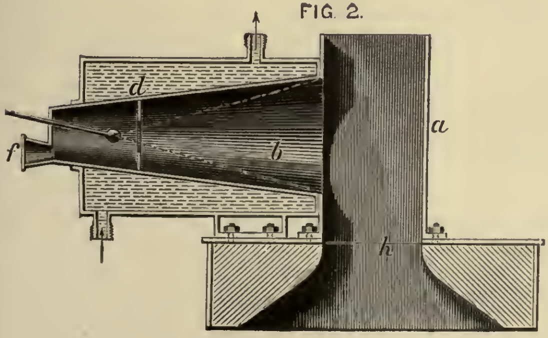


FIG. 3

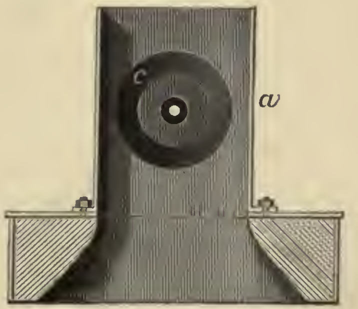


Plate 20. See Chap. X.

Instrument for measuring the Radiation from Incandescent Planes. Designed by John Ericsson.

Manufactured at New York, 1872.

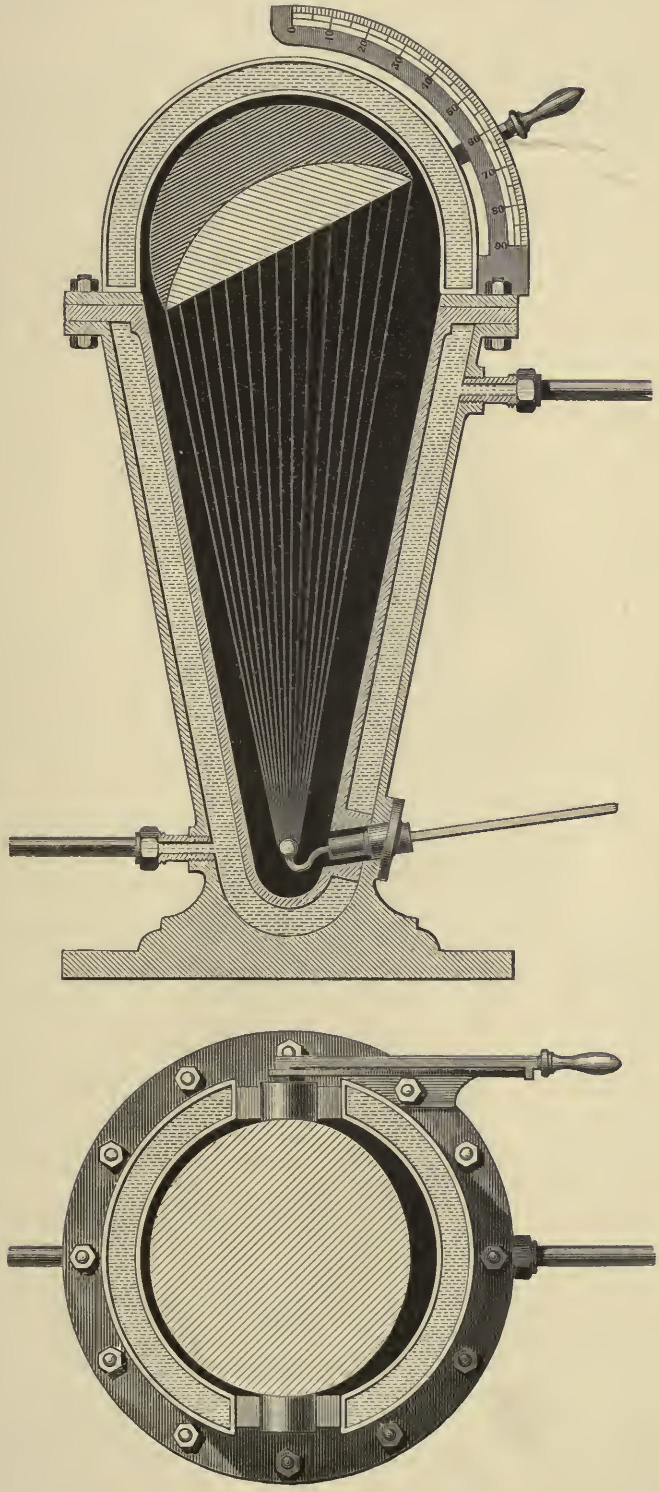


Plate 21. See Chap. XI.

Diagrams showing the Radiation at Different Inclinations of Incandescent Planes.

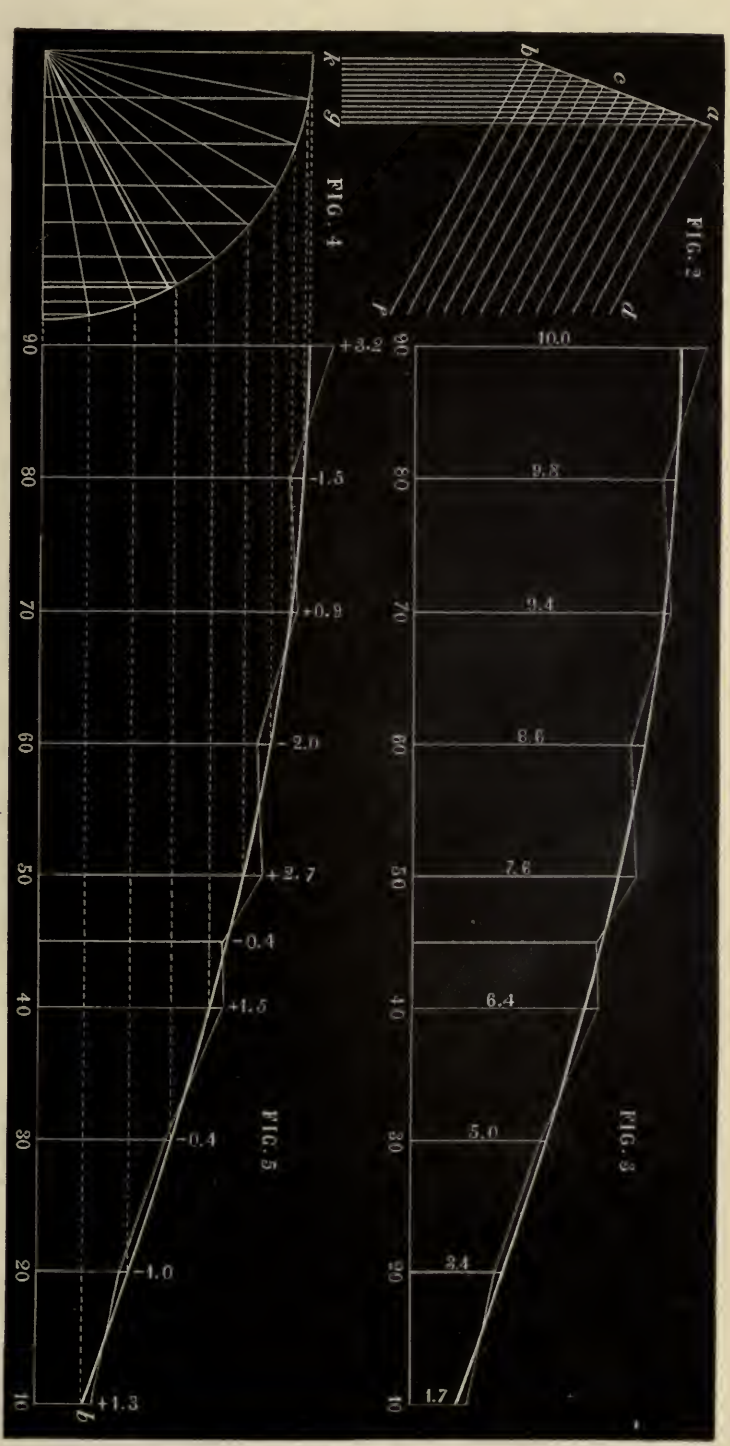


Plate 22. See Chap. XI.

Instrument for measuring the Radiation from Different Zones
of Incandescent Spheres. Designed by John Ericsson.
Manufactured at New York, 1872.

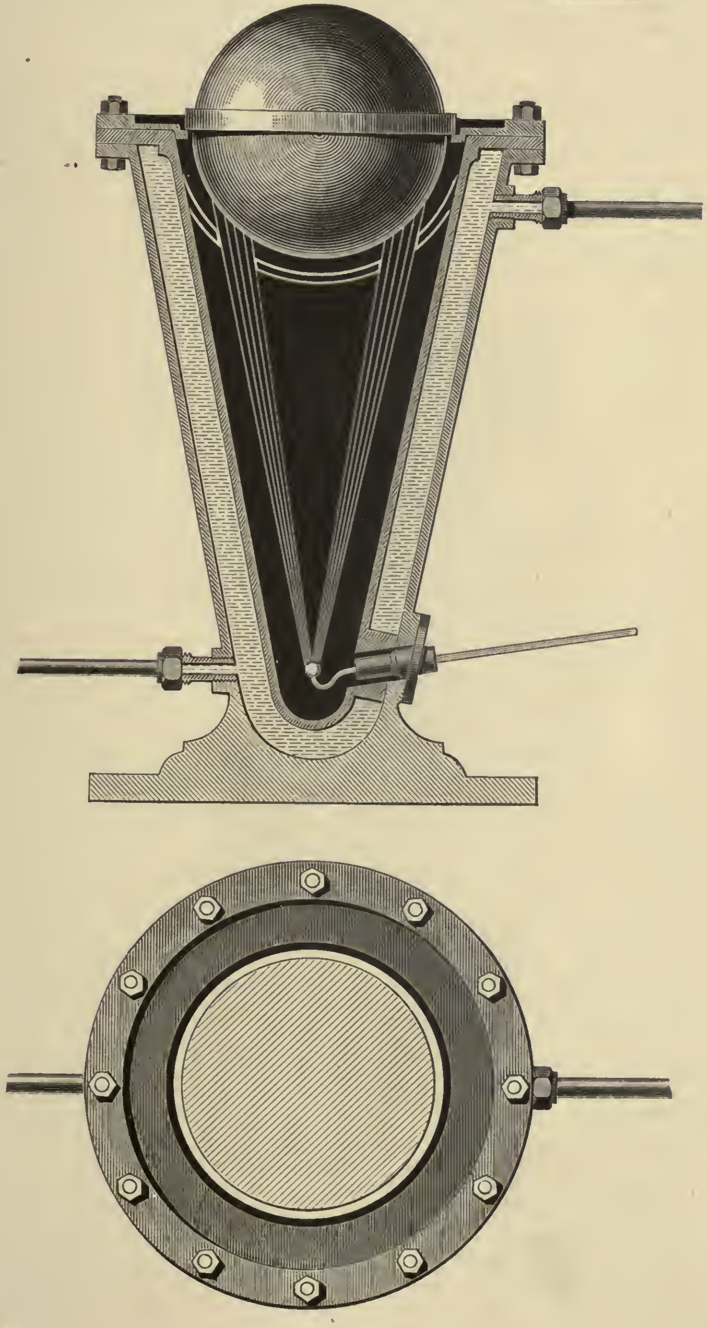


Plate 23. See Chap. XII.

Diagrams showing the Radiation from Different Zones of Incandescent Spheres.

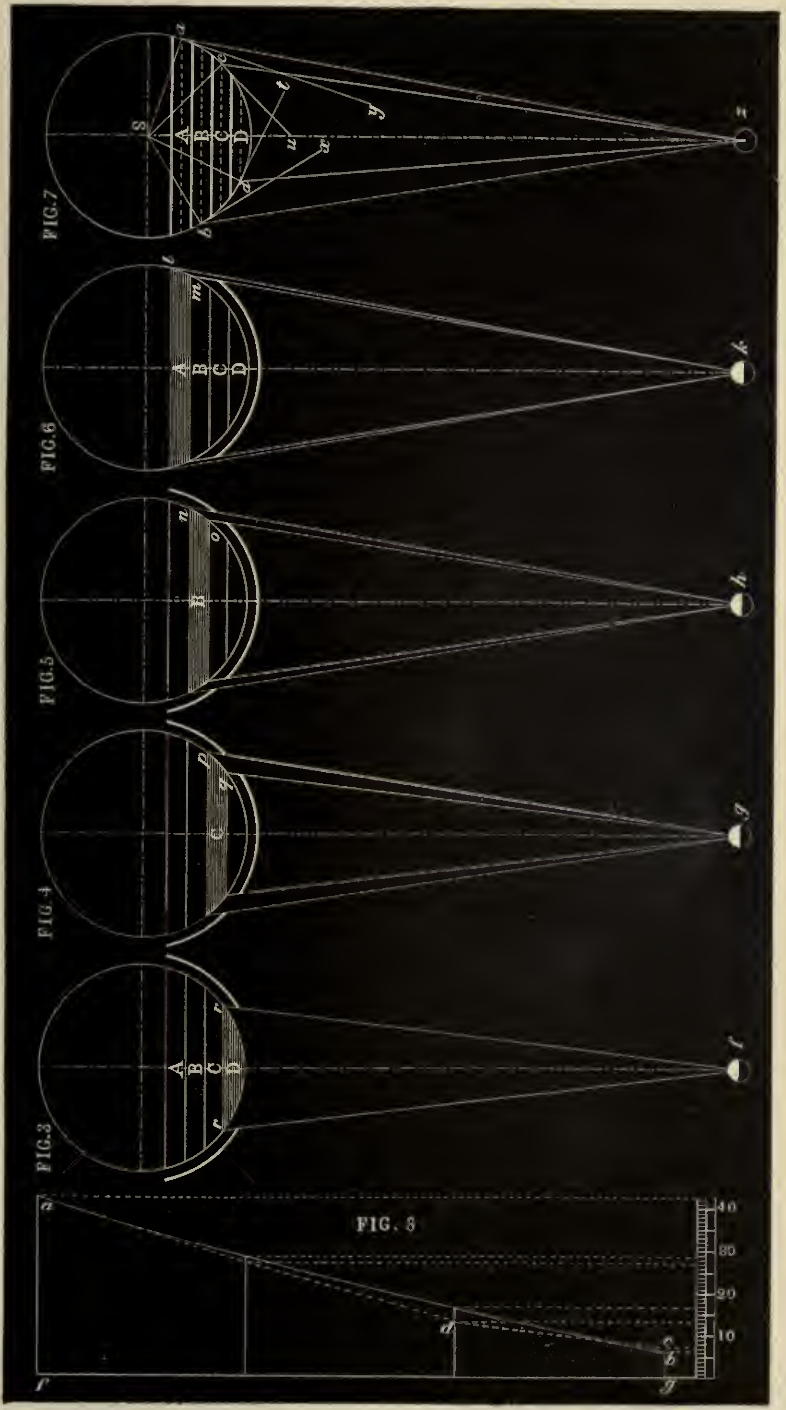


Plate 24. See Chap. XII.

CALORIMETER, FOR MEASURING THE ENERGY DEVELOPED BY RADIATION OF FUSED IRON. DESIGNED BY JOHN ERICSSON.

CONSTRUCTED AT NEW YORK, 1872.

Fig. 1.

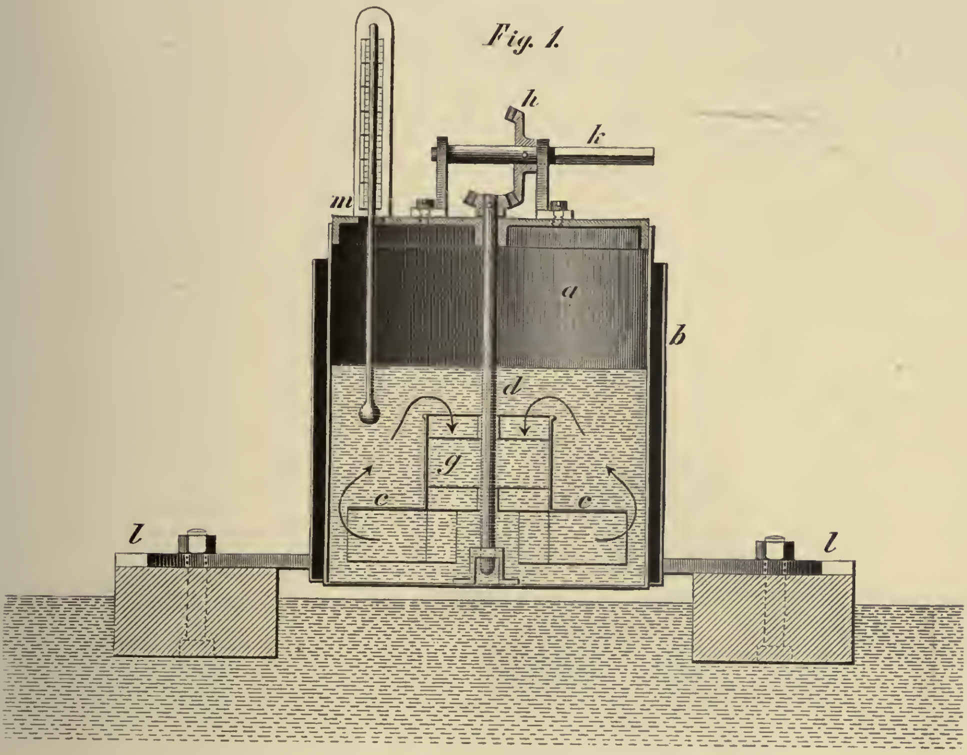


Fig. 2

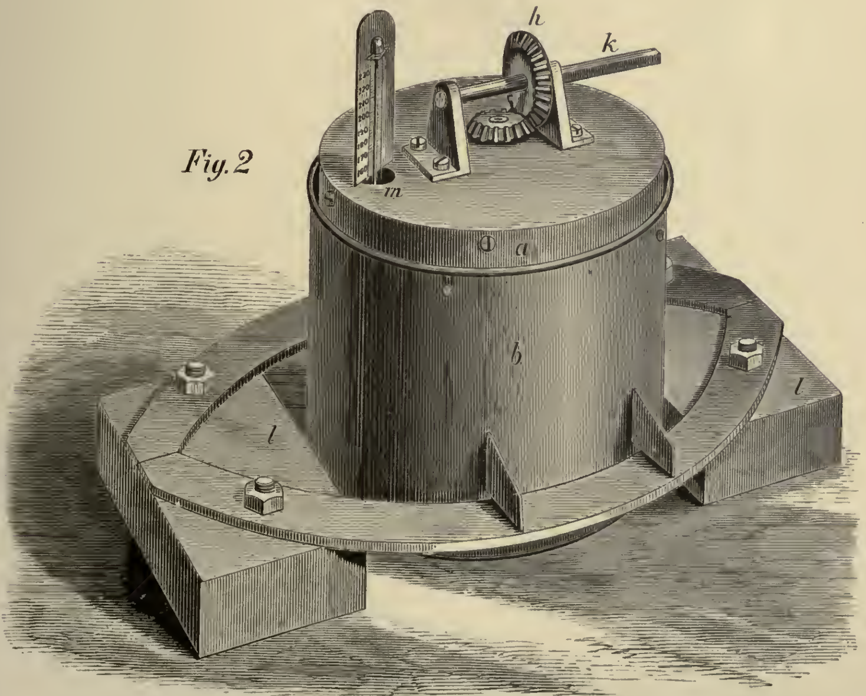


PLATE 25. SEE CHAP. XIII.

APPARATUS FOR MEASURING RADIANT HEAT BY MEANS OF THE THERMO-ELECTRIC PILE. DESIGNED BY JOHN ERICSSON.

CONSTRUCTED AT NEW YORK, 1874.

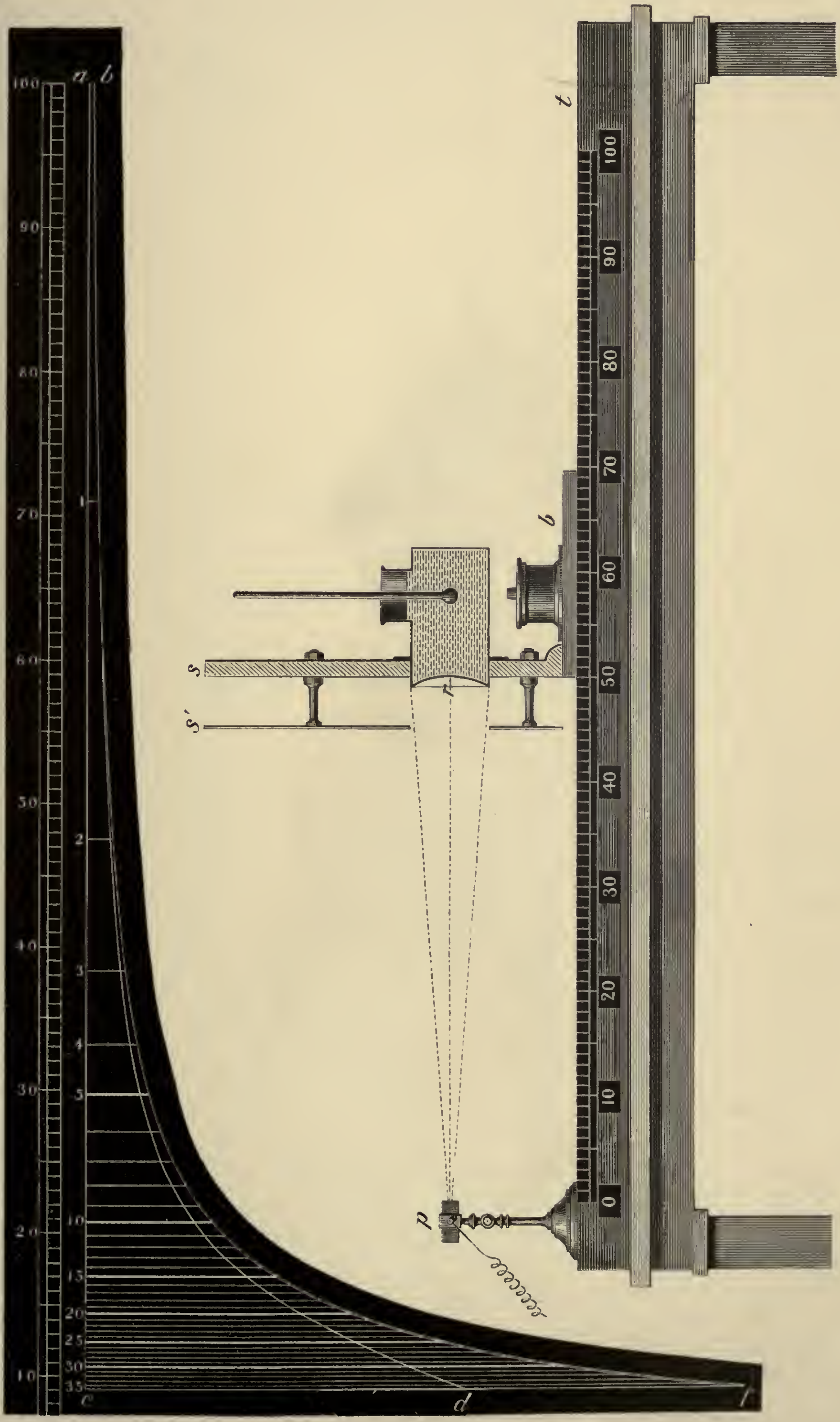


PLATE 26. SEE CHAP. XIV.

Barometric Actinometer, for measuring the Intensity of
Solar Radiation. Designed by John Ericsson.
Manufactured at New York, 1874.

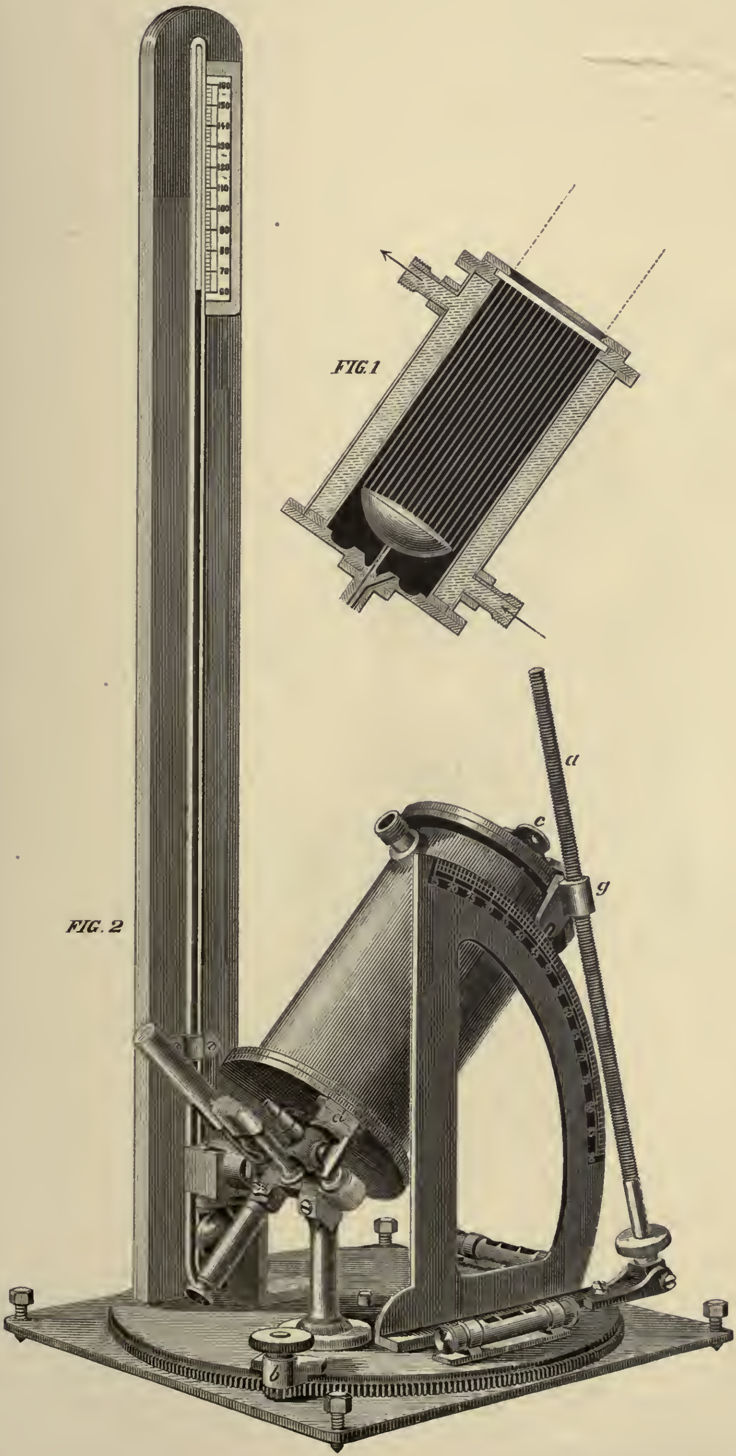


FIG. 1

FIG. 2

Plate 27. See Chap. XVI.

APPARATUS FOR ASCERTAINING THE CONDUCTIVITY OF MERCURY. DESIGNED BY JOHN ERICSSON. MANUFACTURED AT NEW YORK, 1872.

FIG. I.

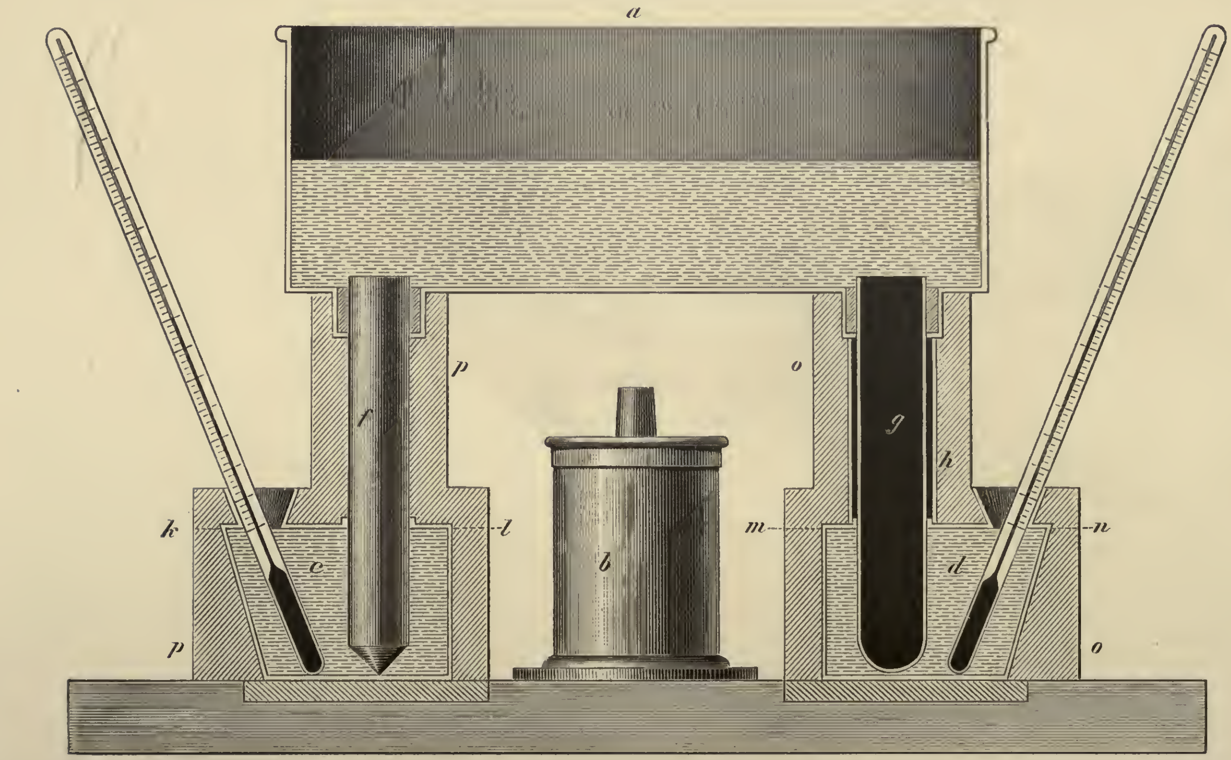


PLATE 28. SEE CHAP. XVII.

CONCAVE SPHERICAL RADIATOR, FOR TESTING THE ACCURACY OF THE SOLAR PYROMETER.

DESIGNED BY JOHN ERICSSON. CONSTRUCTED AT NEW YORK, 1871.

FIG. 1

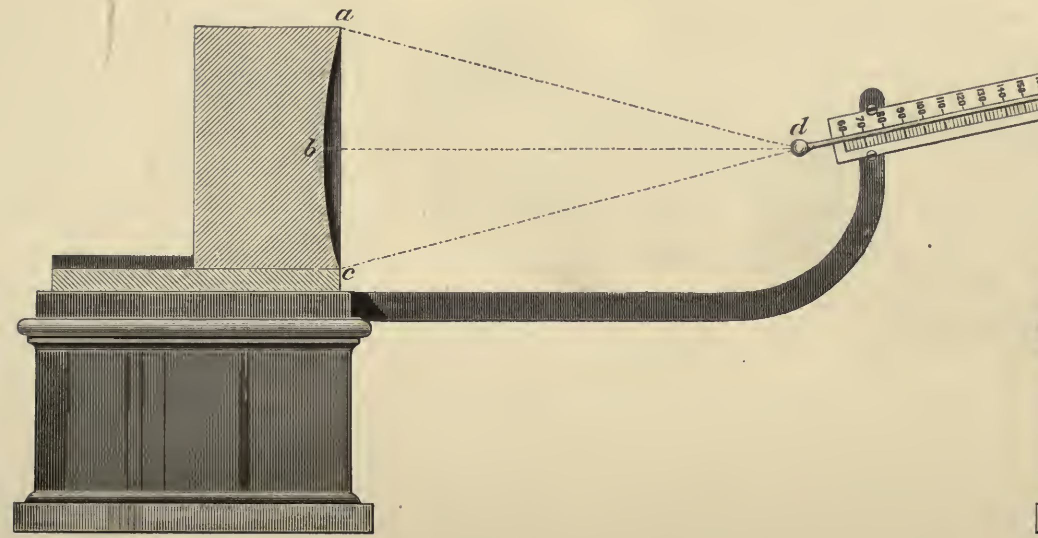


FIG. 2

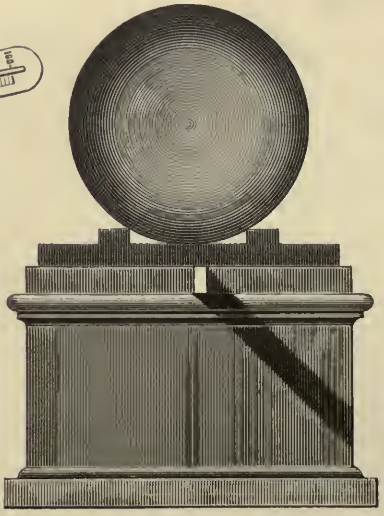


PLATE 29. SEE CHAP. XVIII.

INSTRUMENT FOR MEASURING THE REFLECTIVE POWER OF SILVER AND OTHER METALS. DESIGNED BY JOHN ERICSSON.

MANUFACTURED AT NEW YORK, 1874.

FIG. 1

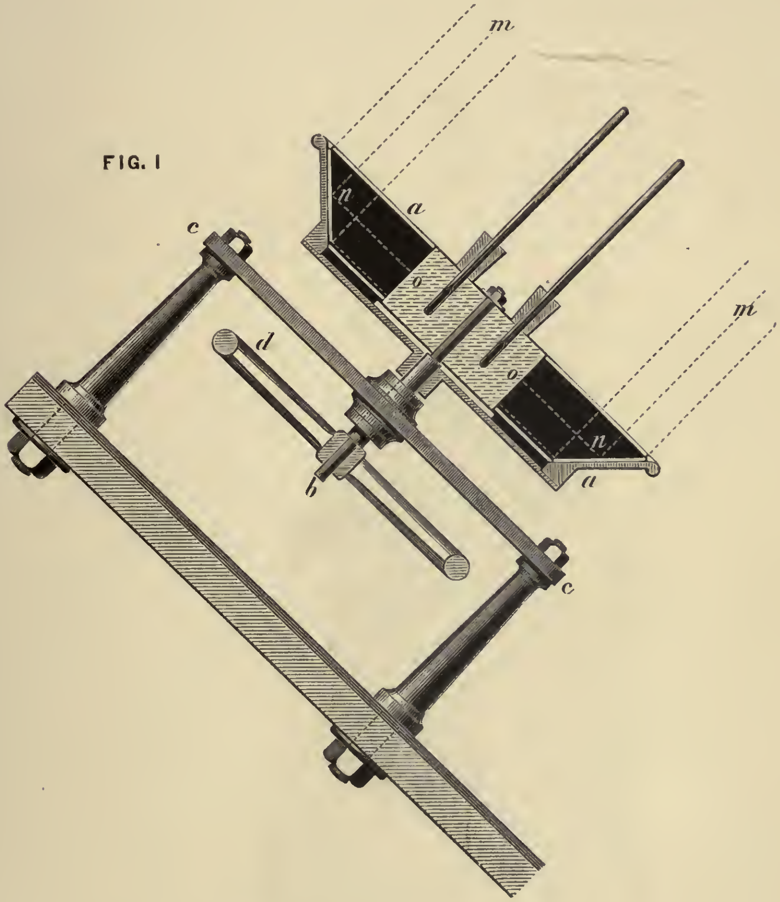


FIG. 2.

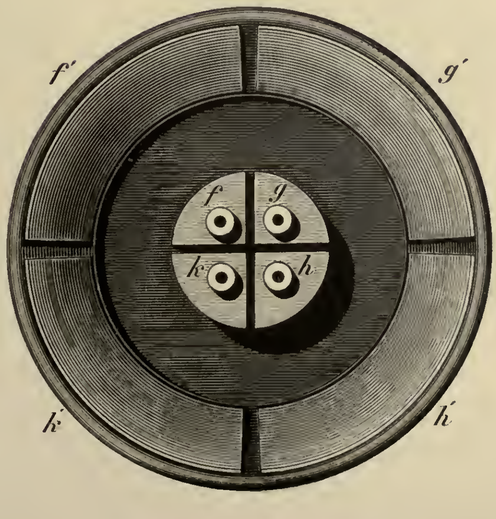


PLATE 30. SEE CHAP. XIX.

Rapid-Indication Actinometer, for measuring the Intensity of Solar Radiation. Designed by John Ericsson.

Manufactured at New York, 1873.

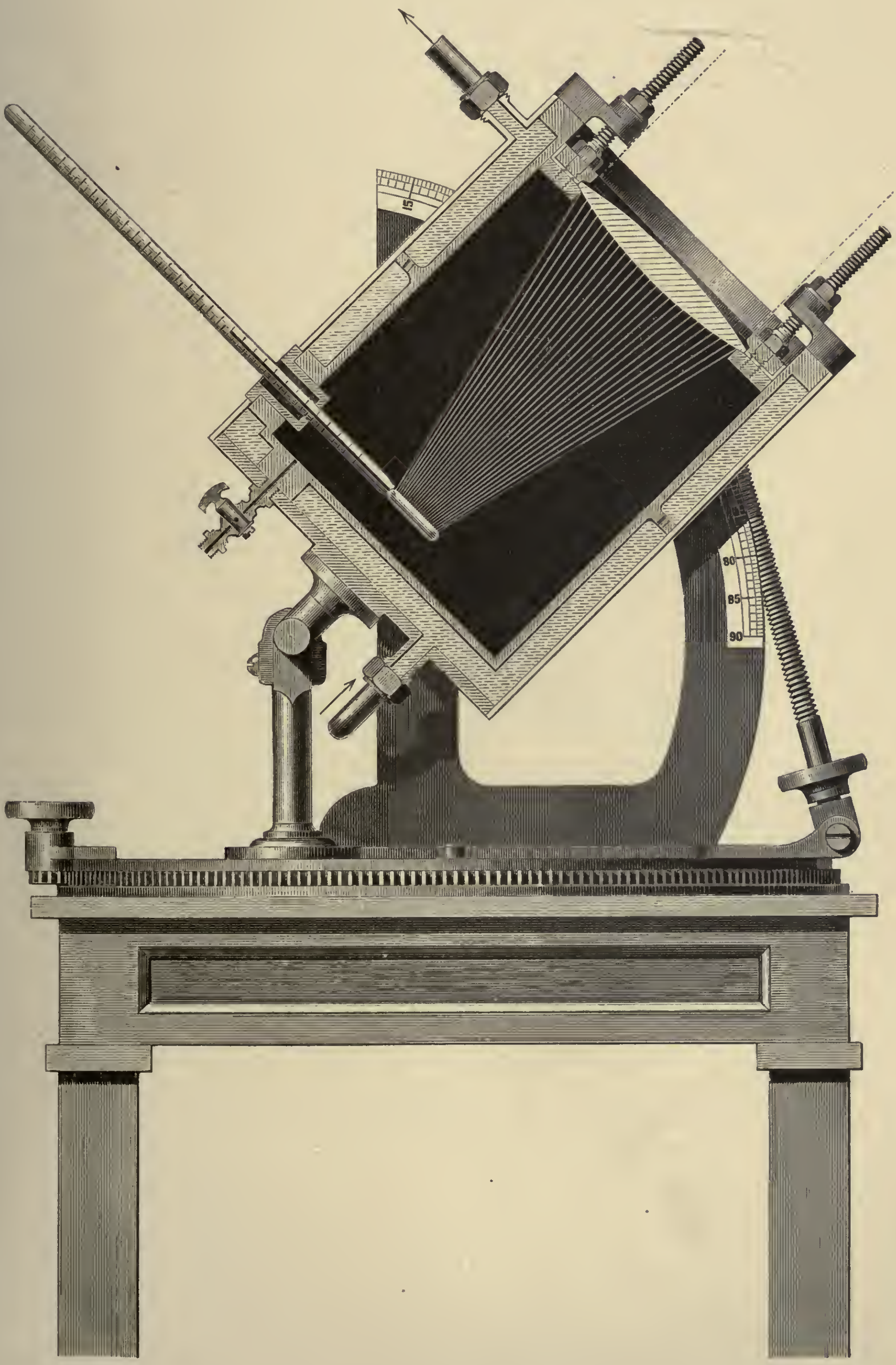


Plate 31. See Chap. XX.

Apparatus for ascertaining the Diathermancy of Flames.

Designed by John Ericsson. Constructed at New York, 1872.

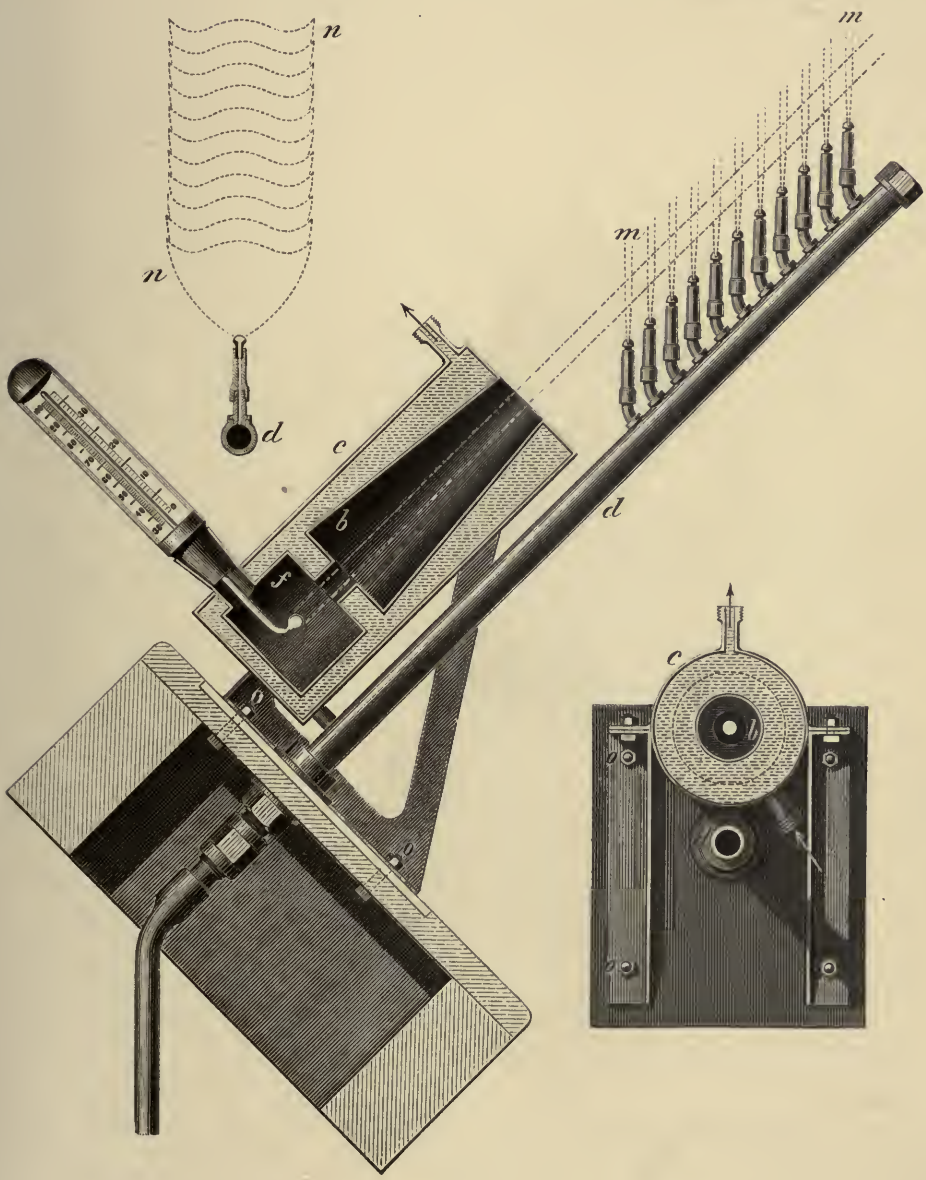


Plate 32. See Chap. XXI.

DIAGRAM REPRESENTING A SECTION OF THE EARTH AND CERTAIN RIVER BASINS.

PLATE 33. SEE CHAP. XXII.

DYNAMIC REGISTER FOR MEASURING THE RELATIVE POWER OF CURRENTS OF WATER AND VAPOR. DESIGNED BY JOHN ERICSSON.

MANUFACTURED AT NEW YORK, 1871.

FIG. I

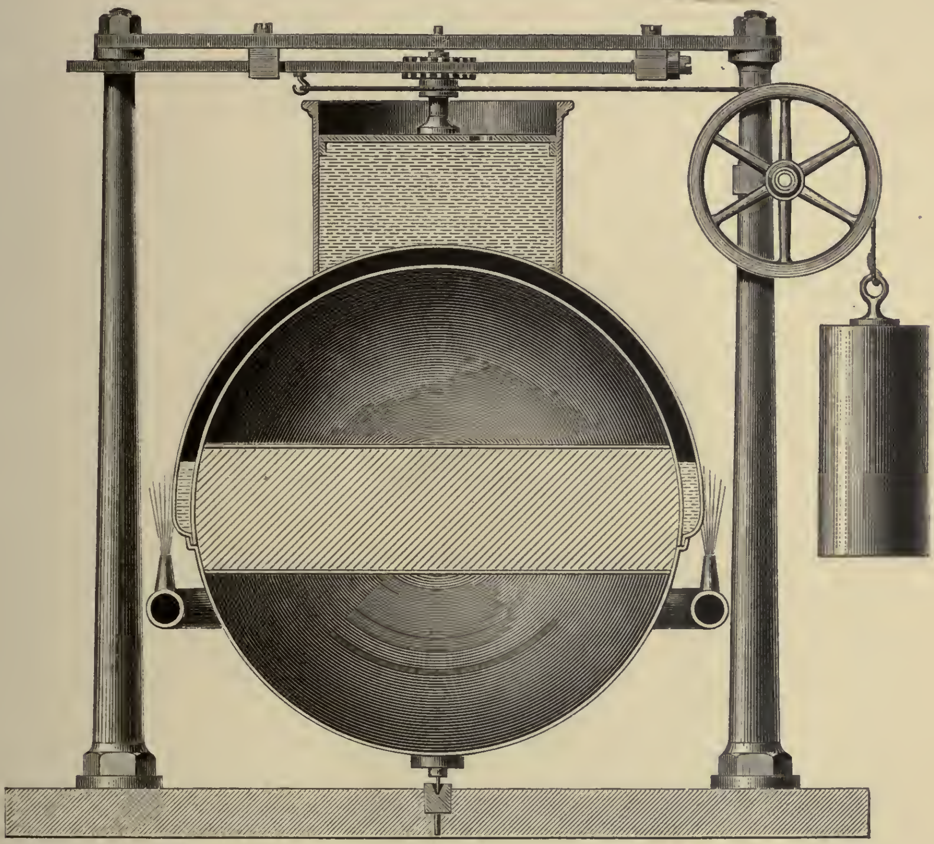


FIG. II

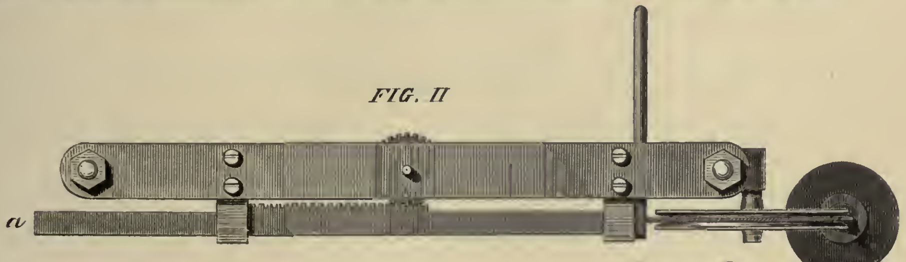


FIG. III

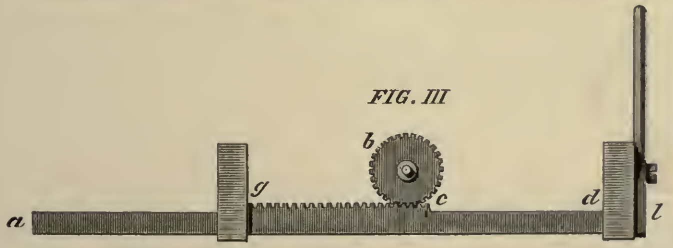


FIG. IV

PLATE 34. SEE CHAP. XXII.

Diagram showing the Result of Experiments with the Dynamic Register.

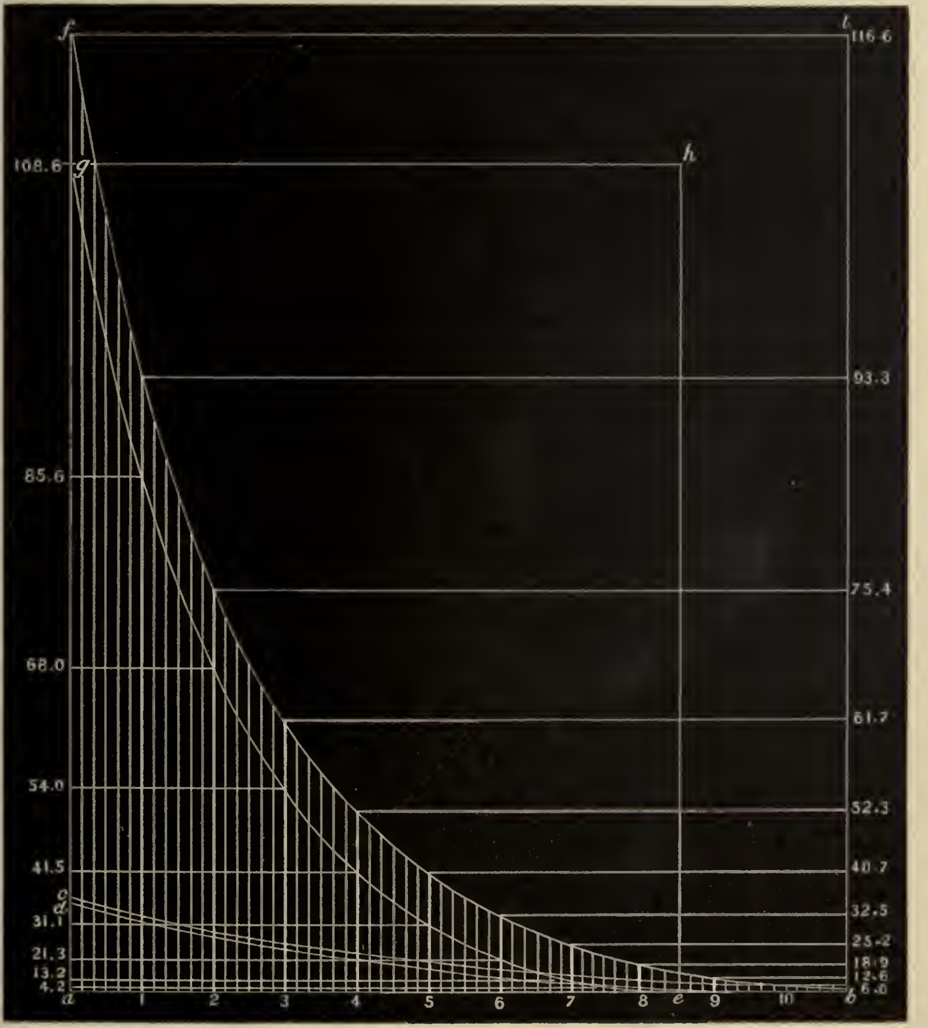


Plate 35. See Chap. XXII.

DISTANCE INSTRUMENT FOR MEASURING DISTANCES AT SEA.

DESIGNED BY JOHN ERICSSON. MANUFACTURED AT NEW YORK, 1841.

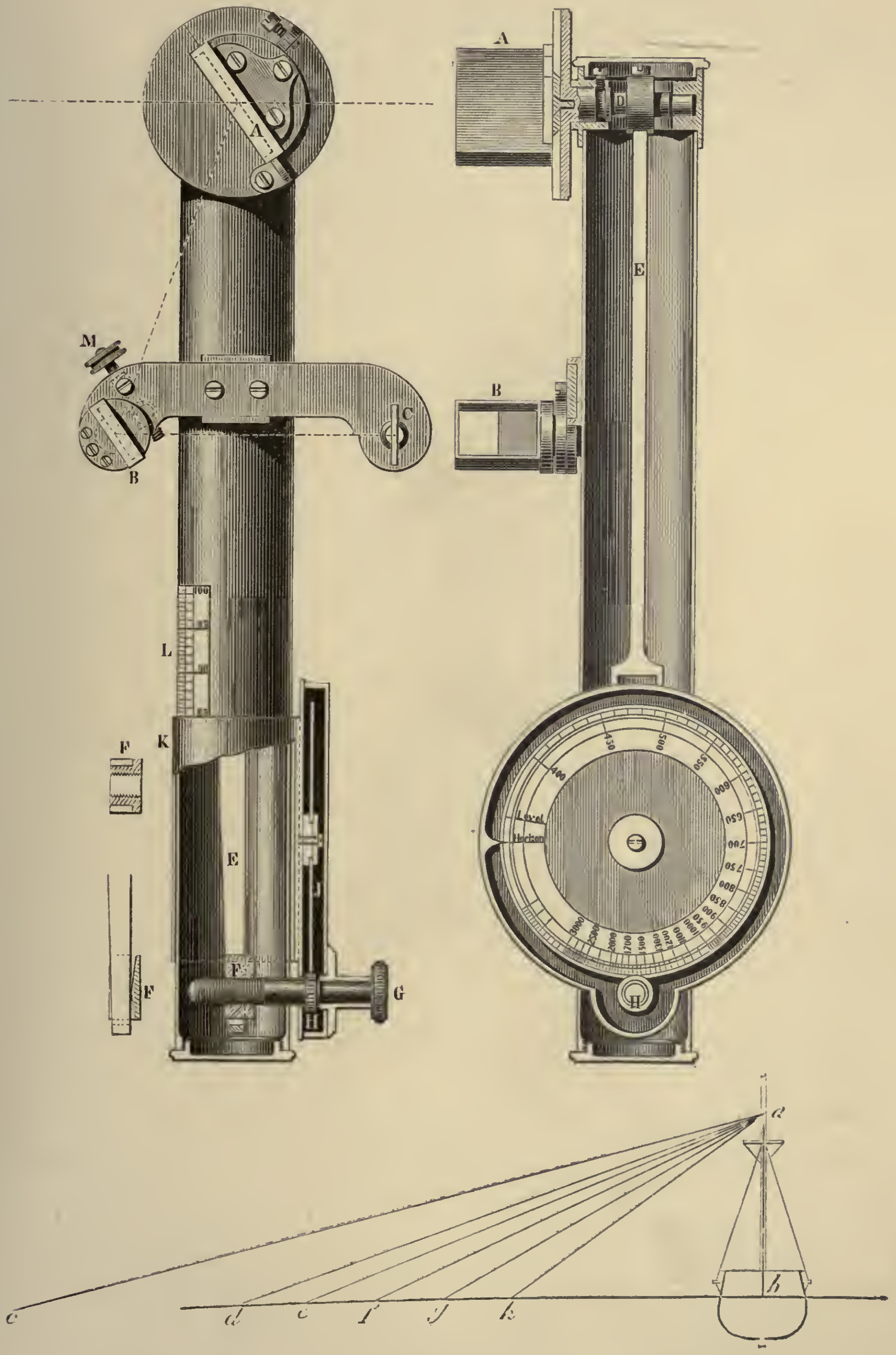


PLATE 36. SEE CHAP. XXIII.

STEAM FIRE-ENGINE. DESIGNED BY JOHN ERICSSON, 1841.

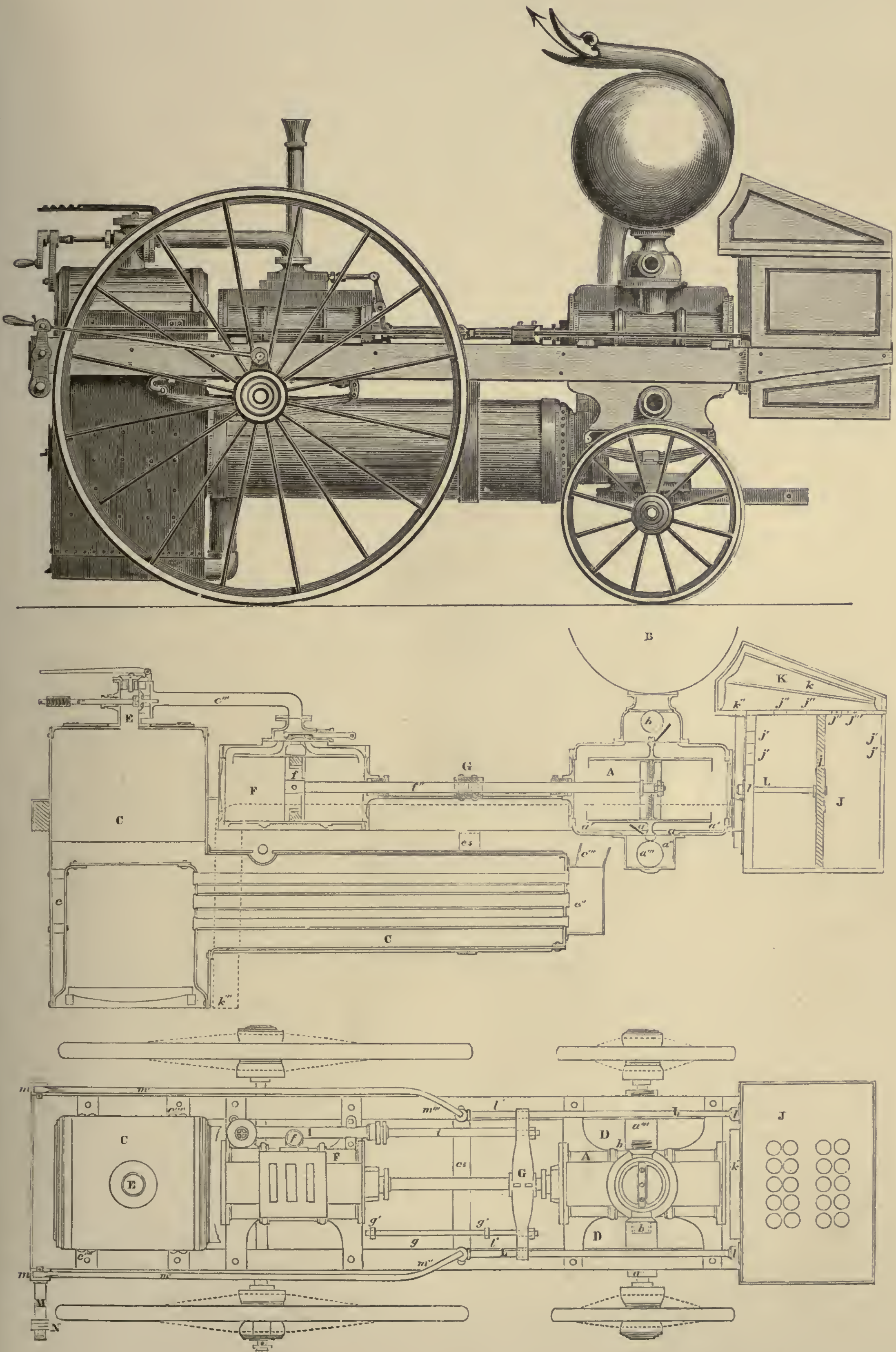


PLATE 37. SEE CHAP. XXIV.

ENGINES OF THE "PRINCETON." DESIGNED BY JOHN ERICSSON. BUILT AT PHILADELPHIA, 1842

TRANSVERSE SECTION OF SEMI-CYLINDER AND PISTON.

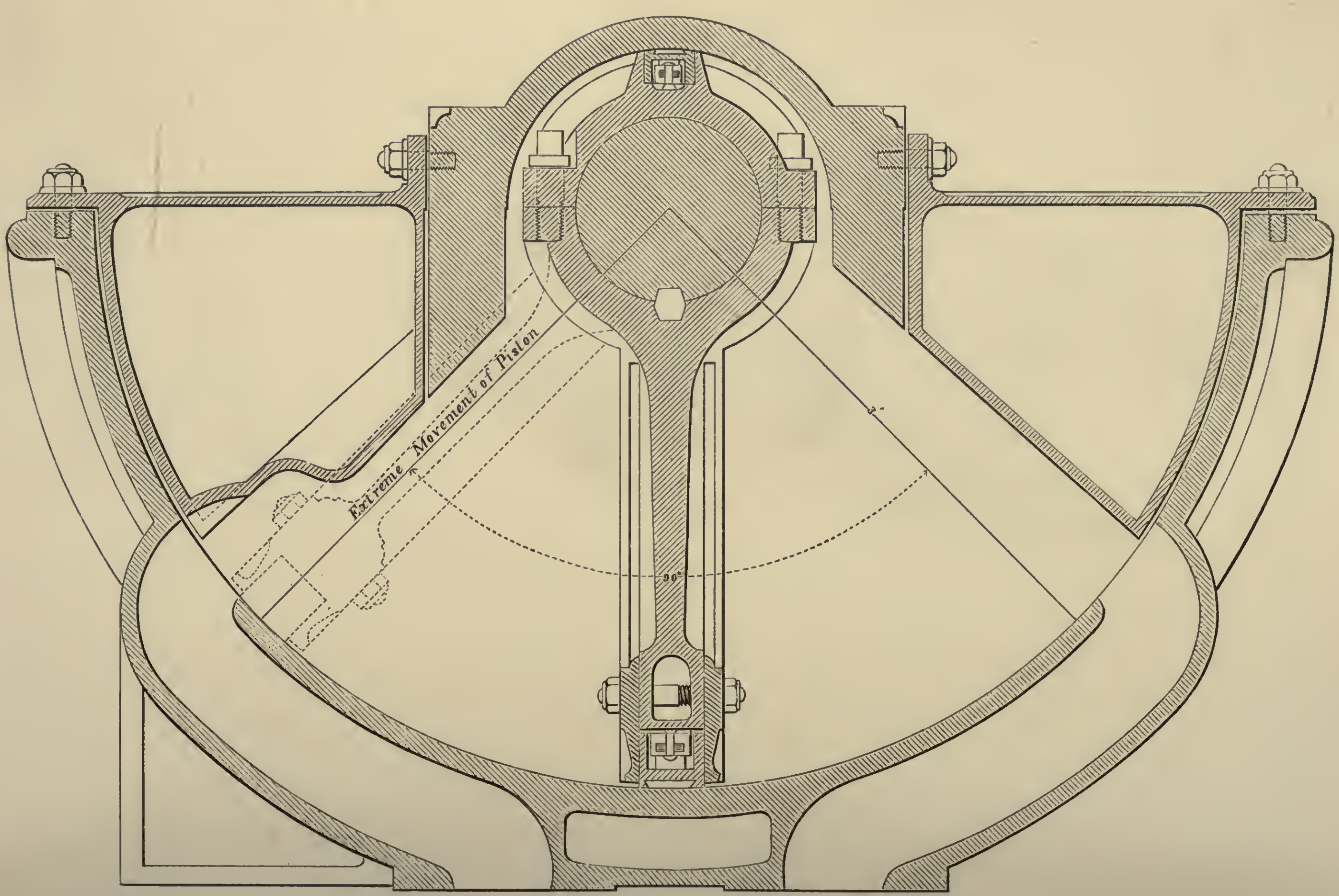


PLATE 38. SEE CHAP. XXV.

Engines of the "Princeton." Designed by John Ericsson. Built at Philadelphia, 1842.

FRONT ELEVATION.

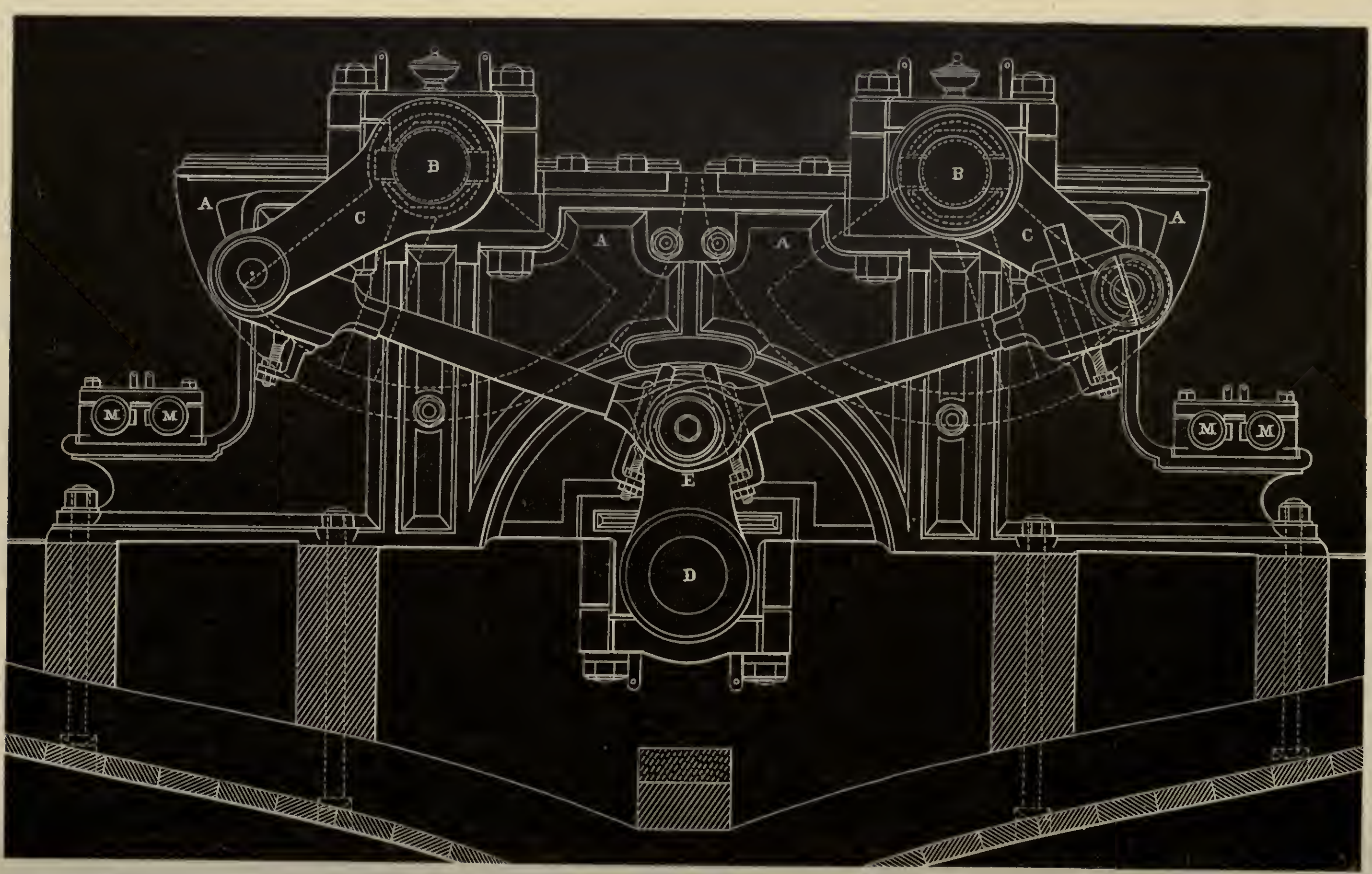


Plate 39. See Chap. XXV.

Engines of the "Princeton." Designed by John Ericsson. Built at Philadelphia, 1842.

ELEVATION VIEWED FROM THE STERN.

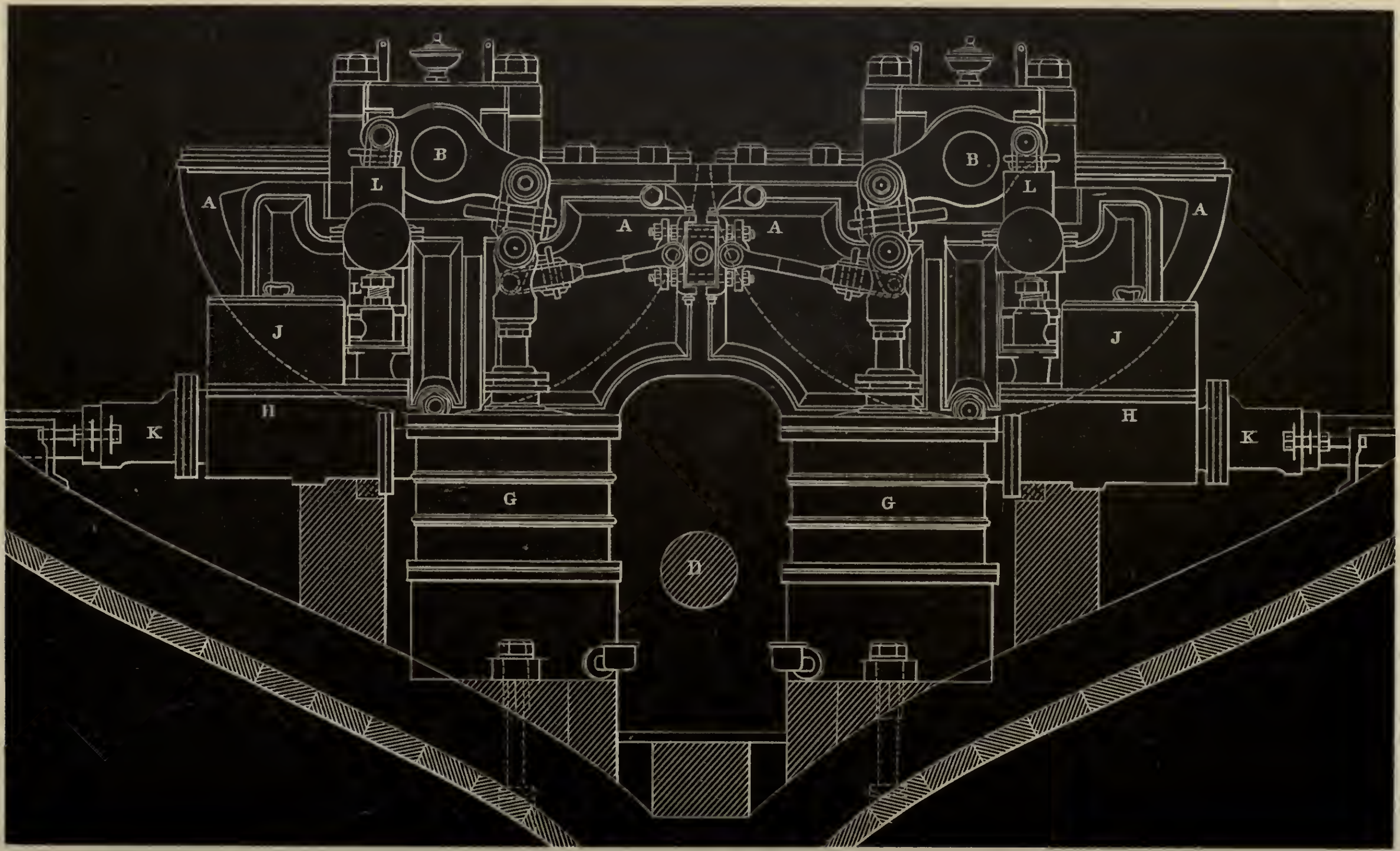


Plate 40. See Chap. XXV.

TWELVE-INCH WROUGHT-IRON GUN AND CARRIAGE. DESIGNED BY JOHN ERICSSON.

MOUNTED ON BOARD THE STEAMSHIP PRINCETON, 1843.

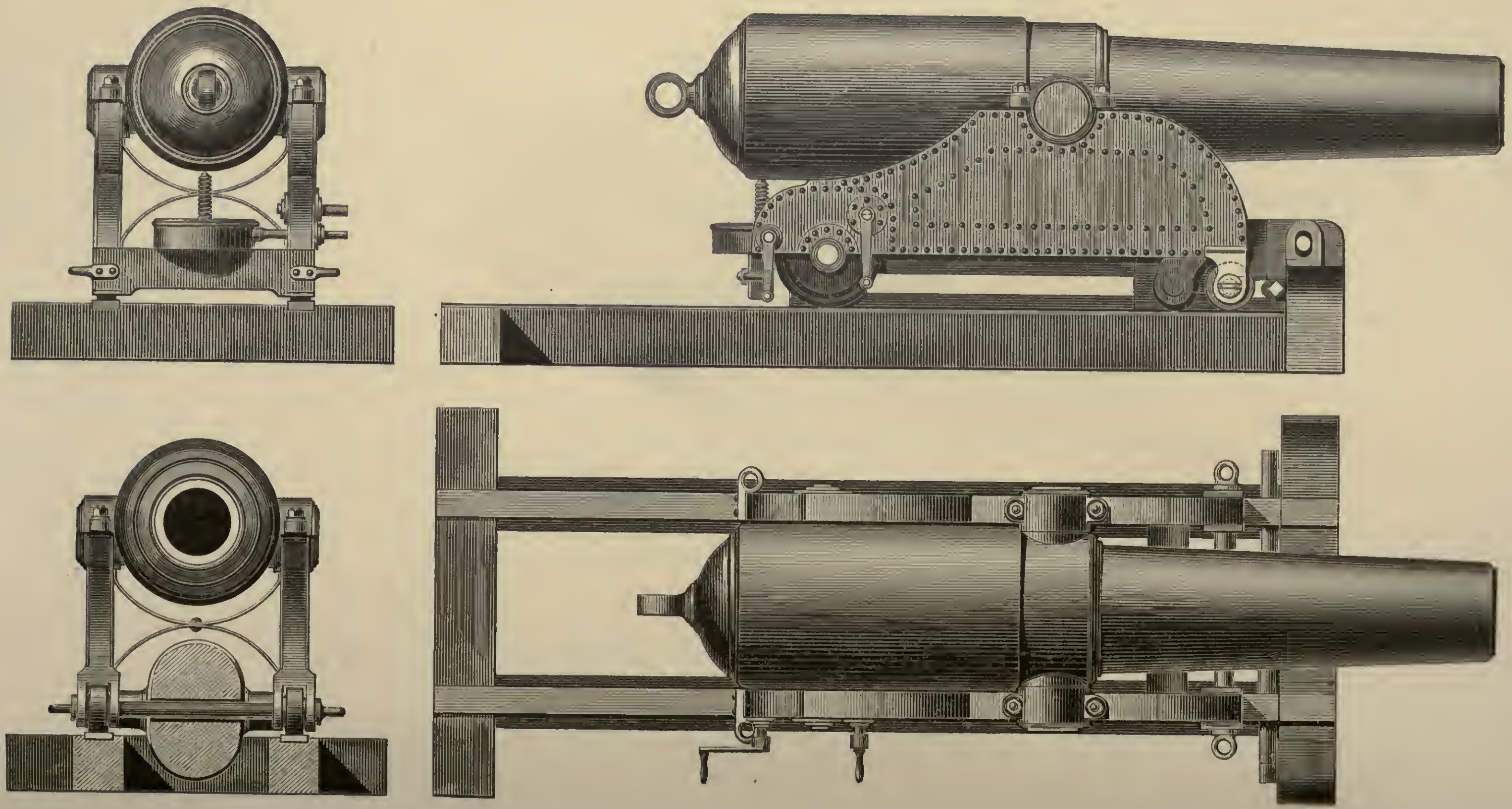


PLATE 41. SEE CHAP. XXVI.

Iron-clad Cupola Vessel. Designed by John Ericsson, 1854.

SIDE ELEVATION AND TRANSVERSE SECTION.

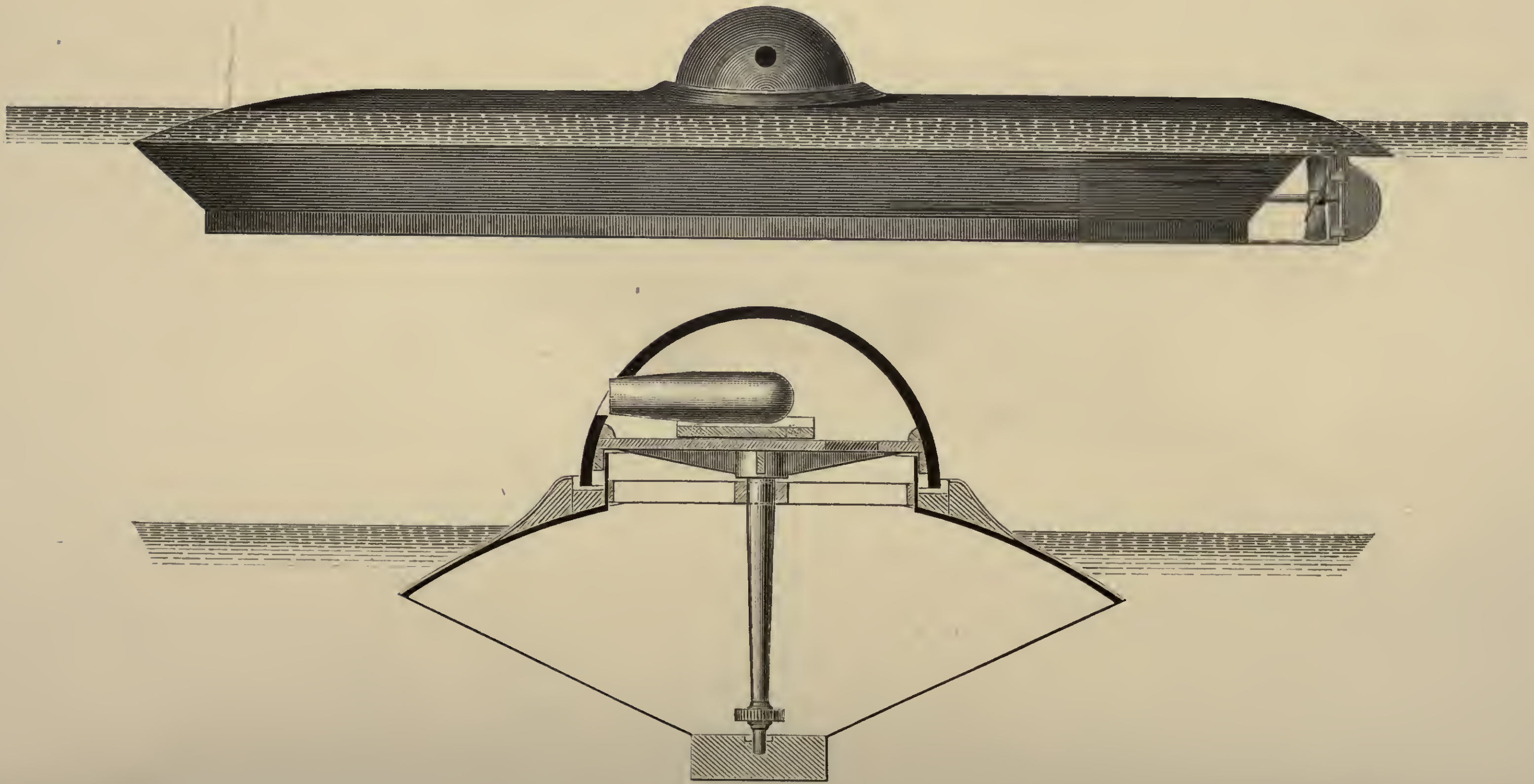


Plate 42. See Chap. XXVIII.

SURFACE-CONDENSER. DESIGNED AND PATENTED BY JOHN ERICSSON, 1849.

BUILT AT NEW YORK.

FIG. 1.

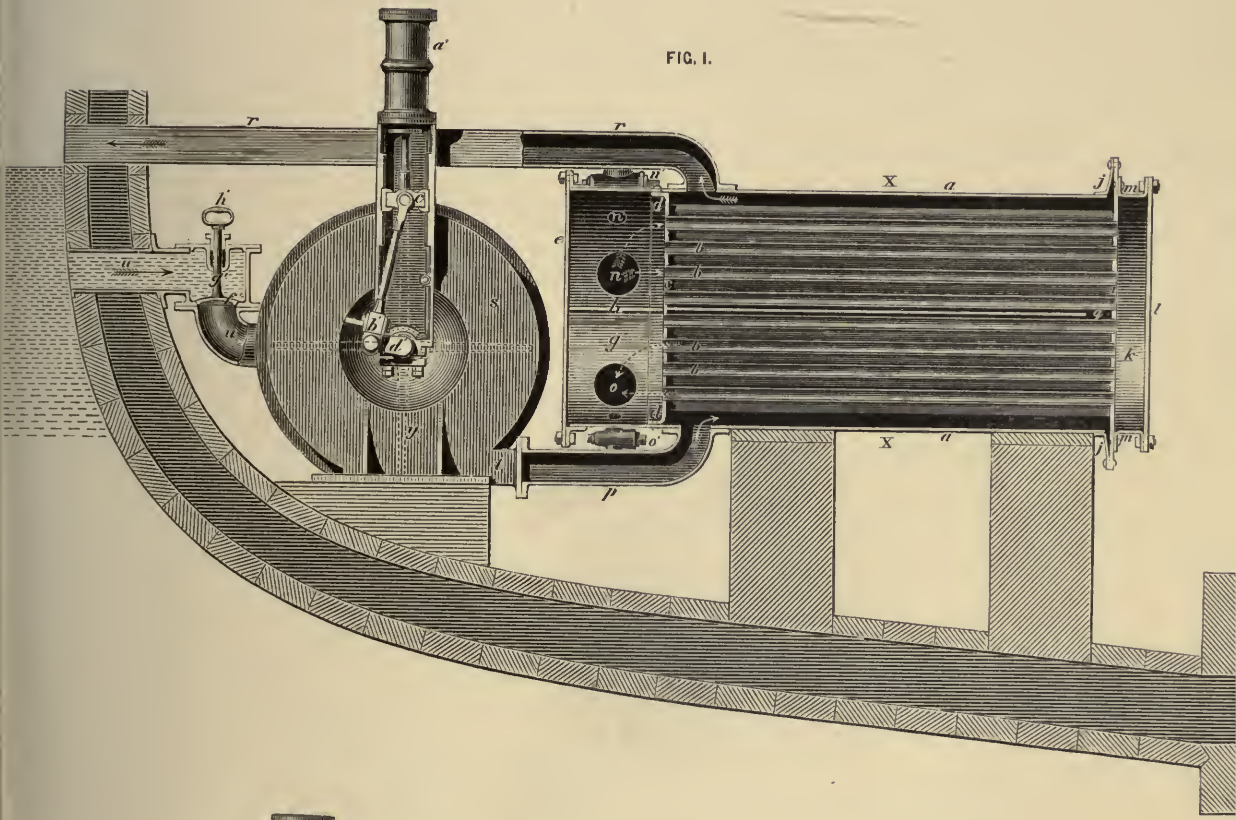


FIG. 3.

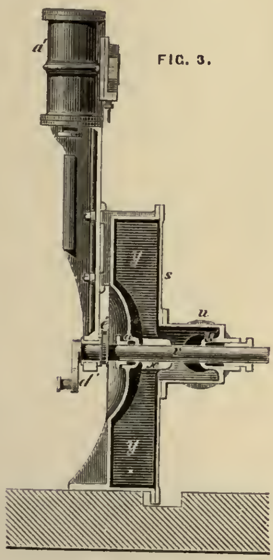


FIG. 2.

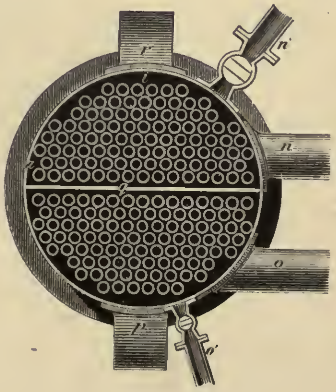


Plate 43. See Chap. XXIX.

EXPERIMENTAL CALORIC ENGINE. DESIGNED BY JOHN ERICSSON.

BUILT AT NEW YORK, 1851.

TRANSVERSE SECTION.

FIG. I

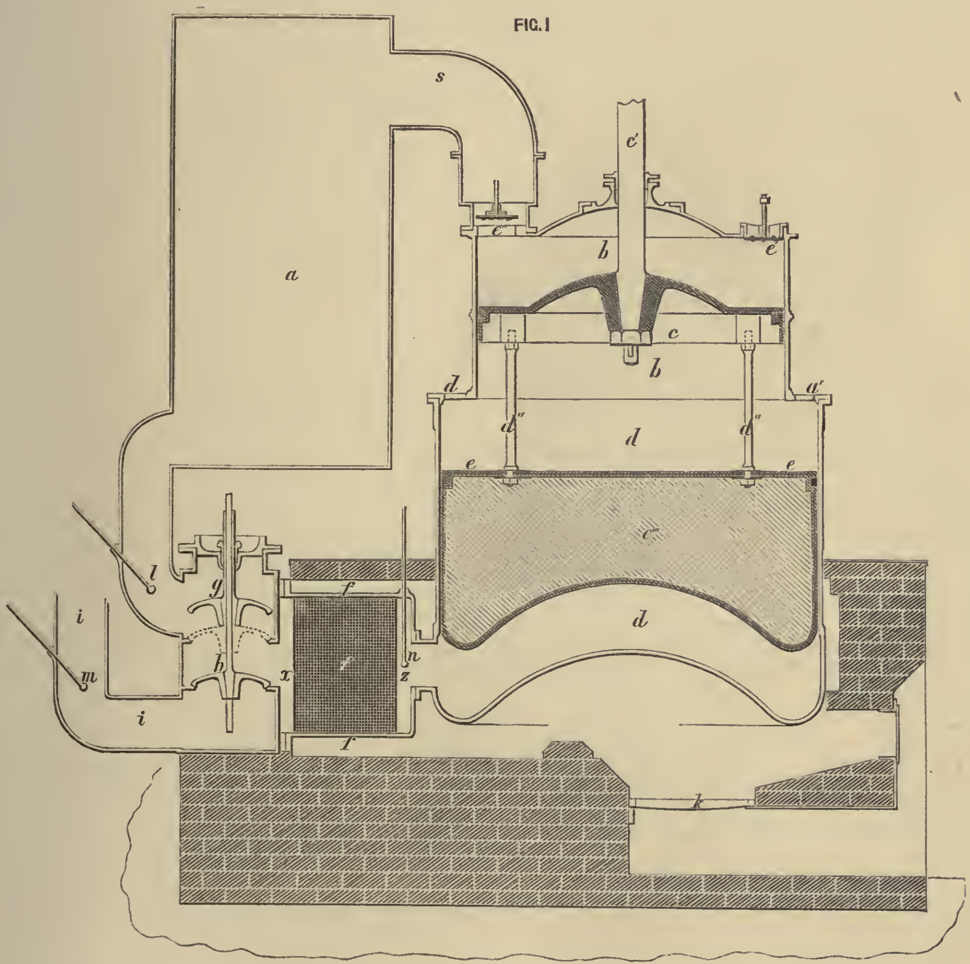


Plate 44. See Chap. XXX.

EXPERIMENTAL CALORIC ENGINE. DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1851.

LONGITUDINAL SECTION.

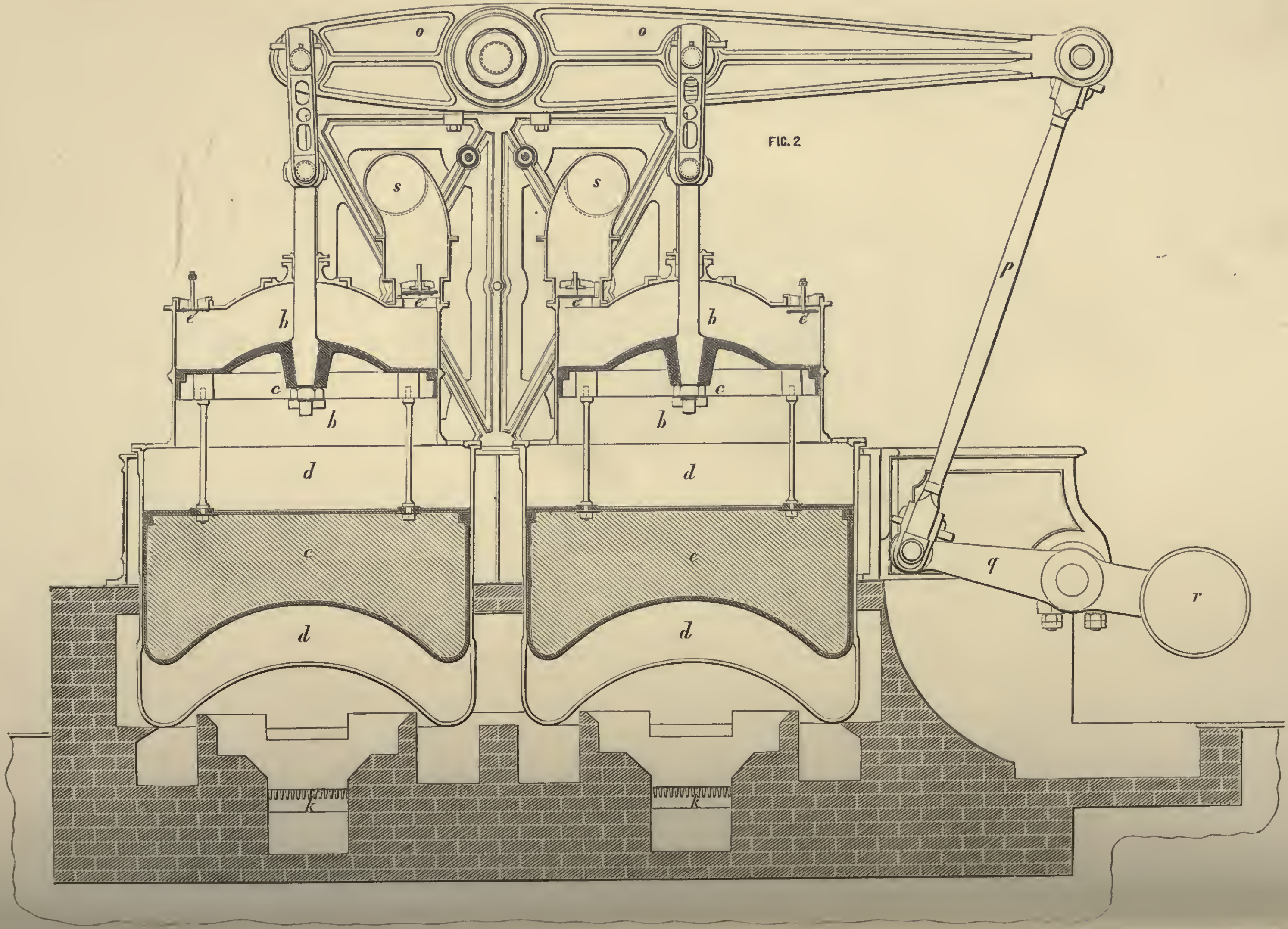


FIG. 2

PLATE 45. SEE CHAP. XXX.

CALORIC ENGINE FOR DOMESTIC PURPOSES. DESIGNED BY JOHN ERICSSON.

BUILT IN AMERICA AND EUROPE DURING A SERIES OF YEARS.

LONGITUDINAL SECTION.

FIG. I.

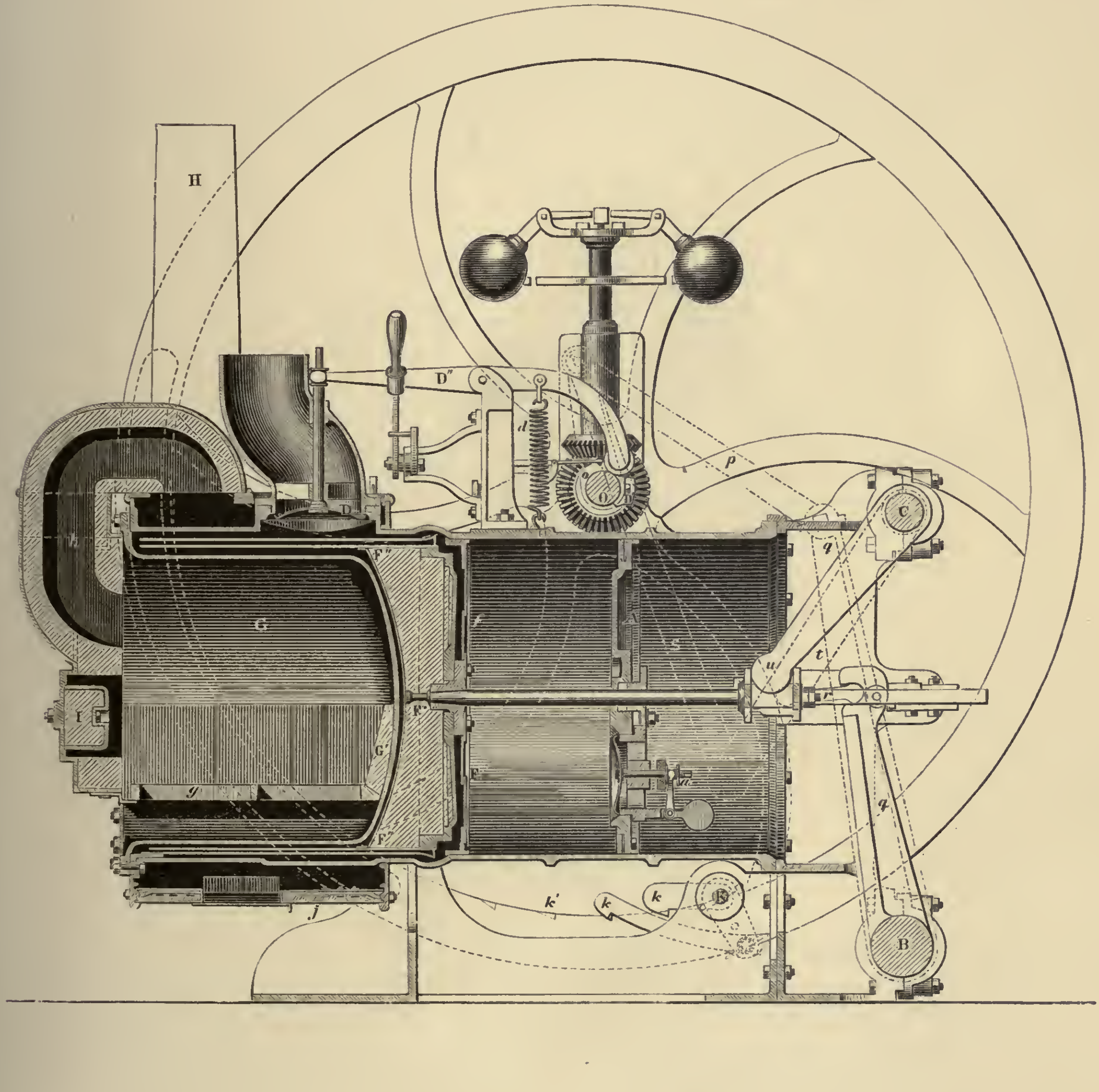
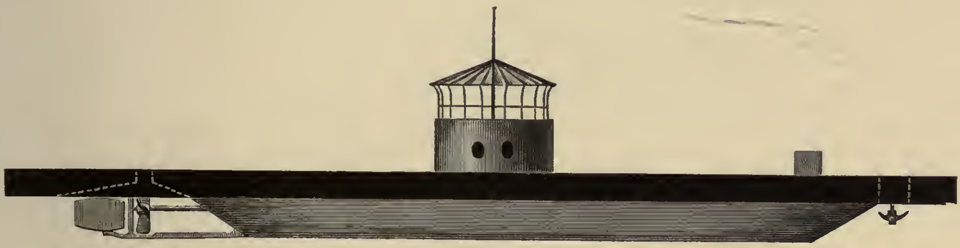


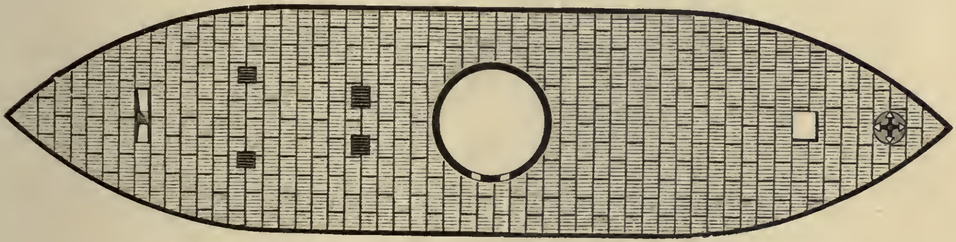
PLATE 46. SEE CHAP. XXXI.

THE "MONITOR." DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1861.

SIDE ELEVATION.



DECK PLAN.



TRANSVERSE SECTION OF HULL AND TURRET.

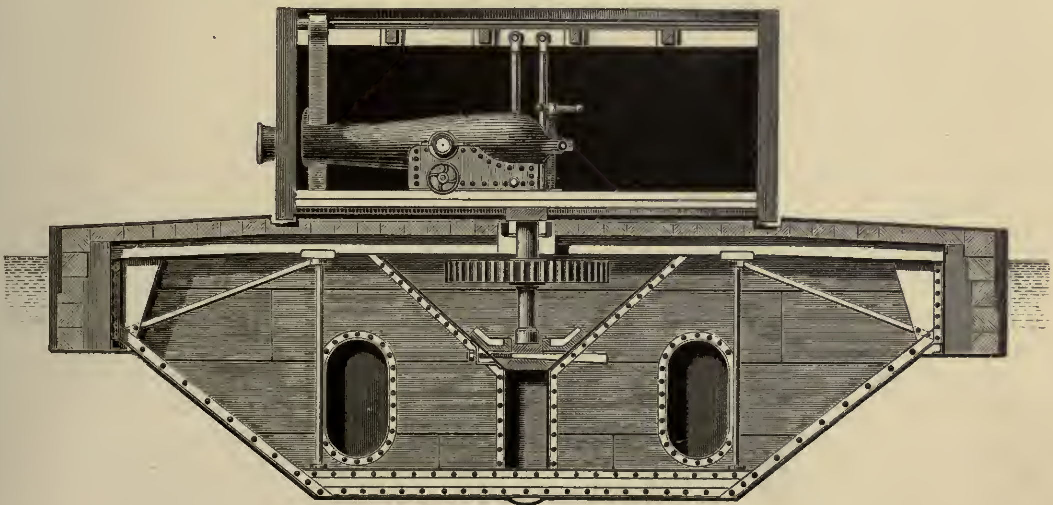


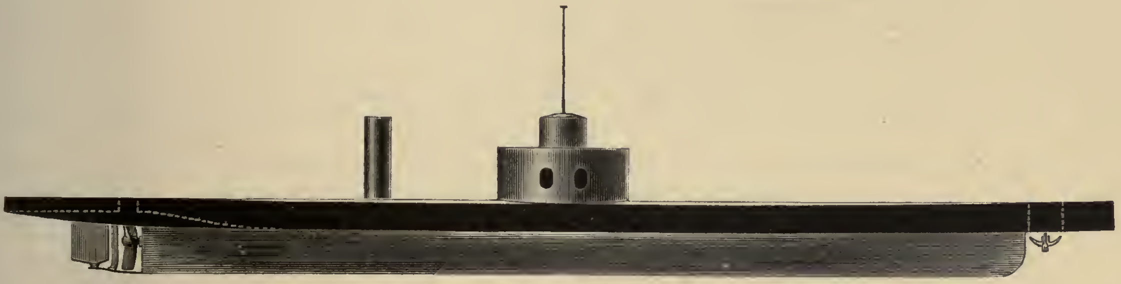
Plate 47. See Chap. XXXII.

MONITOR "WEEHAWKEN" AT SEA. DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1862.

PLATE 48. SEE CHAP. XXXII.

MONITOR OF THE "PASSAIC" CLASS. DESIGNED BY JOHN ERICSSON.
TEN MONITORS OF THIS CLASS BUILT AT NEW YORK AND OTHER PLACES.

SIDE ELEVATION.



TRANSVERSE SECTION OF TURRET AND PILOT-HOUSE.

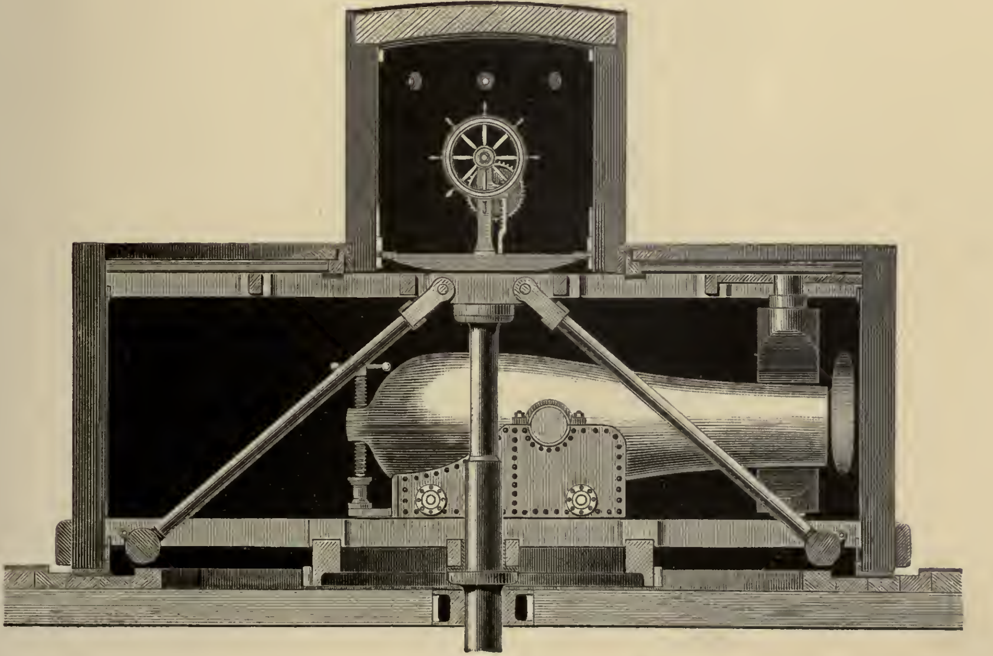


PLATE 49. SEE CHAP. XXXIII.

THE MONITOR ENGINE.

DESIGNED BY JOHN ERICSSON. BUILT AT NUMEROUS ESTABLISHMENTS, 1862.

TOP VIEW.

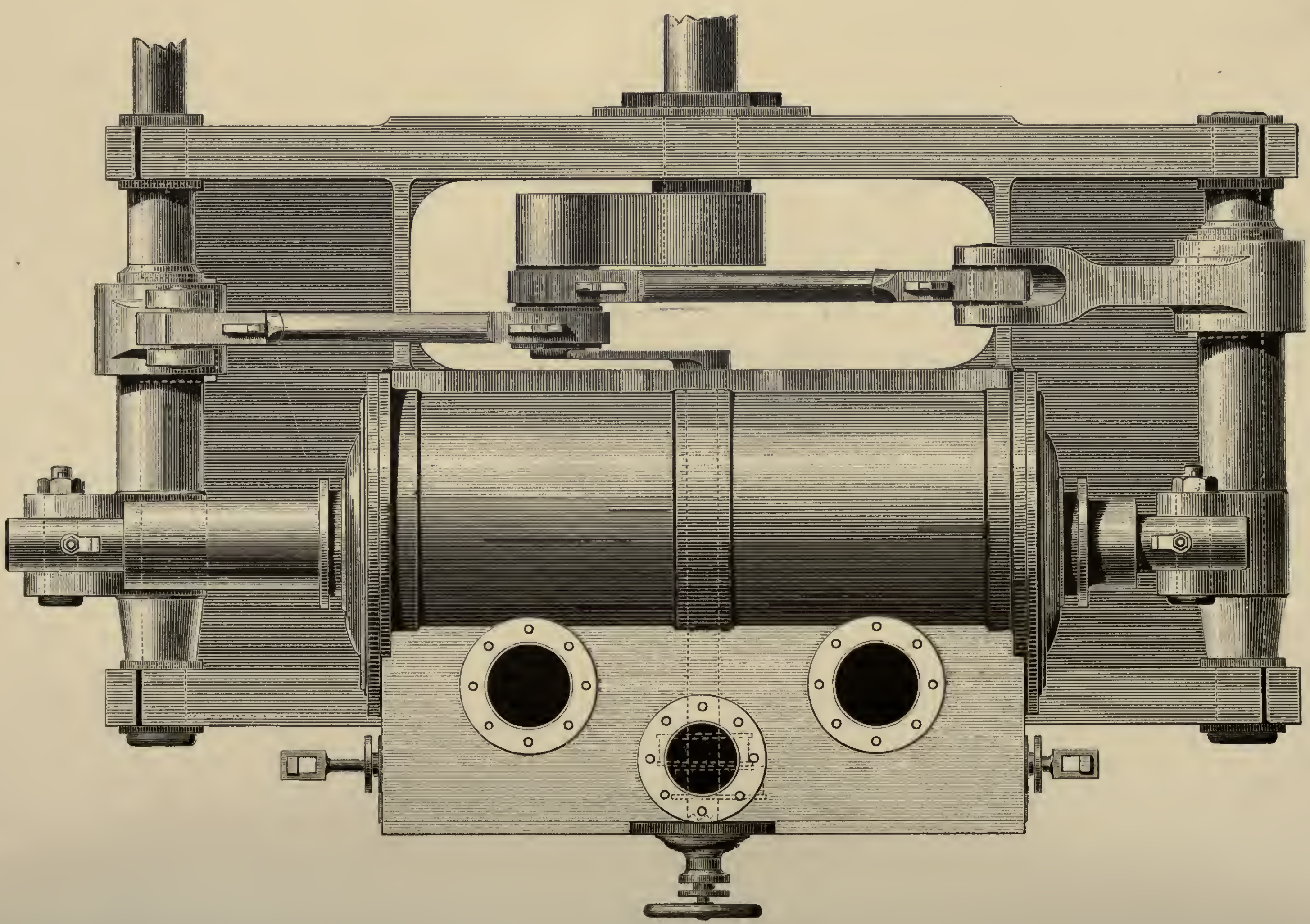


PLATE 50. SEE CHAP. XXXIV.

THE MONITOR ENGINE.

DESIGNED BY JOHN ERICSSON. BUILT AT NUMEROUS ESTABLISHMENTS, 1862.

FRONT ELEVATION.

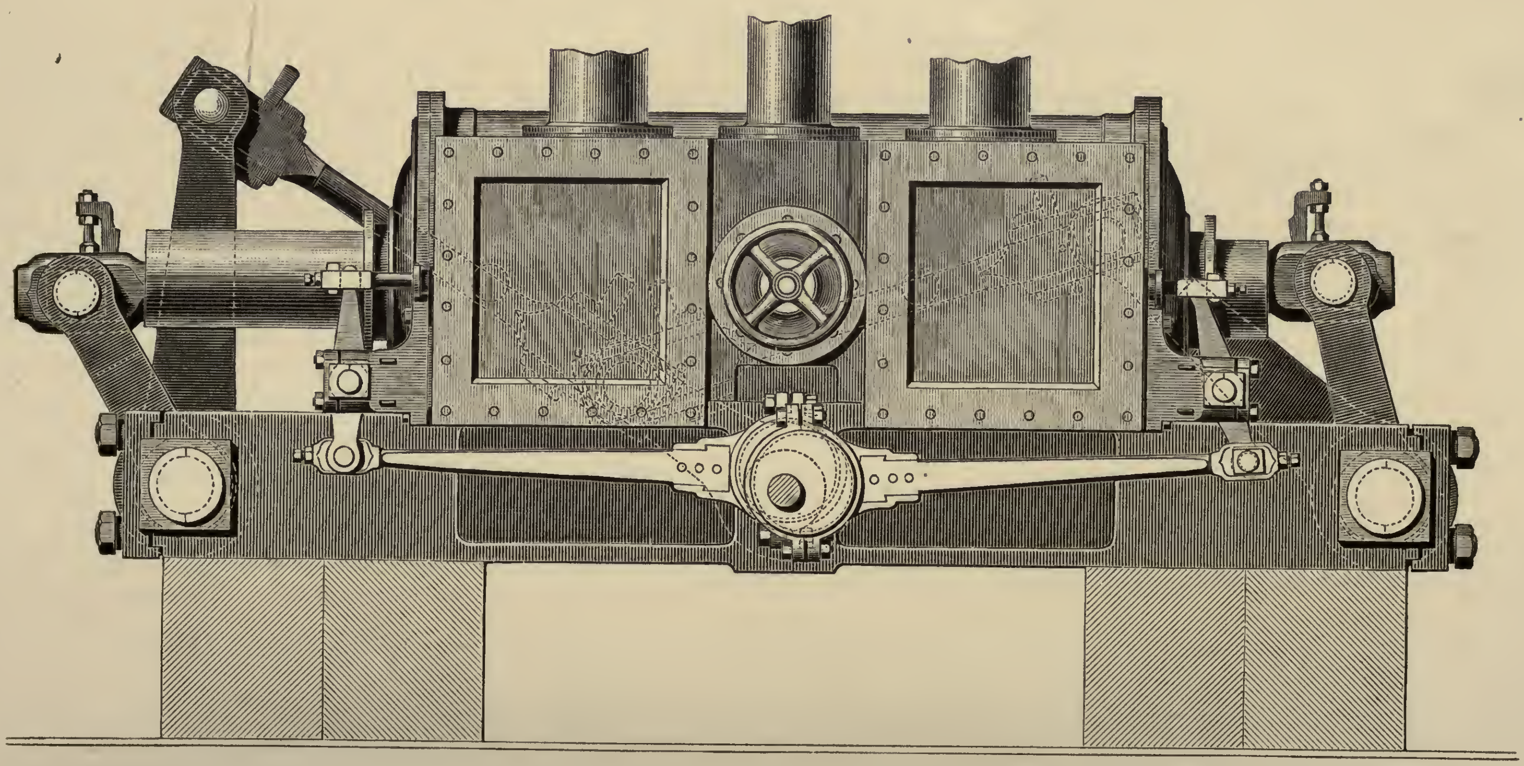
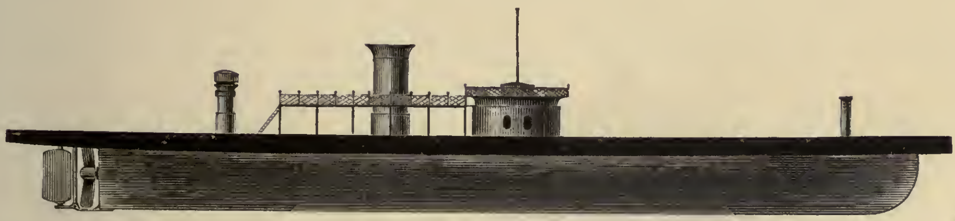


PLATE 51. SEE CHAP. XXXIV.

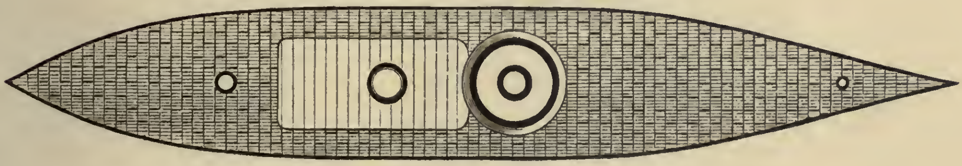
Monitor "Dictator." Designed by John Ericsson.

Built at New York, 1862.

SIDE ELEVATION.



DECK PLAN.



LENGTH ON DECK, 312 FEET. BEAM, 50 FEET. DEPTH, 21 FEET 6 INCHES.
STEAM-CYLINDERS, 100 INCHES DIAMETER, 4 FEET STROKE.
PROPELLER, 21 FEET 6 INCHES DIAMETER.

Plate 52. See Chap. XXXV.

MONITOR "DICTATOR." DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1862.

TRANSVERSE SECTION OF ENGINES AND SHIP.

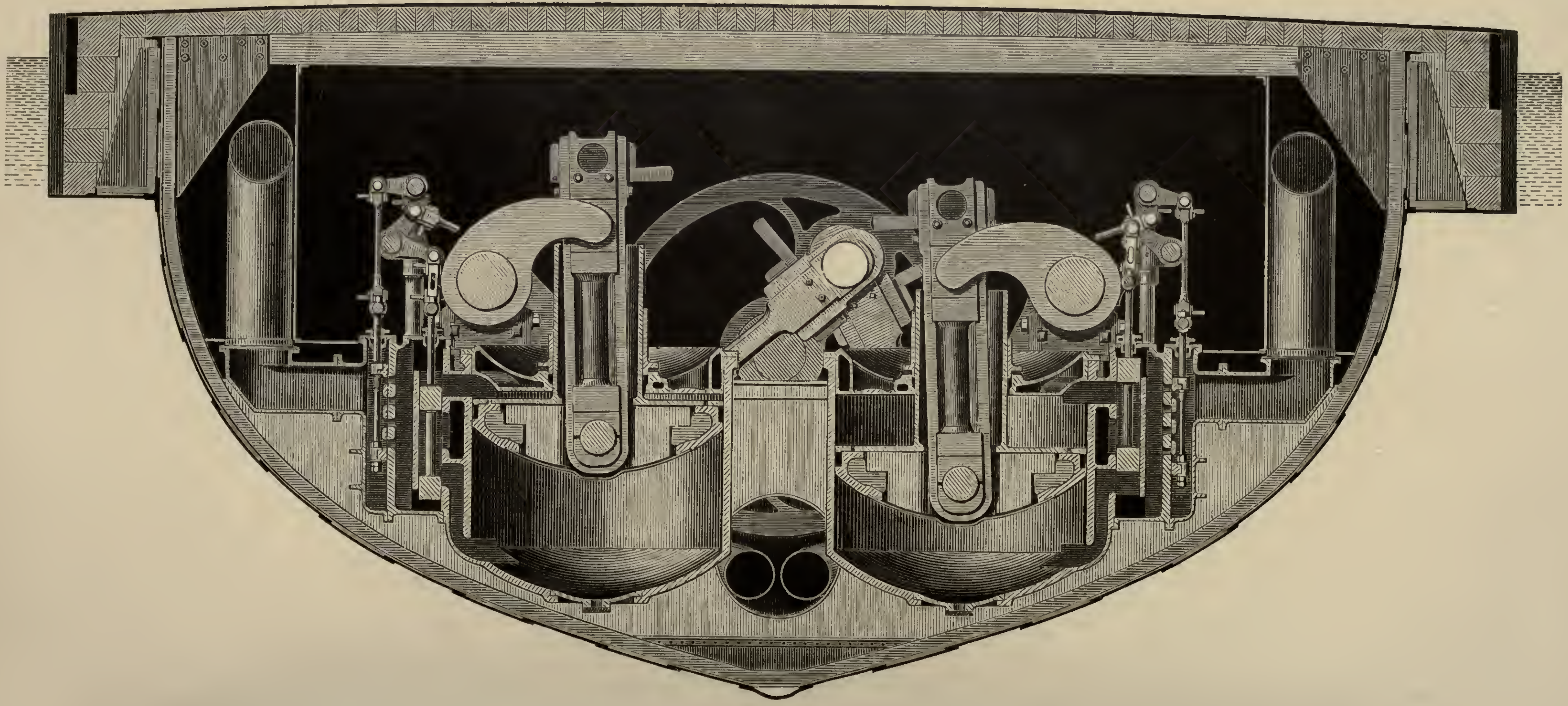


PLATE 53. SEE CHAP. XXXV.

MONITOR "DICTATOR." DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1862.

TOP VIEW OF ENGINES.

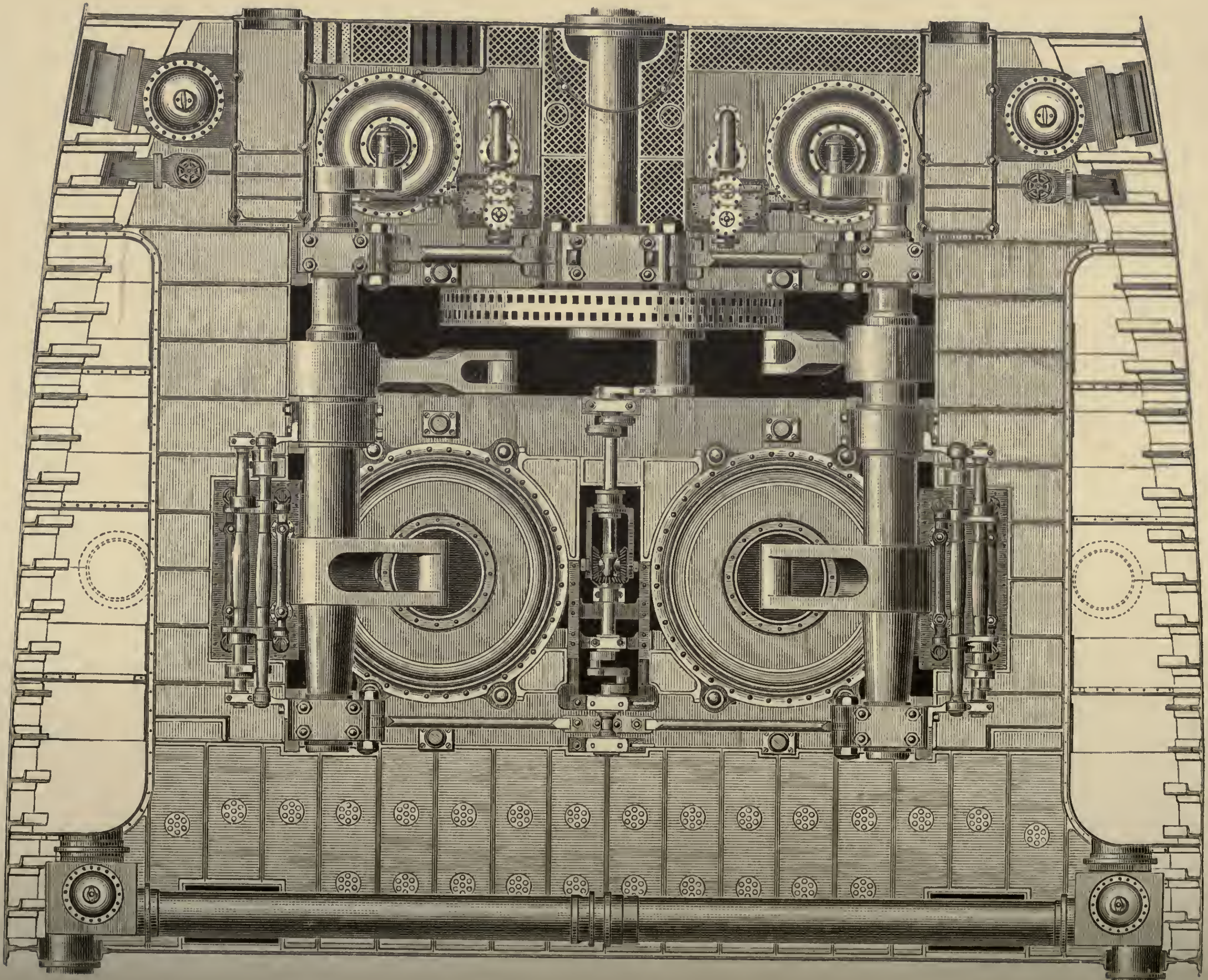


PLATE 54. SEE CHAP. XXXV.

MONITOR "DICTATOR" ON THE STOCKS PREPARED FOR LAUNCHING.

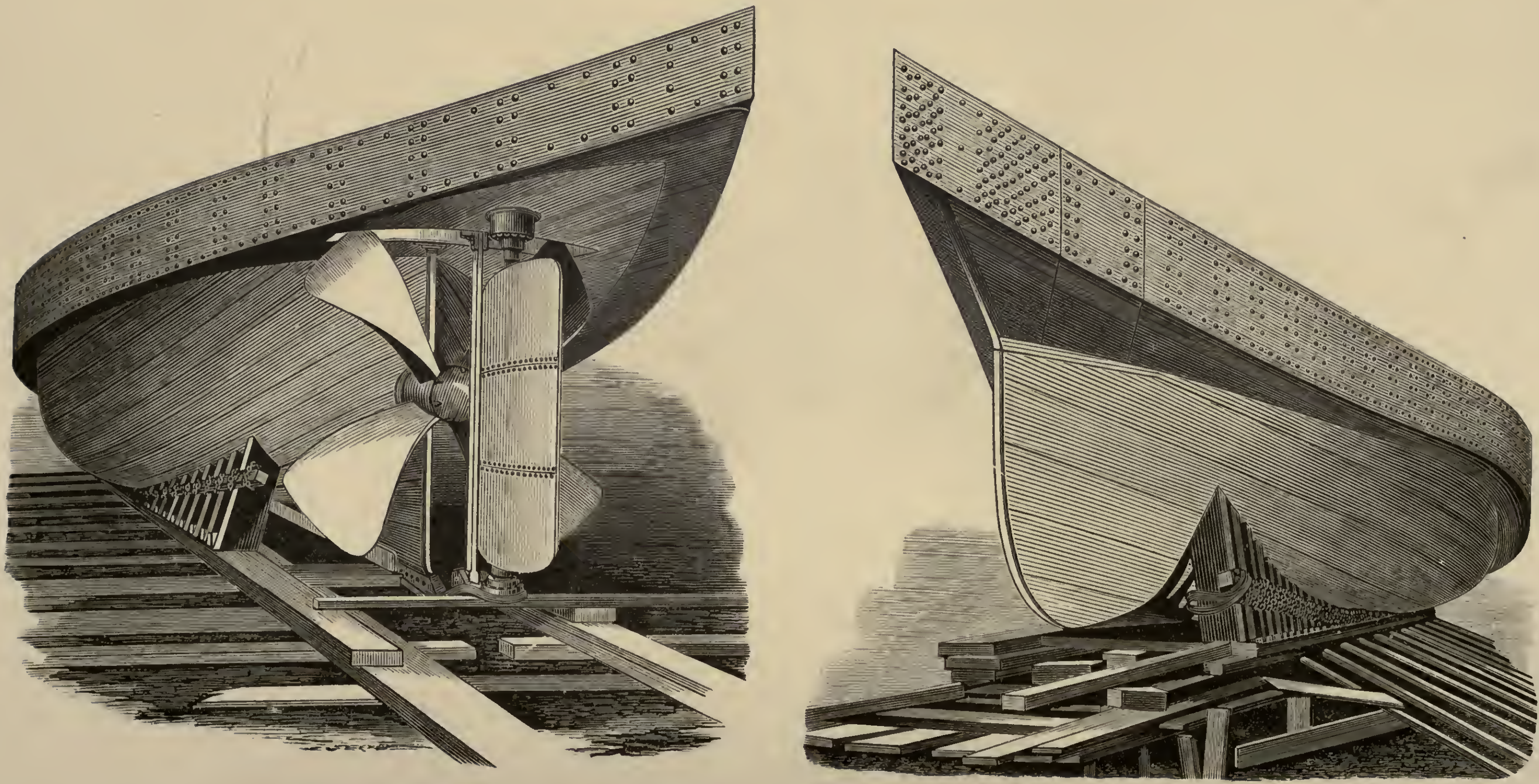
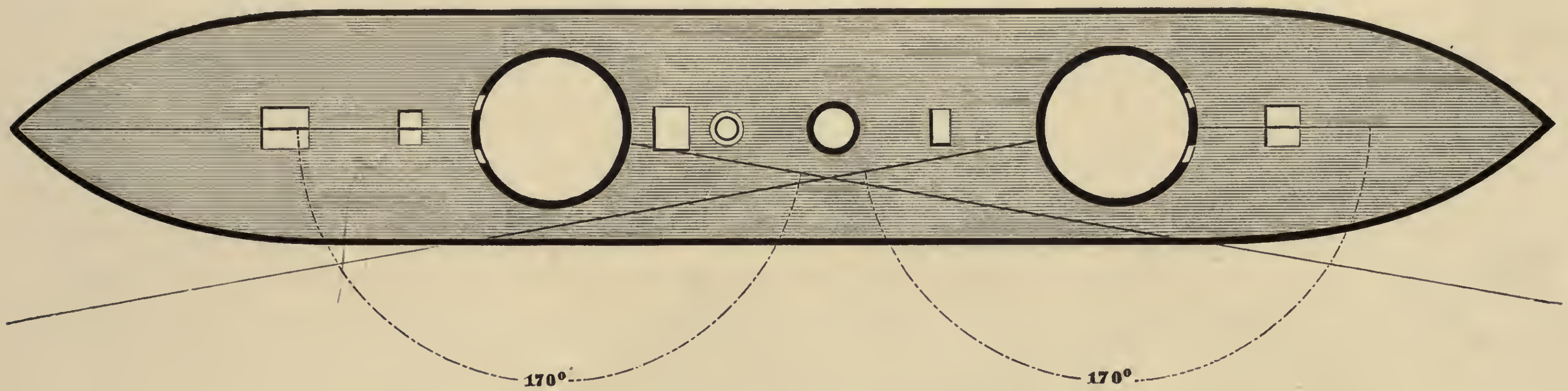


PLATE 55. SEE CHAP. XXXV.

THE MONITOR TURRET AND THE CASEMATE.

DECK PLAN OF A MONITOR WITH TWO TURRETS.

LENGTH, 230 FEET. BEAM, 35 FEET 6 INCHES. ARMAMENT, FOUR 24-TON GUNS.



DECK PLAN OF THE TURKISH IRON-CLAD "MOYINI ZAFFER."

LENGTH, 230 FEET. BEAM, 35 FEET 6 INCHES. ARMAMENT, FOUR 12-TON GUNS.

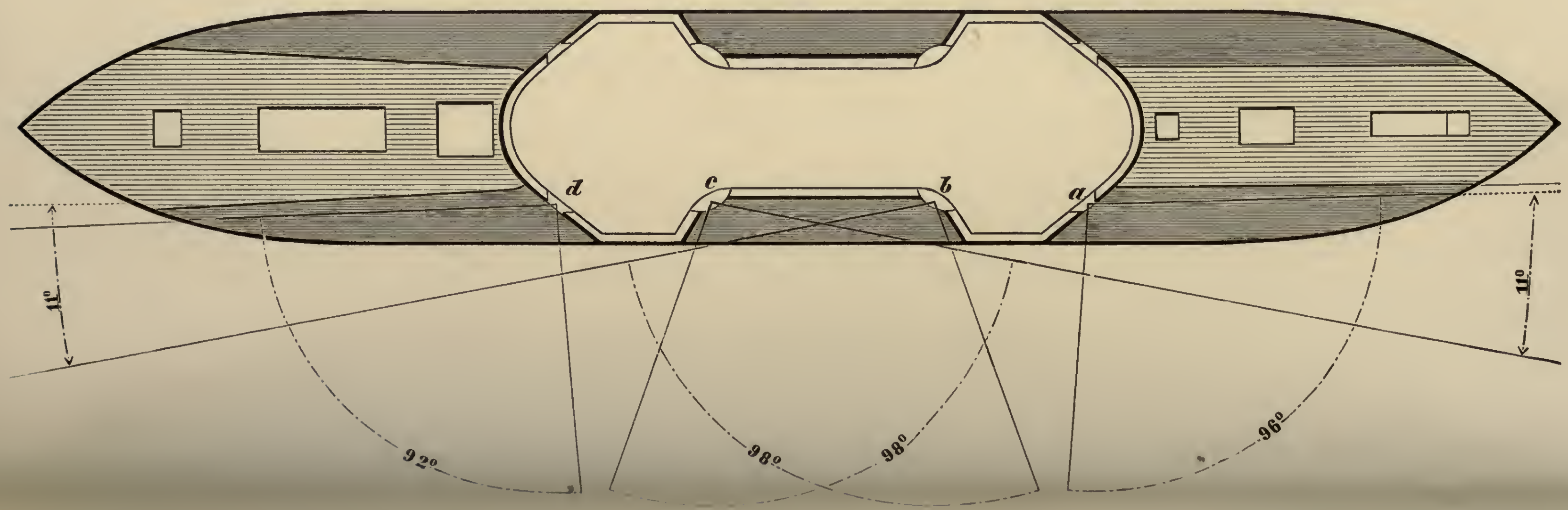
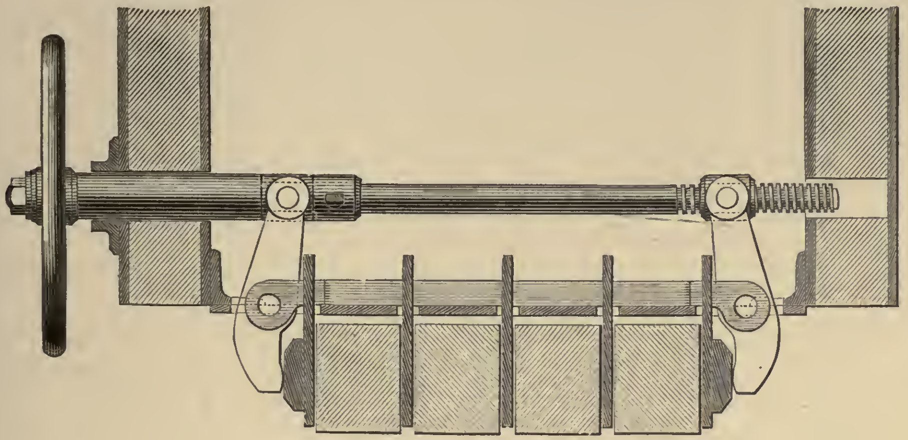


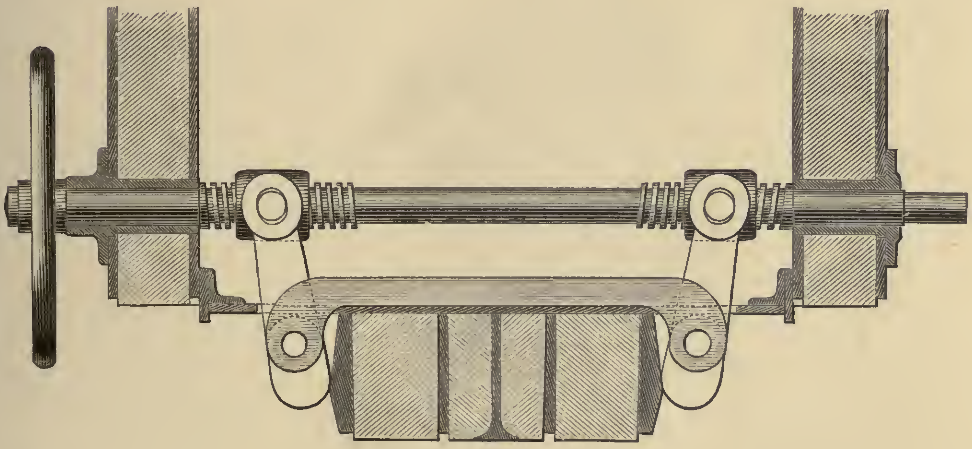
PLATE 56. SEE CHAP. XXXVI.

Carriages for Heavy Ordnance. Designed by John Ericsson, 1861.

SECTION SHOWING THE FRICTION-GEAR APPLIED TO THE GUN-CARRIAGES OF THE UNITED STATES IRON-CLAD FLEET.



SECTION SHOWING CAPTAIN SCOTT'S PLAGIARISM.



SECTION SHOWING SIR WILLIAM ARMSTRONG'S PLAGIARISM.

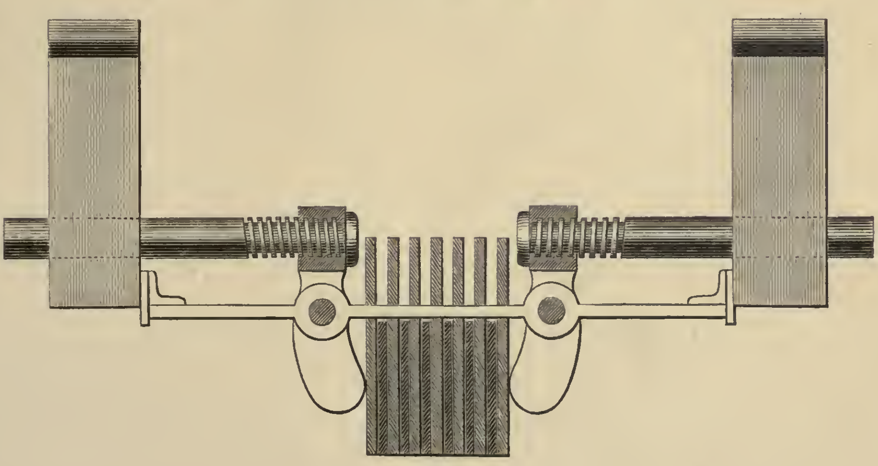


Plate 57. See Chap. XXXVII.

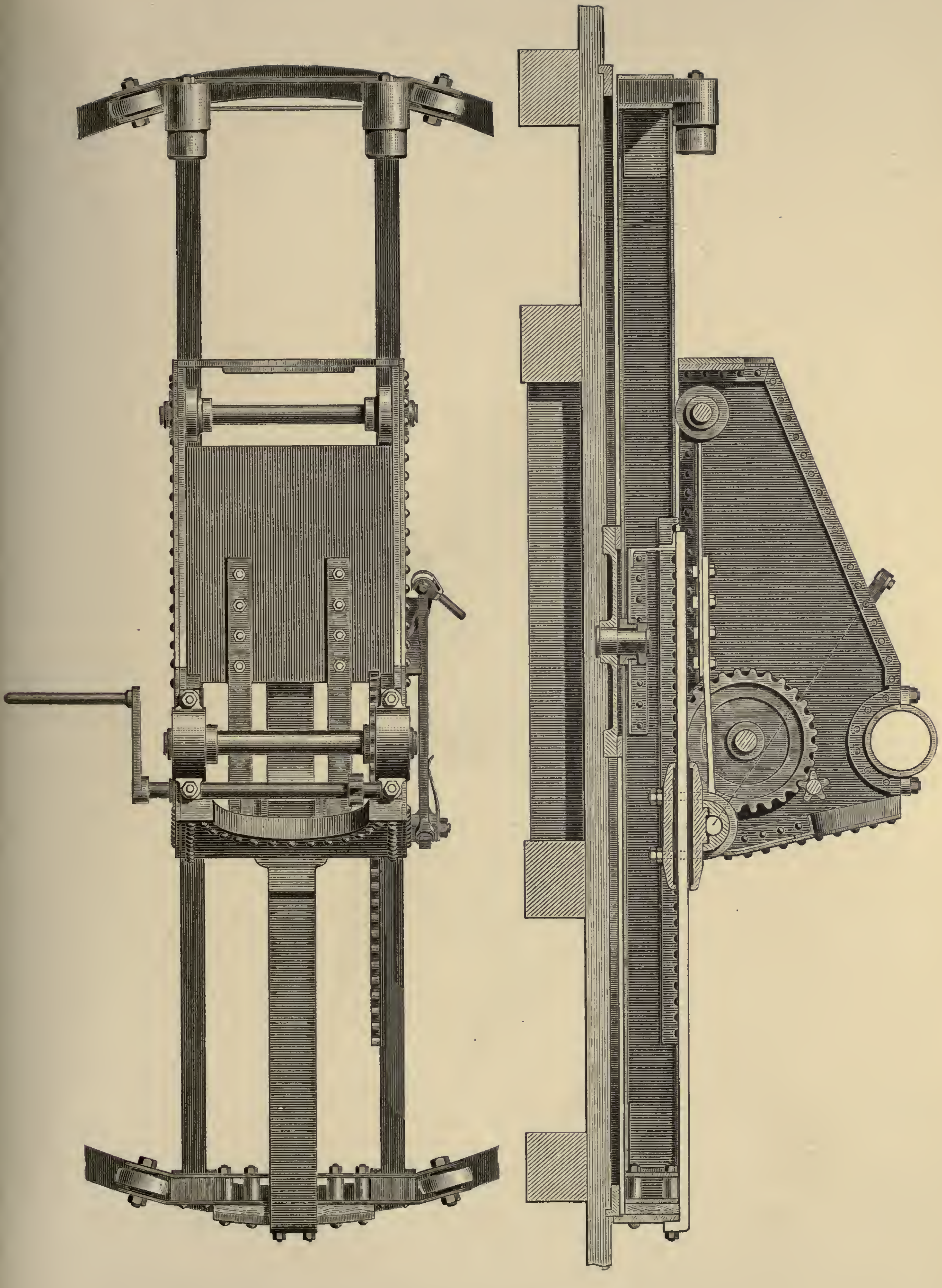


PLATE 58. SEE CHAP. XXXVIII.

Rotary Gun-Carriage and Transit Platform applied to the Spanish Gunboat "Tornado."

Designed by John Ericsson. Built at New York, 1873.

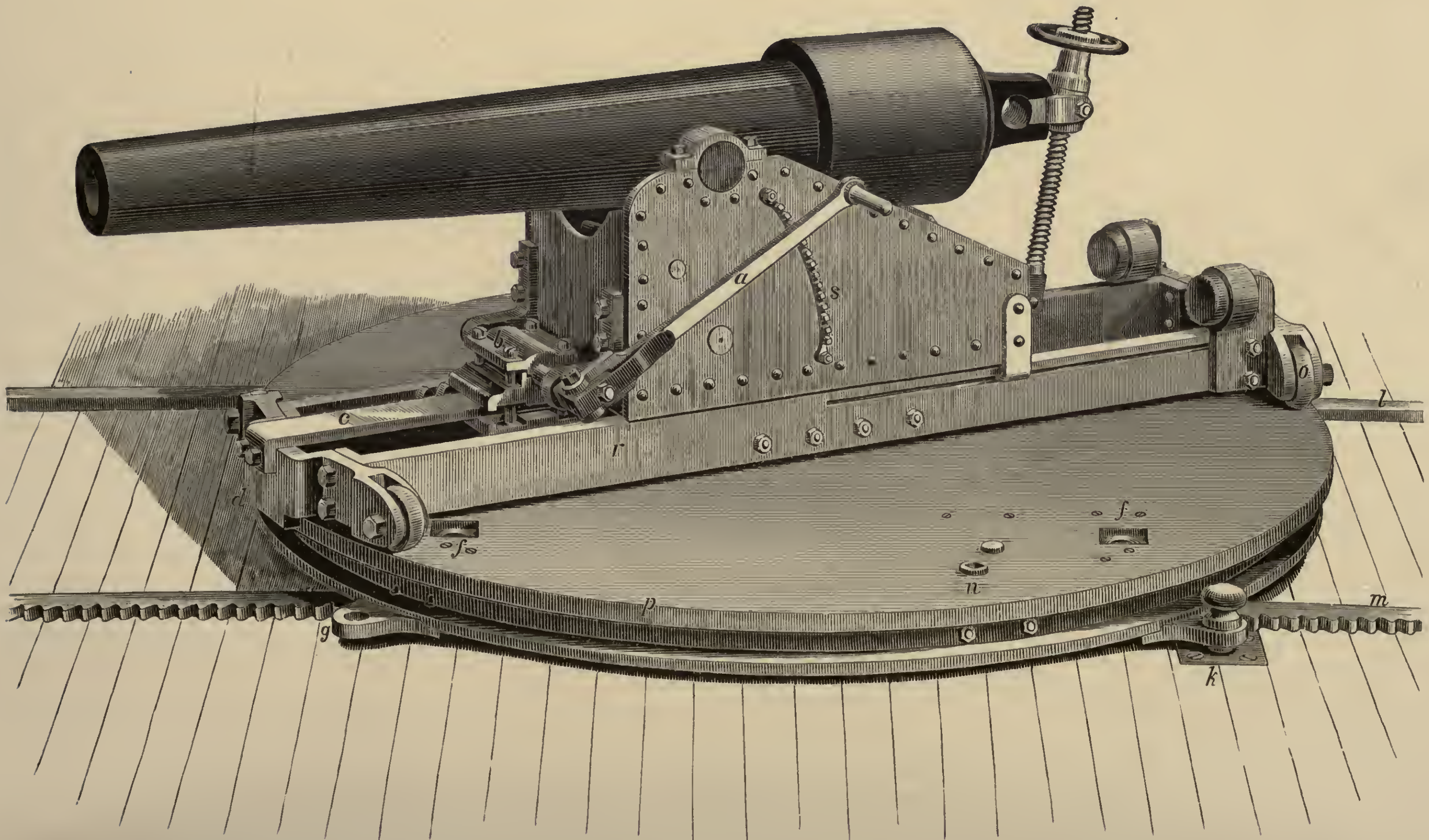
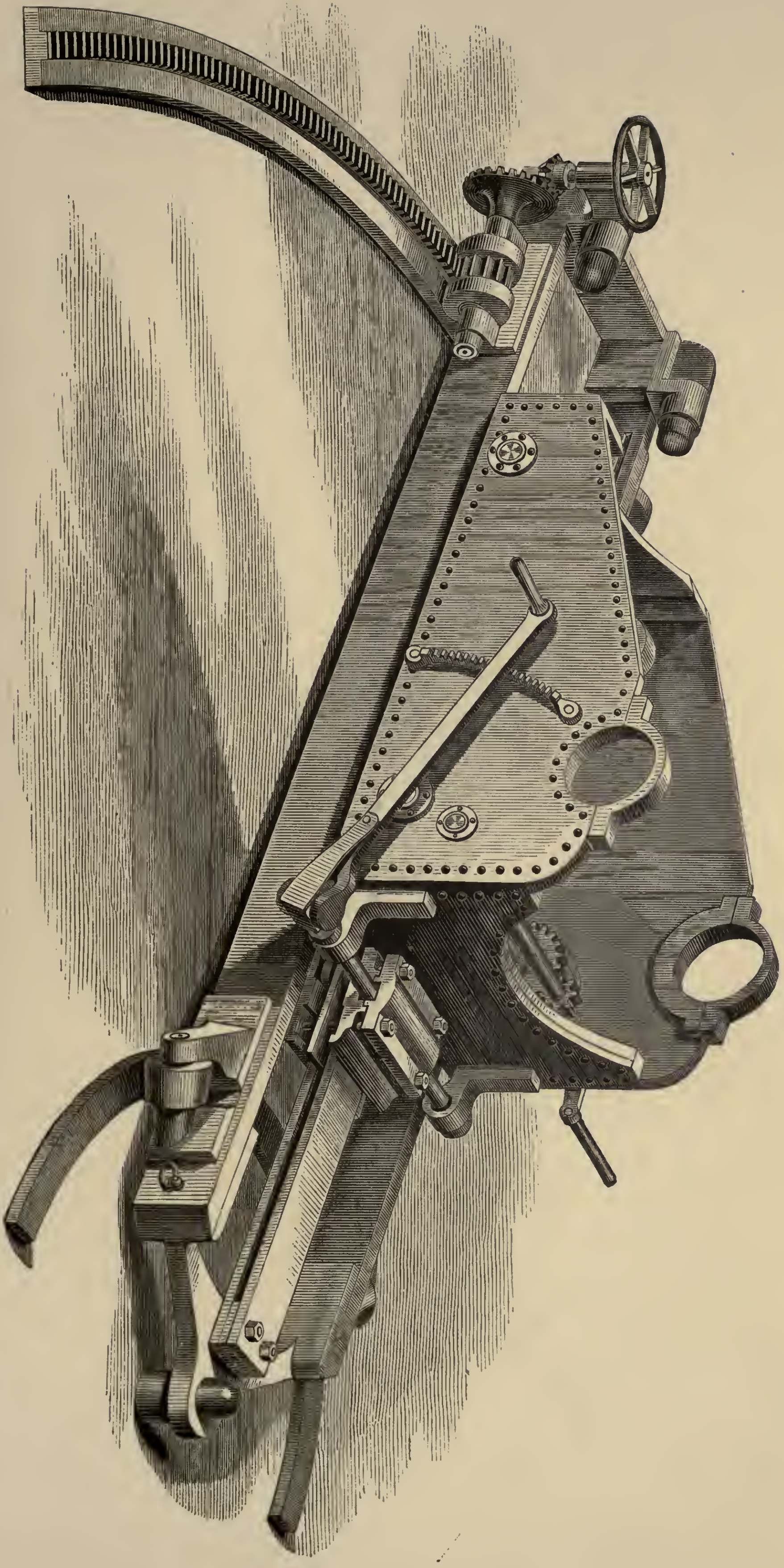


Plate 59. See Chap. XXXIX.



Gun-Carriage for Coast Defence. Designed by John Ericsson. Built at New York, 1872.

Plate 60. See Chap. XL.

The Spanish Gunboat Engines. Designed by John Ericsson.

Built at New York, 1869.

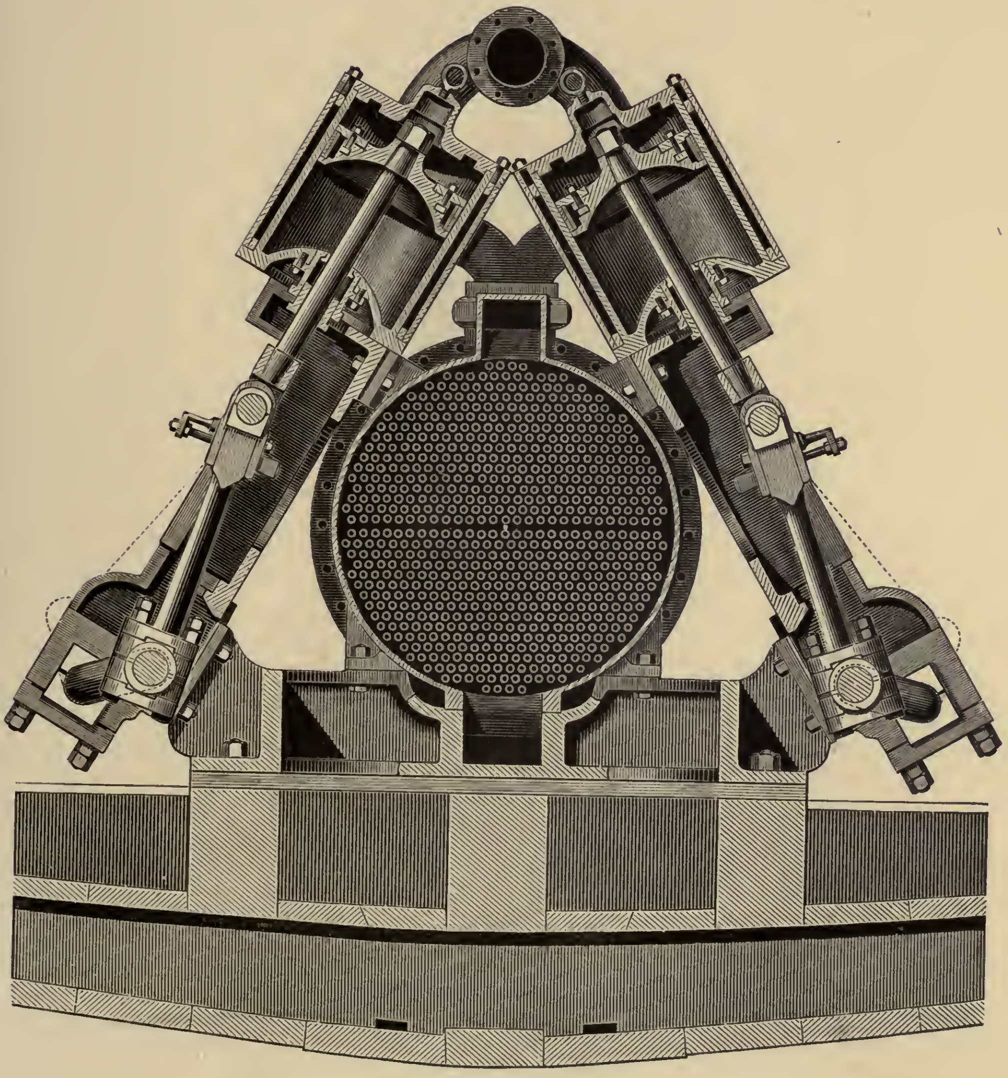


Plate 61. See Chap. XLI.

A New System of Naval Attack. Planned by John Ericsson. Published 1870.

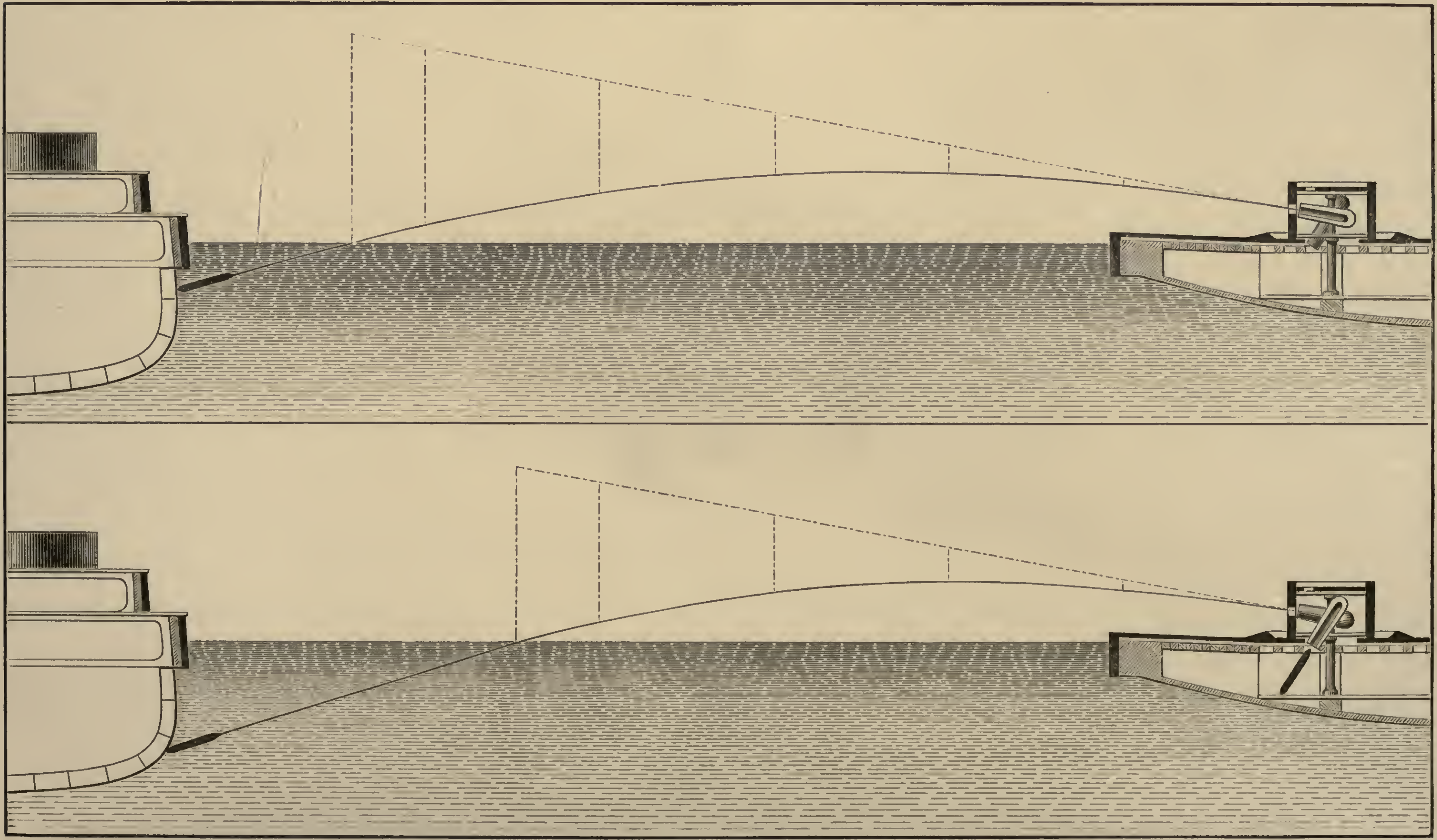


Plate 62. See Chap. XLII.

MOVABLE TORPEDO. DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1873.

FIG. 1.

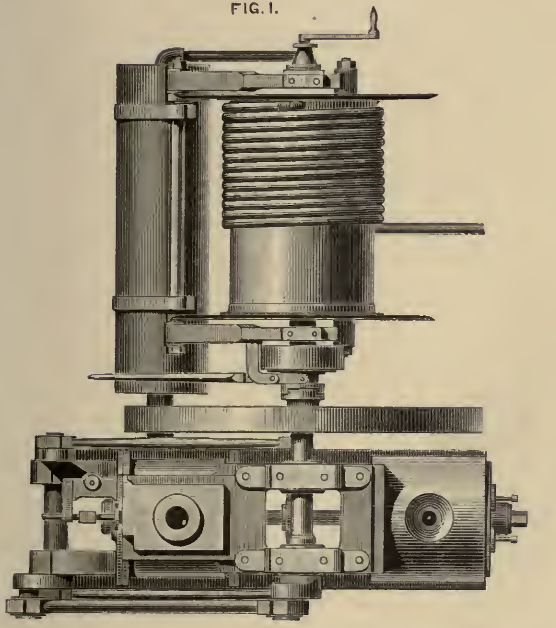


FIG. 2.

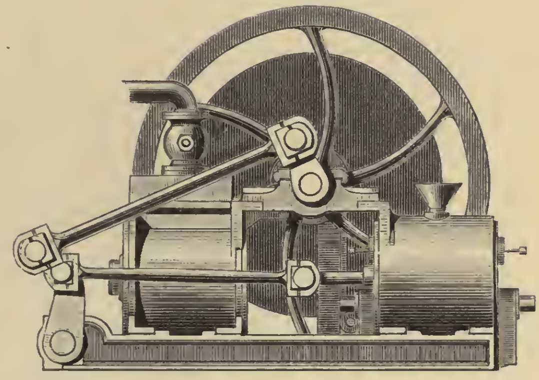


FIG. 3

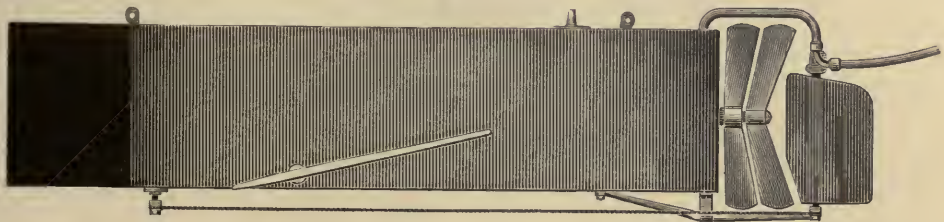


FIG. 4.

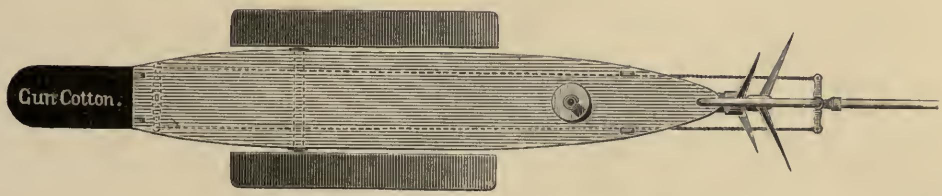


PLATE 63. SEE CHAP. XLIII.

AIR-COMPRESSOR, FOR THE TRANSMISSION OF MECHANICAL POWER.

DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1873.

PERSPECTIVE VIEW.

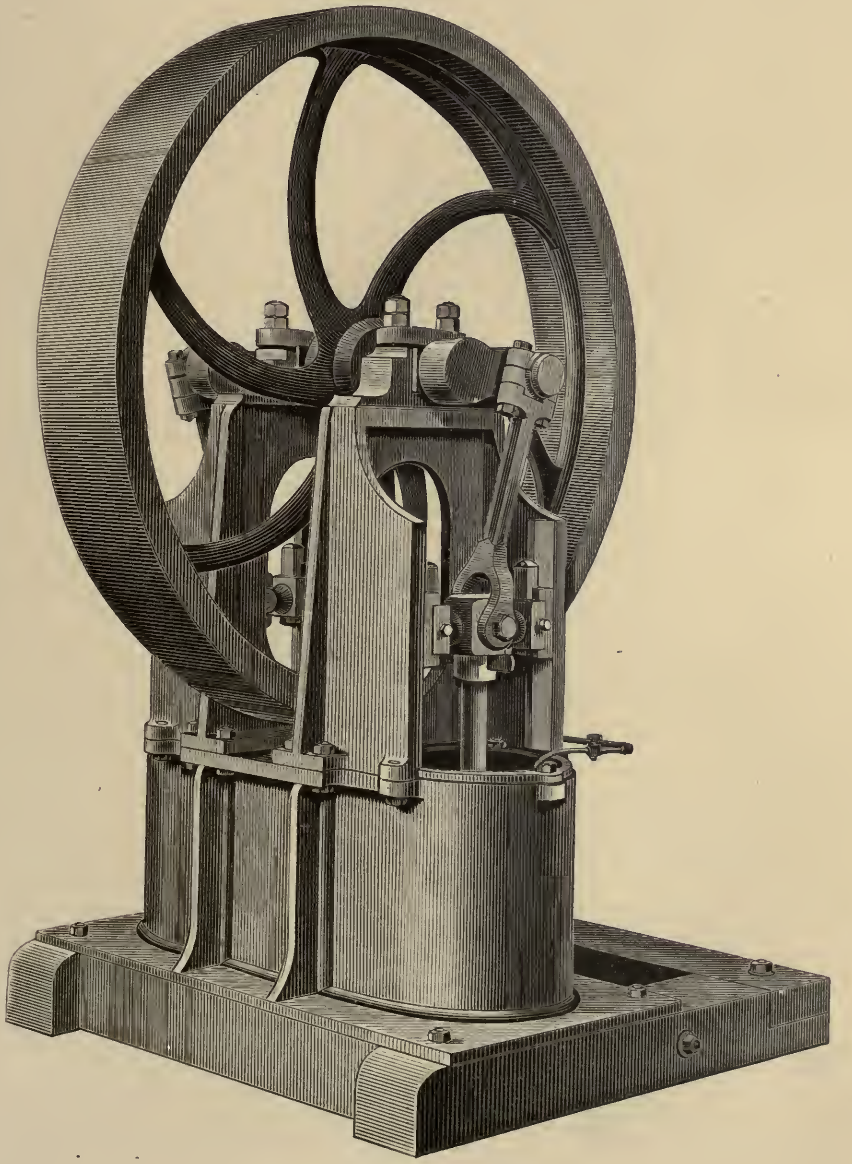


PLATE 64. SEE CHAP. XLIV.

AIR-COMPRESSOR, FOR THE TRANSMISSION OF MECHANICAL POWER.

DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1873.

TRANSVERSE SECTION.

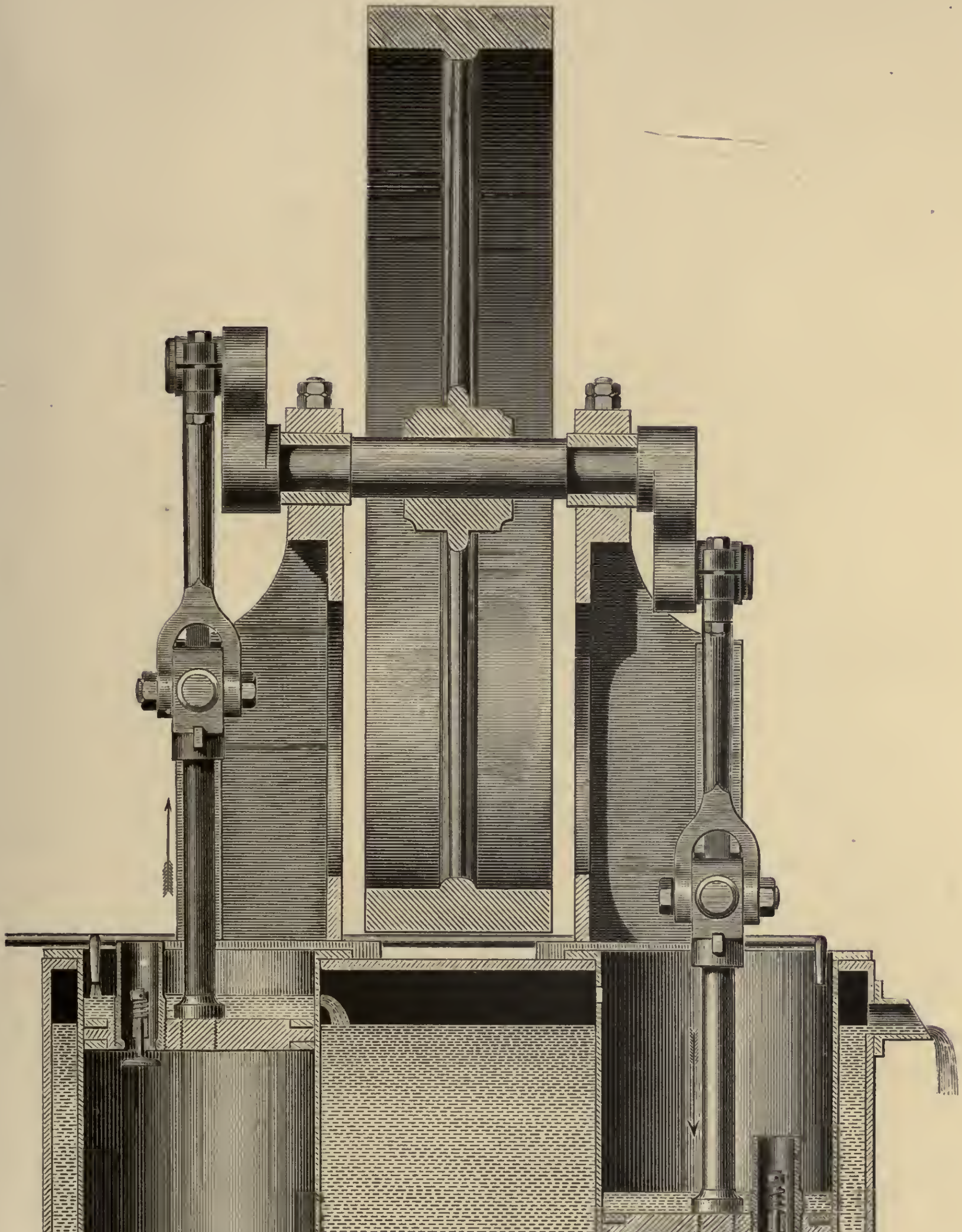
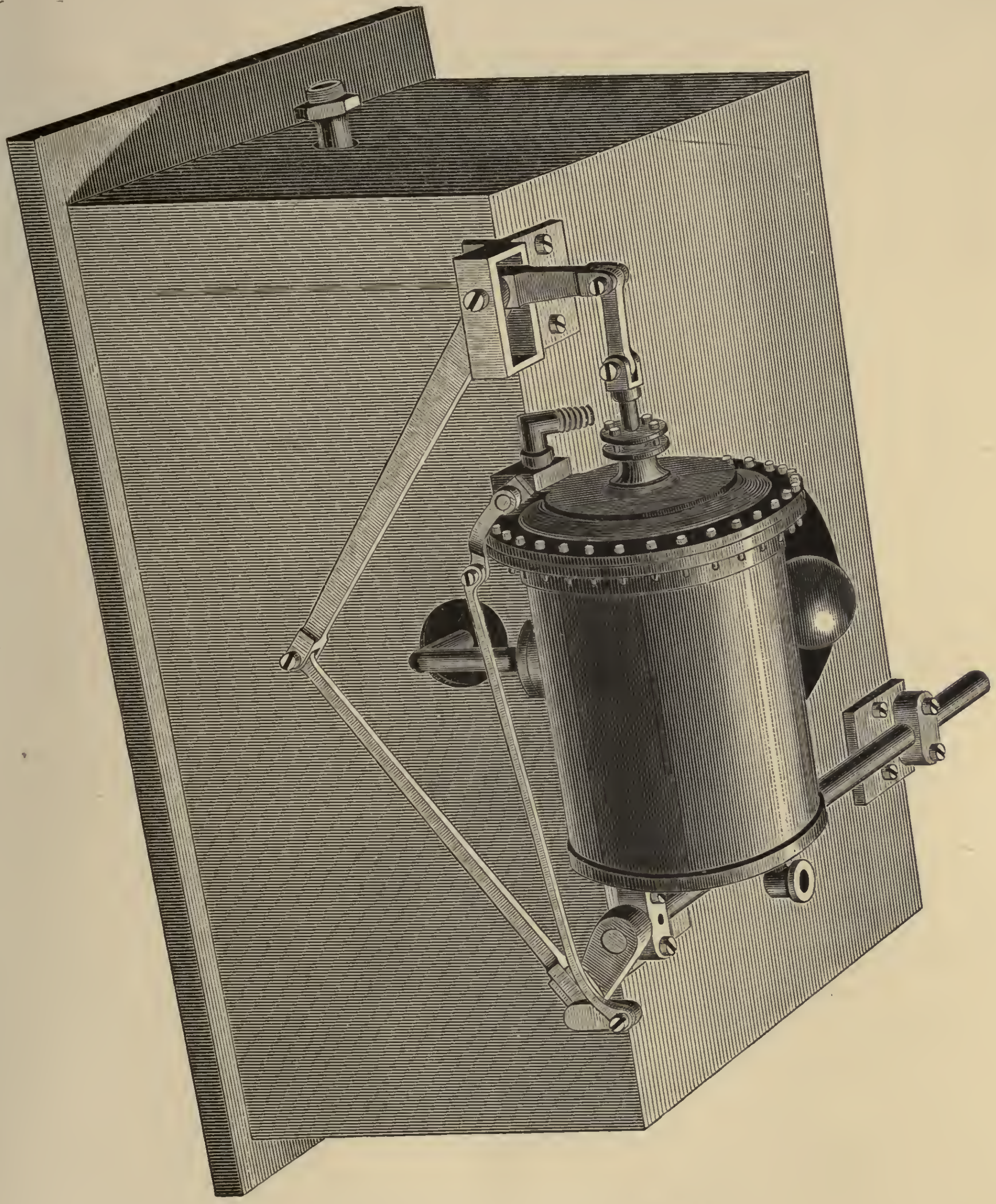


PLATE 65. SEE CHAP. XLIV.



Designed by John Ericsson. Built at New York, 1870.

Plate 66. See Chap. XLV.

SOLAR ENGINE, OPERATED BY THE INTERVENTION OF ATMOSPHERIC AIR.

DESIGNED BY JOHN ERICSSON. BUILT AT NEW YORK, 1872.

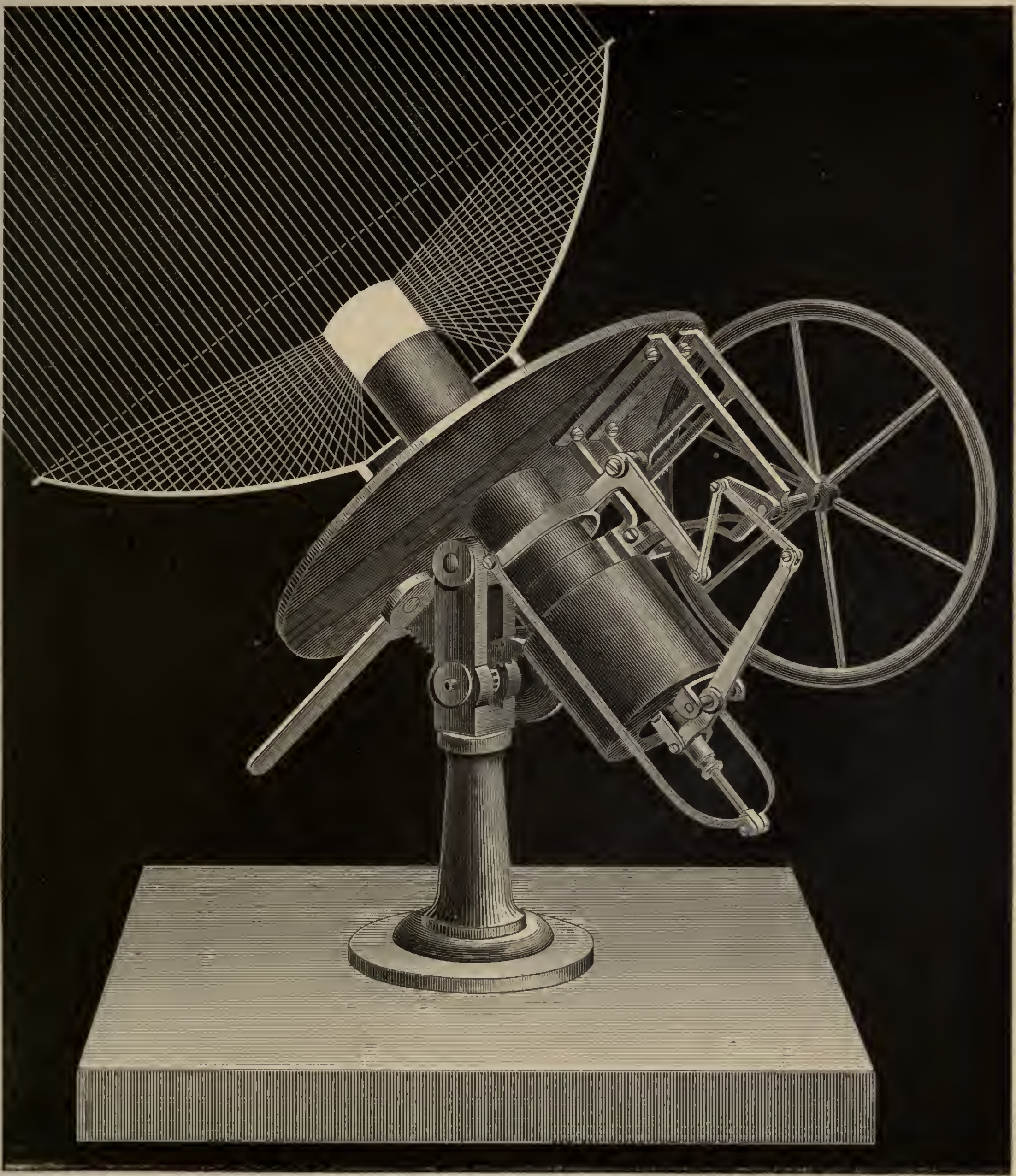


PLATE 67. SEE CHAP. XLV.