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A RESPIRATION CALORIMETER

WITH APPLIANCES

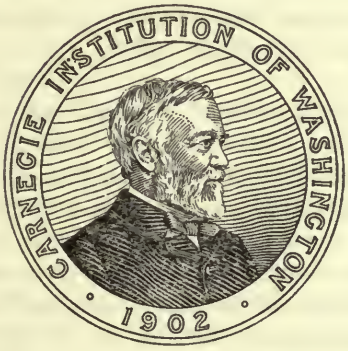
FOR THE

DIRECT DETERMINATION OF OXYGEN

BY

W. O. ATWATER and F. G. BENEDICT

OF WESLEYAN UNIVERSITY



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PREFACE.

The apparatus to be described in this report has been in process of development for twelve years. During this time the resources of Wesleyan University have been supplemented by appropriations from the United States Department of Agriculture and the Connecticut (Storrs) Agricultural Experiment Station, and by contributions from private individuals. In aid of a series of experiments with the apparatus in its earlier stages, grants from the Elizabeth Thompson Science Fund and the Bache Fund were obtained. The addition of the apparatus for the determination of oxygen was made possible by liberal grants from the Carnegie Institution of Washington.

In the development of apparatus necessarily so elaborate as this the active coöperation of a skillful instrument builder is absolutely essential. It has been our good fortune to have the service of Mr. S. C. Dinsmore, whose mechanical skill has insured the successful operation of many parts of the apparatus. Dr. Paul Murrill, formerly associated with this research, rendered invaluable assistance in devising the methods of computation. Mr. R. D. Milner and Mr. H. L. Knight have assisted materially in the preparation of this report.

Dr. E. B. Rosa, physicist of the National Bureau of Standards, but previously professor of physics at Wesleyan University, was actively engaged in this investigation in its earlier stages and has subsequently from time to time given advice which has assisted greatly in the furtherance of the work.

The first grant of the Carnegie Institution for the development of the apparatus for the direct determination of oxygen was made to my colleague, Prof. W. O. Atwater. It was then expected that the report containing the description of the apparatus would be issued under the joint authorship of Professor Atwater and the writer. It has been deemed fitting, therefore, to retain his name on the title page of this report. A serious illness has compelled his untimely retirement from the work, and the writer, who has had the personal supervision of the development of the apparatus since 1895, has continued the research.

Inasmuch as this report has been written, some of the apparatus herein described has been developed, and the experiment with man has been carried out subsequent to Professor Atwater's retirement, the writer assumes full responsibility for this report as it stands, and against him alone should adverse criticism be directed.

FRANCIS GANO BENEDICT.

August, 1905.

CONTENTS.

Page

Introduction 1–4
The respiration calorimeter 4–11
Description of the apparatus in its earlier form 5
Description of laboratory and arrangement of apparatus 7
The respiration apparatus 11–56
General principle 11
The respiration chamber 12
Openings in the chamber 13
Window 13
Food aperture 14
Air-pipe openings 14
Opening for weighing apparatus 16
Opening for the water-pipes 16
Rod for adjusting position of shields 17
Electric-cable tube 17
Piping and valves to the blower 17
The rotary blower 18
Mercury valves 20
Apparatus for the determination of water 23–27
Collection of drip 23
Removal of water vapor from the air current 24
Description of the water-absorbers 24
Durability of the water-absorbers 26
Efficiency of the water-absorbers 26
Supply of sulphuric acid 27
Apparatus for the determination of carbon dioxide 27–31
Description of the carbon-dioxide absorbers 27
Vise for tightening absorbers 28
Removal of spent soda lime from the absorbers 29
Preparation of soda lime 29
Efficiency of the carbon-dioxide absorbers 30
Testing the water and carbon-dioxide absorber system 32
Maintenance of the supply of oxygen 32
Analysis of oxygen 34
Preparation of the reagents 37
Converting percentage by volume to percentage by weight 38
Computation of percentage of nitrogen by weight, using factors 38
The tension equalizers 39
Calibration of the pans 41
Possibility of noxious gases in the system 42
Acid fumes carried over by air current 42
Mercury vapor in the air 42
Proportion of water vapor in the air 43

Page

The respiration apparatus—Continued.
Apparatus for the analysis of the residual air 44–56
Apparatus for absorption of water 45
Efficiency of absorption 45
Apparatus for carbon-dioxide absorption 46
Efficiency of absorption 46
The Elster meter 46
Calibration of Elster meter 47
Test for saturation of air passing through the Elster meter 47
Apparatus for drawing sample 48
Apparatus for constant water pressure 50
Process of taking residual samples 50
Sampling the air for the determination of oxygen 51
Method of sampling 52
The analysis of air 53
Accessory apparatus 56–62
Balances 56–58
Analytical 56
Balances for weighing the carbon-dioxide and water absorbers, oxygen cylinders, etc 56
Weights 58
The barometer 60
Observation of temperature 61
Calculation of results 63–95
Amount of water absorbed 63
Amount of carbon dioxide absorbed 65
Amount of oxygen admitted 65
Residual analytical data 66
Data for the rejection of air 67
Corrections for variations in volume and composition of residual air 67–83
Necessity for residual analyses 67
Possibility of leakage 68
Factors used in the calculation of the residual analyses 69
Volume of air in air-circuit 69
Volume in chamber 69
Volume of air in air-pipe from chamber, mercury valves, and blower 70
Volume of air in water-absorbers 70
Volume of air in carbon-dioxide absorbers 70
Volume of remainder of air system 71
Volume of objects in the chamber not permanent 71
Volume in an alcohol check experiment 71
Volume in experiments with man 72
Fluctuations in the air volume 72
Volume in the pans 72
Compression of air in absorbing system. 73

Page

Calculation of results—Continued.
Correction for mercury valve..... 74
Increase in volume of the water-absorbers..... 74
Fluctuations in volume of the carbon-dioxide absorbers..... 74
Interchange of air through the food aperture..... 75
Addition of nitrogen with the oxygen.. 77
The rejection of air..... 77
The respiratory loss..... 79
Subdivision of air volumes..... 80
Composition gradient of air in the closed circuit..... 81
Data used in calculating relation of weights and volumes of gases..... 82
Calculation of residual analyses..... 83–95
Volume of the sample..... 83
Calculation of true volume of sample for determination of carbon dioxide and water..... 85
Calculation of the true volume of air in the closed air-circuit..... 86
Total residual water vapor..... 87
Total residual carbon dioxide..... 87
Oxygen and nitrogen..... 88
The nitrogen in the system..... 88
Calculations for nitrogen..... 89
Calculations for total residual oxygen... 89
Accuracy of calculations of the residual amount of oxygen..... 91
Thermal gradient inside the chamber.. 91
Conclusions regarding the accuracy of the oxygen computation..... 92
Check on the computation method of determining oxygen..... 93
Computation of the total carbon-dioxide and water output and oxygen intake..... 93
Total carbon-dioxide output..... 93
Total output of water vapor..... 94
Computation for total intake of oxygen. 95
Alcohol check experiments..... 96–105
Kind of alcohol used..... 96
Determination of specific gravity..... 97
Alcoholometric tables..... 98
Factors for the actual amounts of carbon dioxide, water, and oxygen..... 98
Alcohol lamp..... 99
Frequency and duration of experiments.. 102
Calculation of the alcohol check experiments..... 102
Determination of carbon dioxide..... 103
Determination of water..... 104
The computations for oxygen..... 104
The calorimeter system and measurements of heat..... 106–169
General principle of the calorimeter..... 106
The calorimeter chamber..... 107
Wooden walls surrounding the chamber..... 107
Air-spaces and heat insulation..... 111

Page

The calorimeter system and measurements of heat—Continued.
Facilities for removing metal chamber..... 112
Methods of preventing gain or loss of heat to the chamber..... 112–123
Prevention of gain or loss through the metal walls..... 112
The thermo-electric elements..... 113
Construction of the elements..... 113
Method of installing elements..... 113
Distribution of elements..... 115
Electrical connection of the elements. 116
Heating and cooling the air-space..... 117
Heating circuits..... 117
Cooling circuits..... 118
Temperature regulations in the outer air-space..... 119
Gain or loss of heat through openings in the chamber..... 120
Gain or loss of heat through the air current. 122
Measurement of heat..... 123–150
The heat-absorbing system..... 123
Regulation of rate of absorption of heat. 125
Supply of water for measuring heat..... 126
Water coolers..... 126
Water meter..... 126
Calibration of the meter..... 132
Accuracy of the meter..... 132
Check measurements of the accuracy of the meter..... 133
Thermometers for measuring temperature of water..... 133
Correction for pressure of water on the mercury bulb..... 134
Measurement of temperature of the calorimeter..... 134
Observer's table..... 136
Electrical connections on the table..... 138
Mercury switch and bridge..... 139
Determination of the quantity of heat eliminated..... 150–169
Latent heat of water vapor..... 150
Sensible heat removed in water current... 151
Unit of heat..... 151
Calculation of the quantity measured... 151
Corrections to measurements of heat 152–167
The hydrothermal equivalent of the calorimeter..... 152
Corrections for temperature of food and dishes..... 153
Adiabatic cooling of gases..... 154
Correction for heat absorbed by bed and bedding..... 154
Correction for change of body temperature and body weight..... 155
Measurement of body temperature... 156
Weighing objects inside the chamber.. 157
Description of weighing apparatus... 158
Weighing the absorbing system..... 161
Routine of the weighings..... 163
Checks on the accuracy..... 164

Page
The calorimeter system and measurements of heat—Continued.
The ergometer..... 164
Correction for the magnetization of the fields of the ergometer..... 166
Blanks used for heat records..... 166
Tests of the accuracy of the heat-measuring apparatus..... 169–176
Electrical check tests..... 169–174
Electrical unit used..... 171
Length and duration of experiments..... 173
Results of electrical check experiments... 174
The combustion of ethyl alcohol as a check on the heat measurements..... 174–176
Heat of combustion of alcohol..... 175
Results of alcohol check experiment..... 176
Experiment with man..... 177–193
Measurement of intake and output of material..... 177
Measurement of intake and output of energy..... 178

Page
Experiment with man—Continued.
Analytical methods..... 178
Metabolism experiment No. 70..... 178–193
Subject..... 178
Food..... 179
Routine of experiment..... 179
Statistics of food, feces, and urine..... 180
Statistics of water eliminated..... 181
Statistics of carbon dioxide eliminated... 182
Statistics of oxygen consumed..... 183
Respiratory quotient..... 184
Summary of calorimetric measurements..... 185
Intake and output of material and energy..... 187
Gains and losses of body material..... 187
Body weight..... 190
Intake and output of energy..... 190
Calculations of energy of body material gained and lost..... 192
Conclusion..... 193

ILLUSTRATIONS.

		Page
FIG. 1.	General plan of the respiration calorimeter laboratory	8
2.	The laboratory room. View from southeast corner	10
3.	The laboratory room. View from east side	10
4.	The laboratory room. View from near sink	10
5.	The laboratory room. View from alcove	10
6.	Diagram of the circulation of air through the respiration apparatus	11
7.	Interior of the respiration chamber	12
8.	Horizontal section of respiration calorimeter chamber	15
9.	Rotary blower	16
10.	Mercury valves	21
11.	Water-absorbers	26
12.	A carbon-dioxide absorber	26
13.	Cross-section of carbon-dioxide absorber	28
14.	Vise for tightening carbon-dioxide absorbers	32
15.	An oxygen cylinder with valve, rubber pressure bag, and purifying attachments	32
16.	Apparatus for analysis of oxygen and air	32
17.	Pans for equalizing pressure	44
18.	Apparatus for analysis of residual air	44
19.	Apparatus for drawing sample of air for residual analysis	49
20.	Water-pressure system	51
21.	Balance for weighing absorbers and oxygen cylinders	58
22.	Alcohol lamp and connections	100
23.	Vertical cross-section of calorimeter chamber through the end	109
24.	Vertical (side) cross-section of calorimeter chamber	110
25.	Rear view of calorimeter chamber	110
26.	A thermo-electric element	114
27.	Thermo-electric element mounted on wooden rod	114
28.	Method of installing thermo-electric elements in metal walls	114
29.	Side view of metal chamber rolled out on tracks	116
30.	Front view of metal chamber removed from wooden casing	116
31.	Details of interior of wooden casing	118
32.	Sectional view of walls of chamber, showing method of installing air-pipes, water-pipes, and rod for raising and lowering shields	124
33.	Interior of respiration calorimeter chamber	124
34.	The water-meter	126
35.	The water-meter. Diagrammatic sections showing front and side views	128
36.	Clutch to regulate tension on water-meter	130
37.	Observer's table	136
38.	Electrical connections on observer's table	138
39.	A unit key of the mercury switch	140
40.	The mercury switch, top removed	140
41.	A general view of mercury switch	140
42.	Under side of mercury switch showing electrical connections	140
43.	Diagram of electrical connections of mercury switch	142
44.	Diagram of simple form of Wheatstone bridge	144
45.	The rectal thermometer	156
46.	Weighing apparatus for objects inside the chamber	159
47.	The bicycle ergometer	164
48.	The electric counter	164
49.	Connections for an electrical check experiment	170

A RESPIRATION CALORIMETER, WITH APPLIANCES FOR THE DIRECT DETERMINATION OF OXYGEN.

By W. O. ATWATER and F. G. BENEDICT.

INTRODUCTION.

For a proper understanding of the metabolism or transformations of matter and energy in the body, a knowledge of both total income and total outgo is indispensable. Physiologists and physicians have long been accustomed to depend very largely upon data from the analysis of urine for information regarding the metabolism of matter, especially of proteid, in the body. In many cases, aside from gross or approximate estimates of the quantities of food ingested, they made no attempt to determine the income, and the outgo of material in the feces was, as a rule, entirely neglected. In a study of the metabolism of proteid in the body the analyses of the urine have a very great significance, which in the light of recent researches, such as those of Folin[1] and Burian,[2] is becoming even more intelligently comprehended. But it has been long understood that many other transformations of matter besides those in which the element nitrogen is involved occur in the body, for the proper study of which a knowledge of the income of carbon, hydrogen, oxygen, water, and mineral matters, in addition to that of nitrogen, is necessary; and, since the disintegration of the proteids as well as of the fats and carbohydrates of the body is accompanied by an absorption of oxygen from the air and an elimination of carbon dioxide and water, our knowledge of the outgo must include not only the quantity of nitrogen in the urine, but also the amounts of carbon dioxide and water excreted by the lungs and skin, and of the carbon, hydrogen, oxygen, and mineral matters of both urine and feces.

Furthermore, for many purposes the measurement of intake and output of matter is not wholly sufficient, but must be supplemented by determinations of the transformations of energy, because one of the chief functions of food is to supply the body with energy. Moreover, the study of the transformations of matter is rendered more complete and intelligible by a knowledge of the transformations of energy.

[1] Amer. Journ. Physiol. (1905), **13**, pp. 45–115.
[2] Zeits. f. physiol. Chem. (1905), **43**, p. 532.

Experiments in which the balance of income and outgo of nitrogen alone is determined are comparatively simple. The intake of nitrogen is that in the food and drink; and since it is commonly accepted by physiologists that none of the nitrogen from food or body material is eliminated in gaseous form, the only sources of output which are ordinarily considered are the urine and feces. Doubtless because of the ease with which such experiments may be conducted, the number of nitrogen metabolism experiments that have been made is very large.

For a study of the metabolism of fats and carbohydrates, however, an estimate of the gaseous output of the respiratory products, *i. e.*, carbon dioxide and water, and of the intake of oxygen, is, as has been stated, also necessary, in addition to the analyses of food, drink, and excreta. These determinations can not be even approximated without the use of apparatus specially constructed for the purpose, known as respiration apparatus, which is usually of necessity somewhat complicated.

For the determinations of income and outgo of energy, which is measured in terms of heat, special forms of apparatus, designated calorimeters, are necessary, and these are likewise complicated.

Since the more complete metabolism experiments are not so easily carried on, they are much less numerous than the simpler nitrogen metabolism experiments; still the number in which more or less complete balances of income and outgo of matter, or energy, or even both, have been determined is relatively large, and several different forms of respiration apparatus and calorimeters have been used. It is not possible to give here a detailed historical review of the development of such apparatus, and indeed it is hardly necessary, as extensive bibliographies and descriptions have been published elsewhere. It will be sufficient for the present purpose to mention these and to point out the different types of apparatus.

Accounts of various types of respiration apparatus have been compiled by Zuntz[1] and Jaquet.[2] The various forms of apparatus which are of sufficient size to permit study of the respiratory changes in man or large animals may be divided into four classes.

In the first class the subject is confined in a closed chamber for varying periods of time. The carbon-dioxide content of the air is determined at the beginning and again at the end, and the volume of the inclosed space being known, the amount of carbon dioxide eliminated during this period is thereby readily calculated. The apparatus of Chauveau[3] and Laulanié[4] were constructed on this plan.

[1] Hermann's Handbuch der Physiologie, **4**, part 2, pp. 88–162.
[2] Ergeb. der Physiol. (1903), **2**, part 1, pp. 458–469.
[3] Traité de Physique Biologique, **1**, p. 744.
[4] Éléments de Physiologie, p. 355.

The second type of apparatus is known as the "closed circuit." The subject is placed in a chamber through which a current of air is passed. The air leaving the chamber is purified by the removal of the carbon dioxide (and in some instances water), replenished with oxygen, and returned to the chamber. This type of apparatus was that originated by Regnault and Reiset.[1] It has been further developed by Hoppe-Seyler and Stroganow,[2] and in principle is the basis of the apparatus to be described later in this report. This method permits of the determination of carbon dioxide, water, and oxygen.

A third form of respiration apparatus is that known as the "open circuit." The subject is placed in a closed chamber through which a current of air is drawn, the incoming and outgoing air being analyzed. This type of apparatus was first brought into successful use by Pettenkofer,[3] and was afterward elaborated for use with man by Sondén and Tigerstedt,[4] and by Atwater, Woods, and Benedict.[5]

It is interesting to note that Jaquet,[6] by using a modification of the apparatus of Petterson for exact gas analysis, has undertaken the determination of oxygen consumed by man in an "open-circuit" apparatus.

The fourth type of apparatus is used primarily for short experiments. By means of appliances attached to the mouth or nose the subject is supplied with normal air of known composition and the products of respiration are collected for analysis. With this apparatus it is possible to determine the oxygen absorbed and the carbon dioxide exhaled. This type has been perfected to a high degree by Zuntz[7] and by Chauveau and Tissot.[8]

The development of calorimetric apparatus for use with animals and with man has been far less extensive than that of respiration apparatus. A summary of the methods and results of experiments on the income and outgo of heat of the animal body, which includes the work done up to about 1882, was published by Rosenthal.[9] A description and discussion of more recent types of calorimeters is given by Laulanié,[10] and also by Sigales.[11] One of the earliest forms suitable for use with man and the larger animals was devised by Scharling[12] in 1849. The subject

[1] Ann. de Chim. et Physique (1849), **3**, xxvi.
[2] Archiv. f. d. ges. Physiol. (1876), **12**, p. 18.
[3] Ann. der Chem. u. Pharm. (1862–3), Supp. **2**, p. 17.
[4] Skand. Archiv. f. Physiol. (1895), **6**, p. 1.
[5] U. S. Dept. of Agr., Office of Experiment Stations Bull. 44.
[6] Verhandlungen der naturforschenden Gesellschaft in Basel, **15** (1904), part 2, p. 252.
[7] Berl. klin. Wchnschr. (1887), p. 429.
[8] Comptes rendus (1899), **129**, p. 249.
[9] Hermann's Handbuch der Physiologie, **4**, part 2, pp. 289–456.
[10] Éléments de Physiologie, pp. 556–565.
[11] Traité de Physique Biologique, **1**, pp. 816–843.
[12] Journ. f. prakt. Chem. (1849), **48**, p. 435.

was placed in a closed chamber inside a larger room of constant temperature. The rise in temperature of the inner chamber was noted and the heat emission thereby calculated. Similar types have been those of d'Arsonval,[1] Hirn,[2] and Vogel.[3]

The newer forms are of two types: First, those in which the heat delivered from the body is lost through the walls by radiation and the calorimeter calibrated by determining the radiation constant; and, second, those in which the heat developed is brought away by a cooling current of water flowing through the calorimeter chamber, the radiation constant being eliminated as far as possible. One of the most recent forms of the first type of apparatus is the "emission" calorimeter of Chauveau;[4] the second type is that employed originally by Atwater and Rosa,[5] and in its more developed form is to be described beyond.

THE RESPIRATION CALORIMETER.

As has been stated, the more satisfactory experiments are those in which the transformations of both matter and energy are studied. For such experiments it is essential that the apparatus used be so constructed as to afford opportunity for measuring at the same time both the respiratory products and the energy given off from the body. Among the various forms of apparatus referred to in the preceding paragraphs some were so constructed, and such is especially the case with the apparatus here to be described. To indicate its twofold function as a respiration apparatus and as a calorimeter, it is designated a "respiration calorimeter." As will be explained in detail, the respiration apparatus is of the "closed-circuit" type of Regnault and Reiset; the calorimeter is a constant-temperature, continuous-flow water calorimeter.

In addition to the measurements of respiratory products and energy made directly by the apparatus, the experiments include, in determinations of matter, the analyses of the air in the apparatus and measurements of the amounts of oxygen introduced, and the weighing and analyzing of the food, drink, and solid and liquid excreta; and in determinations of energy the measurement of the potential energy, *i. e.*, heats of oxidation, of the solid ingredients of food, drink, and excreta. All these data constitute the factors of total income and outgo of both matter and energy.

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[1] Soc. de Biol. (1894), **27**, 1.
[2] Recherches sur l'équivalent mécanique de la chaleur (1858).
[3] Arch. d. Ver. f. wiss. Heilk. (1864), p. 422.
[4] Comptes rendus (1899), **129**, p. 249.
[5] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63.

Many of the forms of apparatus previously referred to were designed for experiments with lower animals, but some of them were for experiments with man. The particular apparatus here described was of this latter type (though it can be, and indeed in its earlier form has been, readily adapted for use with domestic animals). Experimenting with man necessarily involves certain restrictions, such as the requirement of a varied and palatable diet, a rate of ventilation which shall insure proper purification of the air, an experimental period not unduly long, etc.; but it is obvious that in investigations of the problems of nutrition of man it is a decided advantage to experiment directly with man. Otherwise, if domestic animals were used, it would be necessary to draw conclusions for omnivora (man) from results obtained with carnivora (dogs) or herbivora (sheep or cattle). Furthermore, in experimenting with apparatus as elaborate as this must necessarily be, it is of the greatest value to have the intelligent coöperation of the subject within the apparatus; and the fact that there may be reasonable control of the muscular activity and sleep is also an advantage.

As will be seen from the more detailed description beyond, the chamber of the apparatus is large enough to allow a man to stand or lie down at full length, and to move about to a limited extent, and it is provided with a chair, table, and bed, that may be folded up and put aside when not in use, so that the subject may sit, or lie down, or stand and move about at will, or as the conditions of the experiment prescribe. When the experiment involves muscular work, a suitable device on which work may be performed, and by means of which the amount of work done may be determined, is also provided. A window in one end of the chamber admits ample light for reading and writing, and as it faces a window in the laboratory, even allows something of a view out of doors. A telephone affords opportunity for communication with persons outside the apparatus. The air is kept constantly in circulation, the impurities removed from it, and oxygen restored to it. The temperature of the chamber is maintained very uniform, whatever the conditions of activity of the subject. Receptacles for food, drink, and excreta are introduced or removed through an aperture provided for the purpose. Every attempt is made to keep the subject comfortable and to have the conditions as nearly normal as possible.

DESCRIPTION OF THE APPARATUS IN ITS EARLIER FORM.

The respiration calorimeter at Wesleyan University has been in process of development about twelve years. Several publications describing the earlier form of apparatus, with modifications and improvements, and reporting the experiments made with it, have been issued.

An account[1] of the first form of the apparatus, published in 1897, consists of the description of a respiration chamber on the Pettenkofer principle, the arrangements for ventilating the same, and the accessory apparatus for analyzing the air of the chamber. With this description was included a report of four experiments in which the intake and output of nitrogen, carbon dioxide, and water were determined. Satisfactory determinations of the output of energy by means of the apparatus were not yet possible.

In 1899 a description[2] of the apparatus in its next stage was published. This included a discussion of the measurement of heat eliminated from the body, together with a much more detailed description of the respiration chamber, accessory apparatus, and methods of manipulation and analysis. In this report was given a brief account of two experiments with man in which the balance of intake and output of both matter and energy was determined.

A few months later another report,[3] giving a detailed description of six metabolism experiments with men, including the methods of calculating and interpreting the results, was published; and this was followed in 1902 by a report[4] in which were given the results of twenty-four experiments with men and a general discussion of the same. A more extensive report[5] of the results of twenty-six more experiments with men was published in 1903. This report gives also an account of many improvements and modifications of apparatus that had been developed in the course of the experiments; and as the series of investigations with the respiration calorimeter essentially as originally devised was completed, considerable discussion of general principles and deductions based upon results of the whole six years of experimentation was included.

In addition to the research reported in the publications above referred to, the apparatus has been used for an investigation into the nutritive value of alcohol, the results of which are published in a separate report.[6] This report gives the detailed description and discussion of the results obtained in thirteen experiments with men in which alcohol formed a part of the diet.

None of the experiments above referred to, however, were actually complete metabolism experiments, for the reason that determinations of

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 44.
[2] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63.
[3] U. S. Dept. of Agr., Office of Experiment Stations Bull. 69.
[4] U. S. Dept. of Agr., Office of Experiment Stations Bull. 109.
[5] U. S. Dept. of Agr., Office of Experiment Stations Bull. 136.
[6] W. O. Atwater and F. G. Benedict: Mem. Nat. Acad. Sci. (1902), **8**; U. S. Senate, 57th Cong., first sess., Doc. 233, p. 231. An experimental inquiry on the nutritive value of alcohol.

the amounts of oxygen consumed could not be made. It was believed that with accurate determinations of the quantities of the other elements the quantity of oxygen consumed could be approximately estimated by difference, and in one of the reports above mentioned such estimates were made according to the method elaborated by Rosa.[1] It is obviously much more desirable, however, to be able to make the oxygen determinations directly, the same as those of the other elements. As a result of some eight years of experimenting with the apparatus above referred to, plans were gradually evolved for attempting the measurement of the amount of oxygen consumed by men, and thus obtaining data for the calculation of the respiratory quotient. To do this involved considerable modification of the form of apparatus and the addition of several new accessory devices.

Concurrently with the devising of the above modifications, many appliances were developed to insure greater accuracy in the measurements of heat and to extend the range of the calorimeter sufficiently to afford means of measuring heat at the rate of 600 calories per hour. These fundamental changes extend to all parts of the respiration calorimeter, which is consequently so modified in form and principle from what has been previously described as to render it a new apparatus and to call for a new description.

It is the purpose of the present publication, therefore, to describe in detail the respiration calorimeter as now used. In this description the two functions of the apparatus will be treated separately—first the respiration apparatus, and second the calorimeter. Preliminary to these sections is a description of the laboratory in which the respiration calorimeter is installed.

DESCRIPTION OF LABORATORY AND ARRANGEMENT OF APPARATUS.

The respiration calorimeter here described is located in a room in the northeast corner of the basement of a large stone building, known as Orange Judd Hall, of Wesleyan University, at Middletown, Connecticut. The north and east sides of the room are the masonry of the building, about 75 cm. thick. On the south side of the room is a brick partition, about 42 cm. thick, through which are three openings, one with a door opening into a small room, and the other two leading to an alcove. The west side of the room is a wooden partition with a door and a large glass window. The wooden floor is laid on cement.

There are three windows on the north side, about 130 cm. wide and 150 cm. high, and two windows on the east side, about 130 cm. wide

[1] Physical Review (1900), **10**, p. 129.

and 185 cm. high. The eastern exposure affords direct sunlight until about the middle of the morning. After that time the direct light does not enter, but the room is excellently lighted and the walls and ceiling are painted white to aid in the distribution of the light.

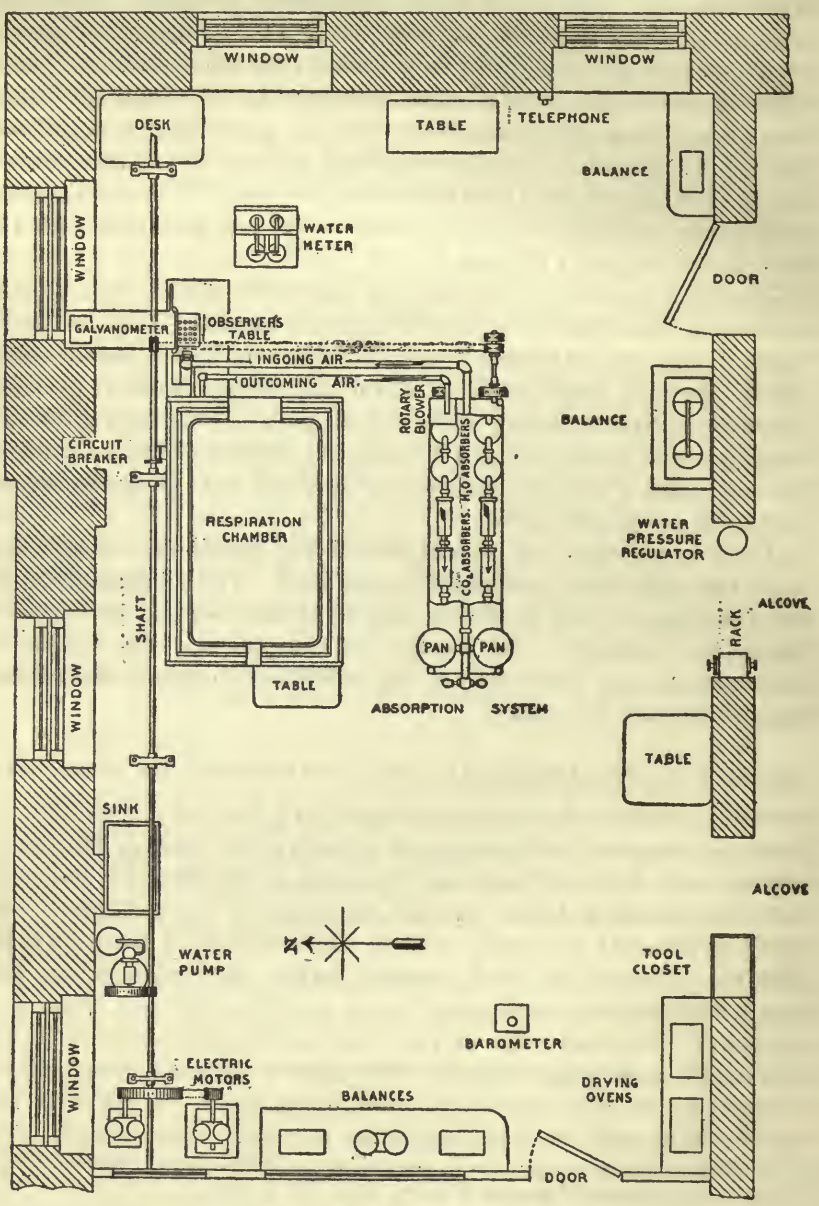

FIG. 1.—General Plan of the Respiration Calorimeter Laboratory.

For protection against severe changes of external temperature during the winter months, double windows are provided. The room is heated by steam-pipes near the ceiling and by gas stoves. Two ventilating fans belted to the main shaft have their blades so adjusted that the warm air at the top of the room is continually forced down. It is possible to keep the temperature of the room comfortable for work, but the regulation is far from that of a constant-temperature room. That accurate calorimetric work can be done in a room with such an uneven temperature is because of the peculiar construction of the calorimeter, as described beyond. The general plan of the laboratory room is shown in figure 1.

The room is entered by the door near the southwest corner. The door near the southeast corner leads into a small annex used for a kitchen, and containing ice-chests and tanks. The two other openings in the south wall lead to an alcove used as a tool and supply room.

The respiration chamber is seen in about the middle of the north side of the laboratory, separated from the north wall by an air-space of about 75 cm. As may be seen in figure 2, the wooden walls surrounding the chamber extend from floor to ceiling. To the south of the respiration chamber, about in the center of the laboratory, is the long table on which are the rotary blower for maintaining a current of air through the apparatus, the absorbers for removing the water vapor and carbon dioxide from the air current, and the appliances for the introduction of oxygen. Suspended from the ceiling at the north side of the laboratory is the shafting by which power from the electric motors on the west side is transmitted to the water-pump and the rotary blower.

The small table at the west of the chamber is convenient for the deposit of articles to be passed into or out of the chamber through the aperture just above it. At the east end of the chamber is the observer's table, and just beside this is the water-meter. Around the walls of the laboratory at convenient points are desks, tables, balances, sink, etc. Near the door entering the laboratory is a barometer, securely attached to stanchions and well isolated from sudden changes in temperature. The rack in one of the entrances to the alcove at the south is for storing extra carbon-dioxide absorbers.

The disposition of the apparatus and accessories in the room was made with a view to facilitating manipulation and to conform to the previously existing shape and construction of the laboratory room, which was in no sense peculiarly adapted for calorimetric work.

A general view of the laboratory room, taken from the southeast window, is shown in figure 2.

In figure 2, the table supporting the absorbing system, the rotary blower, and the apparatus for the introduction of oxygen appear in the center of the foreground. The respiration chamber in its wooden casing, with the glass door in the east end, is immediately at the right, and adjacent thereto are the observer's table and water-meter. The air-pipes conducting air to and from the respiration chamber are suspended near the ceiling and extend across the front end of the chamber. At the left, securely attached to the brick wall, is the balance for weighing the absorbing apparatus. In the rear and immediately at the right of the door is the barometer closet attached to two stanchions.

Another general view of the laboratory, showing more of the detail of the respiration chamber, is given in figure 3. The door of the respiration chamber is open, thus showing a little of the interior. The observer's table, water-meter, and galvanometer hood are at the right, and at the left the absorbing apparatus, rotary blower, and balance are shown.

A view taken from near the sink, figure 4, shows the rear end of the chamber. In the center of this end of the chamber is the opening through which the food and excreta are passed, shown here with the outer door open. On the table immediately beneath it are characteristic vessels used to introduce or remove material from the chamber. The absorbing system is shown immediately at the right. On the end of the absorbing-system table are seen the two pans with rubber diaphragms (one of which is distended) which are used to indicate apparent changes in volume of air in the whole system. Farther at the right is seen the water-pressure regulator standing in the arch leading to the alcove room used for storing apparatus.

The details of the absorbing system are better shown in figure 5, which was taken from a position in the alcove room near the water-pressure regulator shown in figure 4. The smaller of the two pipes near the ceiling at the right conducts the air from the respiration chamber to the rotary blower. The blower forces the air through the absorbers on the table. The air, freed from carbon dioxide and water vapor, then passes upward to the pipe lying on the top shelf of the table, to which the two pans are attached. To the right of the pans the oxygen is supplied to the air in this pipe from the cylinder with a large U tube attached to it, standing upright near the center of the top shelf of the table. After being supplied with oxygen the air proceeds along the horizontal pipe to the end of the table, where it passes through the vertical section, and thence along the ceiling around the corner of the chamber, entering it immediately at the left of the observer's table. The small tubes and the Elster meter at the right, on the top

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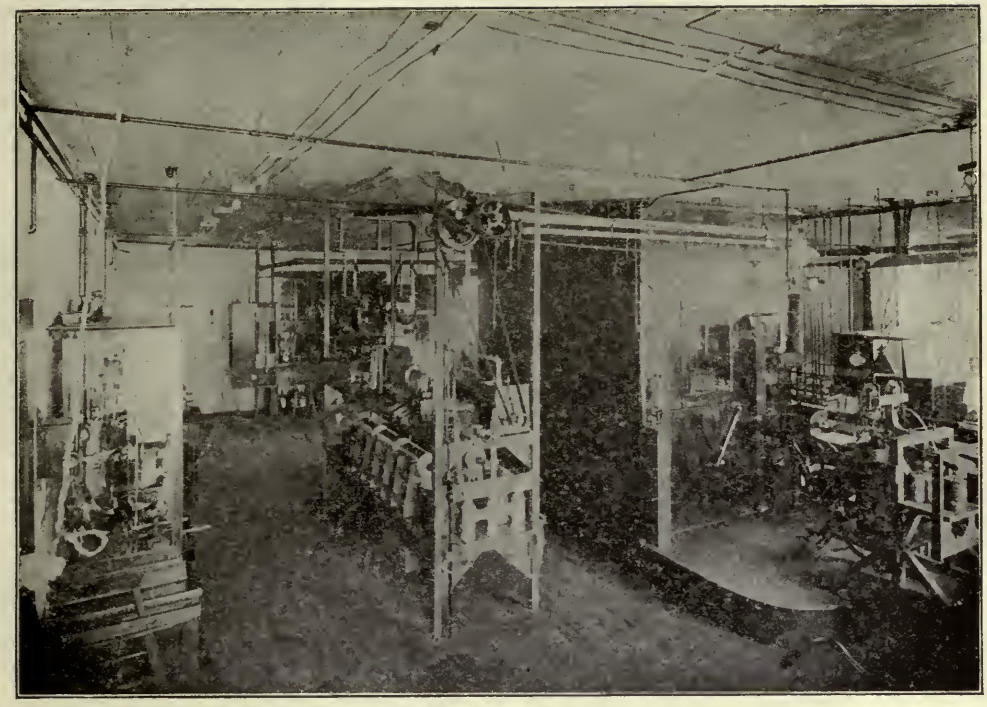

FIG. 2.—The Laboratory Room. View from southeast corner. Respiration Chamber at right; Water and Carbon-Dioxide Absorbing System in center; Balance for Weighing Absorbers at left.

FIG. 3.—Laboratory Room. View from east side. Observer's Table and Water-Meter in foreground; Window of Respiration Chamber open; Absorbing System and Balance at left.

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Fig. 4.—Laboratory Room. View from near the sink. Rear of Respiration Calorimeter Chamber showing Food Aperture. Absorbing System and Pans at right.

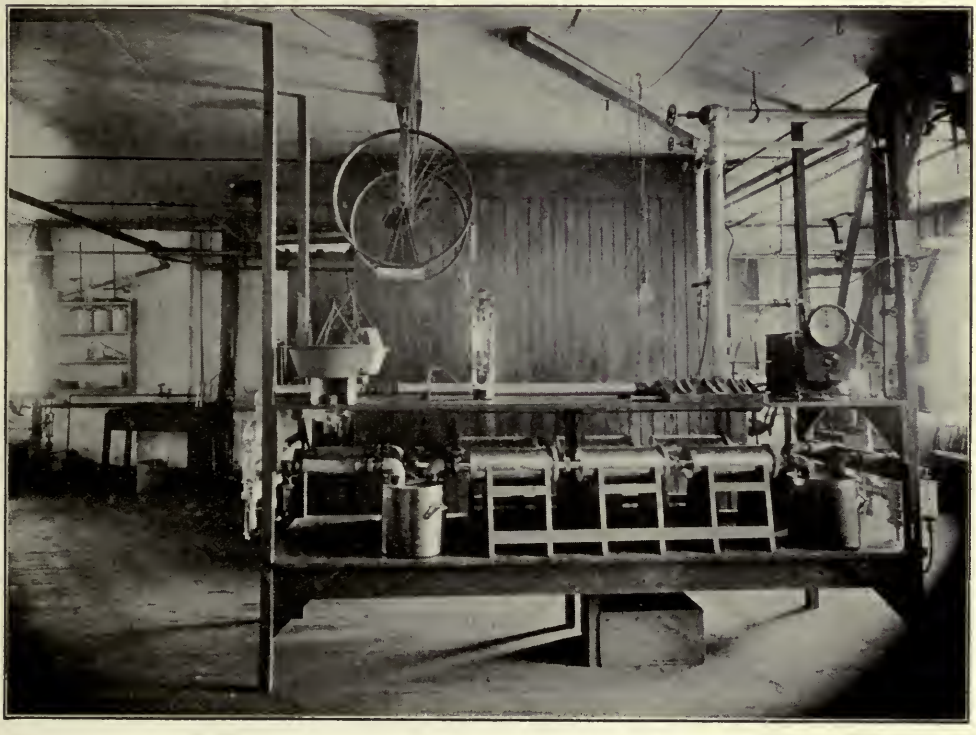

Fig. 5.—Laboratory Room. View from Alcove near Water-Pressure Regulator. Details of Absorbing System, Elster Meter Connections, Oxygen Cylinder, and Pans.

shelf of the table, are used for the analysis of the residual air in the chamber.

These various features of the apparatus are described in more detail beyond. The above description is simply to afford a general idea of the laboratory and apparatus as a whole before the more specific explanation is undertaken.

THE RESPIRATION APPARATUS.

GENERAL PRINCIPLE.

The respiration apparatus in its present modified form is constructed on the "closed-circuit" plan. It consists of a chamber large enough for the subject—a man—to live in comfortably, and ventilated by a current of air which is kept in circulation by a rotary blower. Provision is made for purifying the ventilating current of air, which is, after purification, returned to the chamber. The general scheme of the apparatus is shown diagrammatically in figure 6.

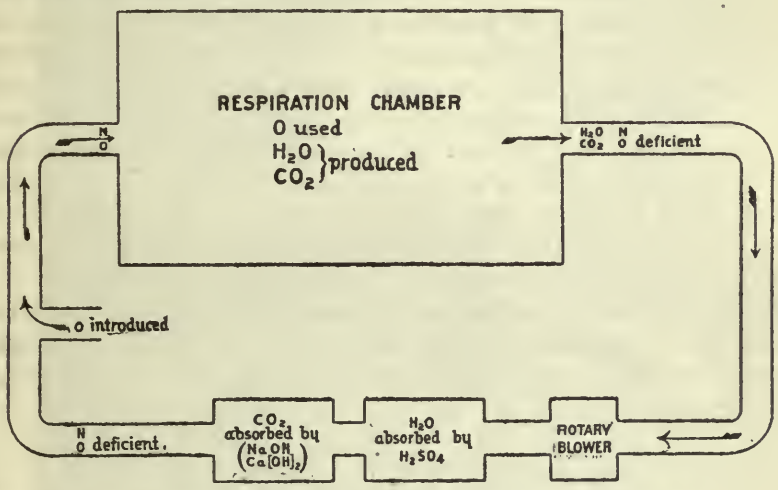

FIG. 6.—Diagram of Circulation of Air through Respiration Apparatus.

In the upper portion of the figure the respiration chamber is shown, and below it the blower and absorbing or purifying system. Air from the chamber, containing nitrogen, carbon dioxide, water vapor, and a somewhat diminished percentage of oxygen, passes through the blower and enters the absorbing system. Here it is forced through sulphuric acid to remove the water vapor, and through a specially prepared soda lime, which takes out the carbon dioxide. The soda lime, however, contains water, more or less of which is taken up by the air current.

The air is therefore again forced through sulphuric acid (not shown in the diagram) and then enters a pipe leading back to the chamber. It is now freed from carbon dioxide and water, but still deficient in oxygen. The oxygen is replenished by admitting the requisite amount from a steel cylinder of compressed oxygen through an opening in the ventilating air-pipe, as shown in the diagram, and the air when restored to a respirable condition reënters the respiration chamber.

The metal walls of the chamber and the metal pipes confine the air in a definite volume, and to allow for expansion or contraction of the air volume as the result of barometric or thermometric fluctuations a compensating device, consisting of two pans with flexible rubber covers, is inserted in the ventilating air-pipe.

The amounts of water and carbon dioxide absorbed by the sulphuric acid and soda lime and of oxygen admitted to the system are obtained by direct weighing on suitable balances. These weights give an approximate estimate as to the carbon dioxide, water, and oxygen involved in the transformations which have taken place in the body. There may be, however, considerable variations in the composition of the air in the system from time to time, especially as regards the oxygen content, which are not detected in this way. Since the volume of air in the closed circuit is comparatively large, even a slight variation produces a considerable error. It is therefore necessary to know the composition of the air at the beginning of an experiment, and also of the residual air at the end of each experimental period. Apparatus suitable for this purpose has been especially devised and is described in connection with the respiration apparatus.

From these data as a whole, with suitable corrections to be explained in detail, it is possible to compute accurately the amounts of oxygen absorbed and carbon dioxide and water eliminated by the subject during an experiment.

THE RESPIRATION CHAMBER.

The respiration chamber is an airtight, constant-temperature room, 2.15 meters long, 1.22 meters wide, and 1.92 meters high, with a total volume of about 5,000 liters. It is lighted by a window on the east side, and has several other openings for the admission and removal of food, air, etc. It is furnished with a table and bed, both of which may be folded against the walls when not in use, a chair, a telephone, and, in certain classes of experiments, with a bicycle ergometer. A view of the interior taken from the window is shown in figure 7, and in figure 8 a cross-section of the chamber showing the location of some

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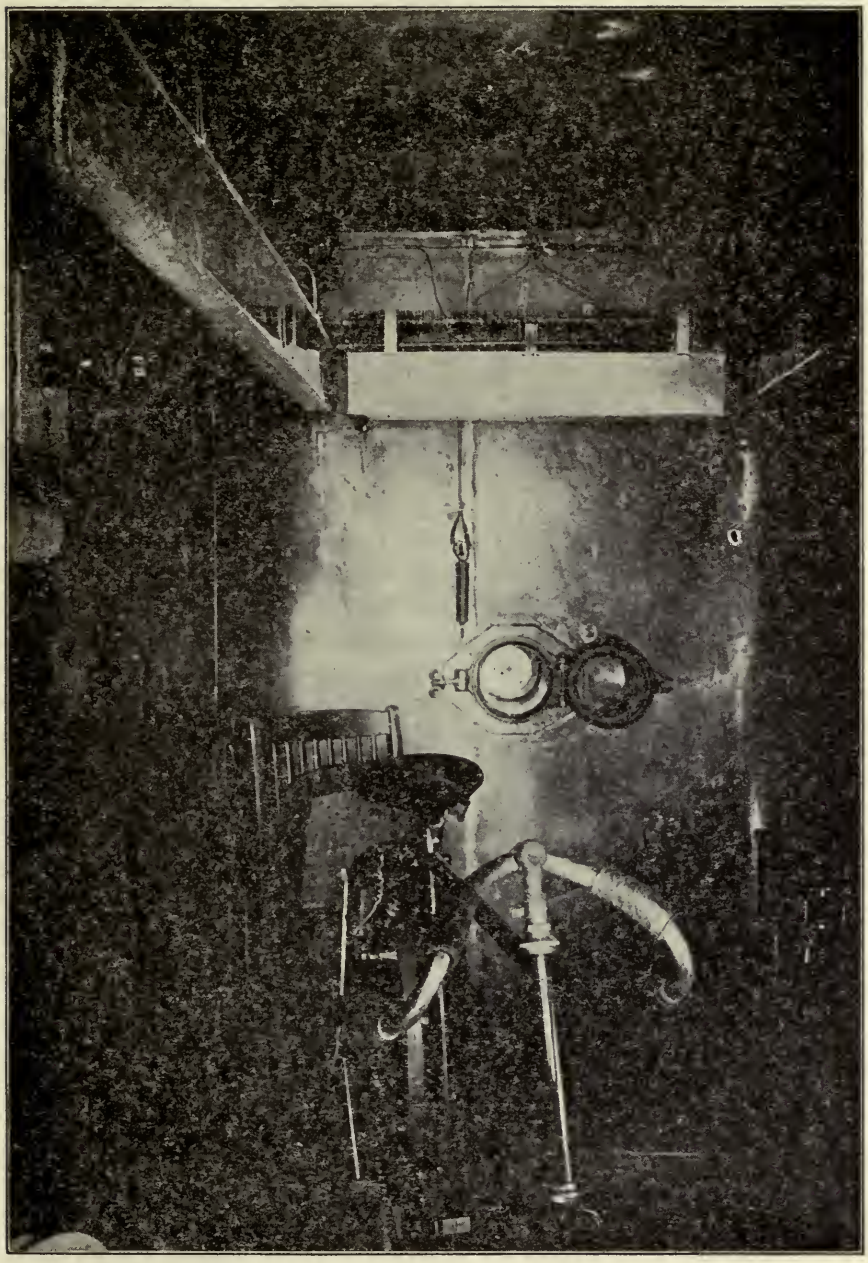

FIG. 7.—Interior of Respiration Chamber. Bicycle Ergometer in Foreground. Food Aperture with door open in rear. Heat-Absorbing System and Alumiuum Troughs near Ceiling. Electrical-Resistance Thermometer-Coil just above Food Aperture.

of the furniture and fixtures is given, while figure 33, on page 124, gives a clearer presentation of the interior appearance.

The ceiling, floor, and walls of the chamber, with the exception of the window and the various other small openings to be described, are constructed of sheet copper. The use of metal is especially advantageous in securing an airtight chamber. A so-called "14-ounce" sheet copper (Brown & Sharpe gage No. 24), cold-rolled, was selected, extra large sheets being specially obtained to reduce the number of seams to a minimum. For the floor of the chamber two of the sheets were soldered together in such a manner that one seam runs lengthwise of the chamber, and were then cut to the area and form of the chamber (the corners being rounded, as shown in several of the figures given). The ceiling is a duplicate of the floor. For the sides and ends of the chamber, five of the sheets were soldered together side to side, and bent to conform with the ceiling and floor, which were then soldered to the upper and lower edges.

The copper chamber thus constructed is fastened to a wooden framework or skeleton by means of strips of copper soldered to the outside of the chamber. Beneath the copper floor the framework is made solid—practically a wooden floor—to prevent the denting and puncturing of the copper when stepped upon.

The respiration chamber also serves as a calorimeter chamber and is fitted with many devices for the maintenance of constant temperature. For this purpose the chamber just described is surrounded by a similar chamber of zinc and an outer casing of wood. Detailed description of these features is deferred to that portion of the report dealing with the calorimetric apparatus.

Openings in the Chamber.

While the copper wall of the chamber is carefully soldered at all joints, and therefore perfectly airtight, it contains, as has been indicated, a number of special openings. Certain precautions are necessary at these points to guard against leakage of air into or out of the system.

Window.—The largest opening is that which serves both as door and window, shown at the front end of the chamber in figures 3 and 8. It is 49 cm. wide and 70 cm. high, being of sufficient size to allow a man to enter comfortably and to introduce and remove the various pieces of apparatus. A strip of metal which forms a small shoulder or beading on the inside of the window frame is securely soldered on all four sides. The opening itself is finally closed by a piece of plate glass which rests

against the metal shoulder and is held in place and made airtight by being thoroughly cemented with a wax prepared by melting together 9 parts of beeswax and 2 parts of Venice turpentine. The wax is first crowded around in the space between the edge of the glass and the metal, and then by means of a soldering iron it is melted and pressed into every crevice. A pin-hole through the wax is disastrous to accurate work. As the result of a number of tests, we have found that this method of closing the window is very satisfactory.

Food aperture.—For passing smaller objects, *e. g.*, food containers, etc., into and out of the respiration chamber during the progress of an experiment, it is necessary to provide an opening which can be opened and closed without leakage of air. The arrangement adopted consists practically of a brass tube through the walls, with a hinged port at each end, such as is used on vessels. (Figs. 8 and 33.)

The inner port is soldered directly to the copper wall and to a metal ring which in turn is soldered between the zinc and the copper wall. The door closes on a rubber gasket making an airtight joint. The outer port is tightly soldered to a brass tube 24.3 cm. long and 15.2 cm. in diameter, which extends into the food aperture to within 5 mm. of the door on the inside. This brass tube has a smaller diameter than that of the metal tube soldered between the metal walls, and there is accordingly an annular space between these metal tubes. Since the inside port is soldered to the ring forming the outer boundary of this annular space and the outside port is soldered to the tube forming the inner boundary, it is only necessary to fill this space completely to make an airtight joint. After considerable experimenting with solid-rubber rings, cement, wax, etc., a flat rubber tube with a smaller tube and valve attached to it in such a manner that it could be inflated like a bicycle tire was utilized. (See D, fig. 8.)

The smaller tube and valve project through the outer wall of the calorimeter just below the opening for the food aperture. The large rubber tube is held in place between the two metal tubes by a thick coating of shellac, and when once put in place and well inflated a tight closure is maintained.

Air-pipe openings.—The openings for the pipes conducting the air into and out of the chamber are placed on the right of the front end of the chamber (see V, figs. 8 and 30) a little above the center line. The two round openings in a rectangular box (see fig. 30) are the air-pipe connections. The construction of the box, the connection of the pipes, and the method of attaching and securing tight closure to the copper wall are shown in detail in figures 32 and 33. Two heavy brass flanges, threaded on the inside, are well soldered to the copper wall, the

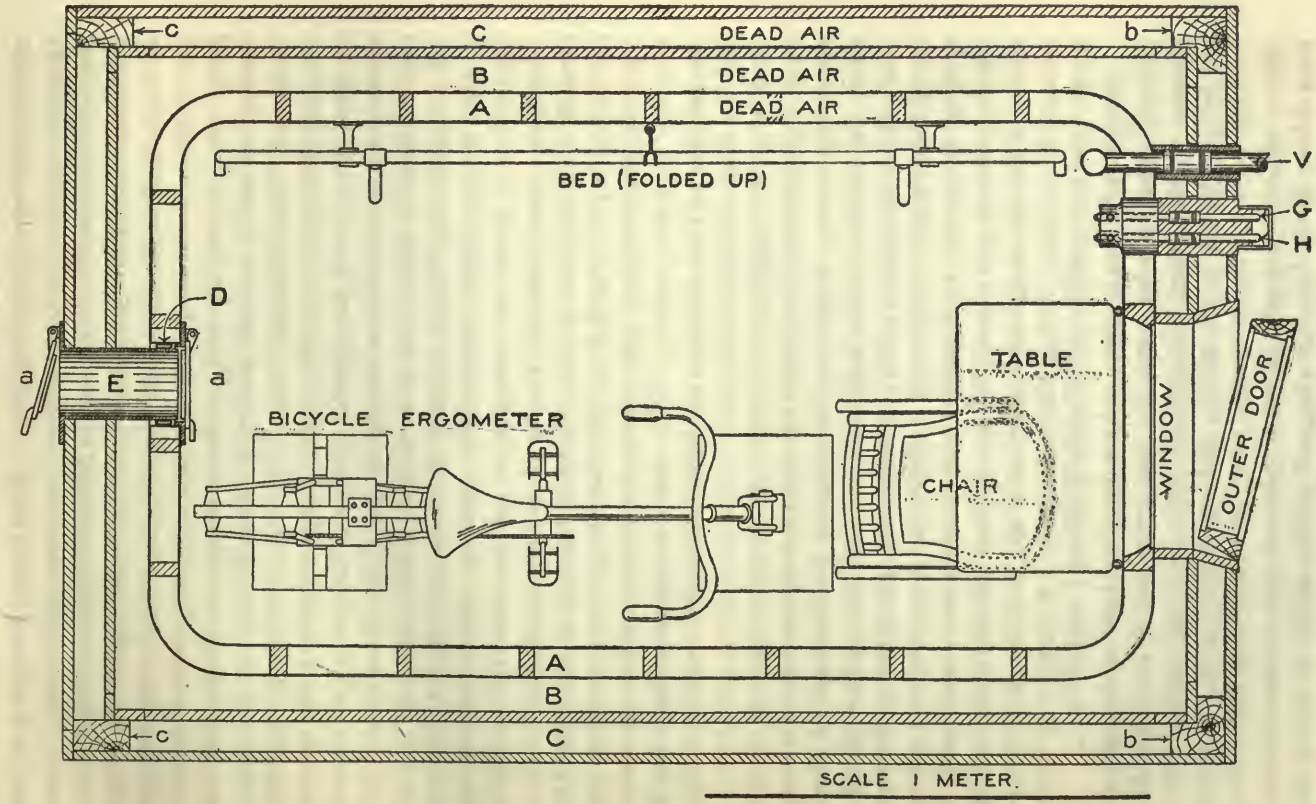

FIG. 8.—Horizontal Section of Respiration Calorimeter Chamber. Portions shaded are of wood.

A, dead-air space between Cu and Zn walls.
B, dead-air space between Zn wall and inside wooden wall.
C, dead-air space between inside and outside wooden walls.
D, pneumatic-packing air and heat insulated.
E, food-aperture tube.
a a, airtight ports (glass).
H, ingoing water for absorbing heat.
G, outcoming water.
V, ventilating air current.

one about 96 mm. above the other. Two brass pipes, 40 mm. internal diameter, 170 mm. long, are screwed into these shoulders. To provide for slight differences in the exact position of the chamber when it is withdrawn and again put in place in the wooden house, it was found desirable to have the final coupling with the outside air-pipes more or less flexible, and consequently the coupling was attached to the brass pipes screwed into the wall by short lengths of thick-walled rubber tubing. A small wooden box with openings for the two pipes was attached by wax and small nails to the zinc wall of the chamber and wooden upright between the zinc and copper walls. The box was so adjusted that it held the flexible couplings in the proper position for satisfactory connection to the outer air-pipes. Plaster of Paris was poured into the top of the box and the whole mass allowed to set; this serves as an excellent support for the pipes, and yet the flexibility of the rubber allows considerable twisting motion in making the connections. When the chamber is put in place in the house the rectangular box supporting the air-pipes fits perfectly into an opening through the two front panels, shown to the left of the window opening in figure 31. The box is sufficiently long to project clear through both wooden walls and thus allow the making of an easy connection with the air-pipes outside. With this arrangement there can be no leakage through the air-pipes or through the joint between the air-pipe and the inner copper wall.

Opening for weighing apparatus.—In order to permit of accurate weighing of the subject inside the respiration chamber, the weighing apparatus shown in figure 46 is situated on the floor of the room above the chamber and a metal rod connects the scales with the chair upon which the subject sits; consequently an opening through the top of the chamber is necessary to allow the passage of this rod. This opening is 35 mm. in diameter, and consists of a hard rubber tube tightly screwed into a metal flange soldered to the top of the copper wall. When the weighing apparatus is not in actual use the opening is closed by a tightly fitting rubber stopper. A number of tests have shown that this closure can be made uniformly without leak.

Opening for the water-pipes.—As is described in detail beyond, a water current is used to bring away the heat generated by the subject. The passage of this current through the metal walls was secured by soldering to the opening in the walls a stiff metal ring, as in the case of the food aperture. A round wooden plug, previously well boiled with paraffin to render it non-porous and so prevent gain or loss of water, was then driven firmly into this ring and tightly sealed by means of wax. The plug is shown in position in figure 30 immediately at the right and

a little below the window opening, and also in figure 32. The water-pipes were embedded in this plug, side by side, about 55 mm. apart, and the orifice sealed with wax at the point where the pipes leave the plug inside the chamber. By this means it is possible to have the water current enter and leave the chamber without leakage of water or air. Through the wooden plug also pass two wires used in the measurement of the temperature of the incoming air current (p. 122). The openings through which these wires pass are likewise sealed with wax.

Rod for adjusting position of shields.—In order to raise and lower the aluminum shields of the heat-absorbing system described beyond, a rod passes through the metal walls and connects on the outside with a lever handle shown immediately beneath the window in figure 2, and with a metal quadrant (see fig. 32) to which the phosphor-bronze cables leading to the shields are attached on the inside of the chamber. In order to make the closure through which this rod passes airtight, we rely on a long close telescope-fit between the outside of the steel rod and the inner wall of the brass tube, which is soldered between the two metal walls. As an additional precaution, two or three layers of cotton wicking, well soaked with vaseline, are wound around the steel rod next the copper wall, the pressure of the lever handle on the outside holding the wicking tightly in place.

Electric-cable tube.—The various electric circuits used in temperature measurements and for the telephone are brought together to form a large cable which passes through an opening in the two metal walls, shown in figure 29, a little above the center of the side of the chamber. In this opening, as in the food aperture and wooden plug, a copper tube was soldered to both the zinc and the copper walls. The cable was then inserted and the absolute closure made by coating the space between the cable and both the inside and the outside ends of the copper tube between the two walls with wax. Furthermore, to prevent a leakage of air through the cable itself (between the strands), wax was melted into the end of the cable at the point where the wires separate.

PIPING AND VALVES TO THE BLOWER.

The air from the chamber passes through the opening A_2 (fig. 33) to the air-pipe leading to the blower. This pipe is of galvanized iron 25 mm. in diameter, with ordinary steam fittings and connections. After the piping had been put in place it was subjected to a test of 50 pounds pressure to the square inch.

The air leaves the chamber, rises through a short length of pipe, and then passes along the ceiling, makes a turn at the corner of the

chamber, and descends into the blower. The passage of 75 liters of air through this size and length of pipe results in a slightly diminished pressure (3 cm. of water).

From time to time a sample of air is withdrawn from this pipe for analysis, it being assumed that the composition of the air in the pipe between the chamber and blower is essentially that of the air in the chamber. (See p. 81.) To obtain a valve that will close completely, an opening in the pipe in which there is a diminished pressure has been found a difficult thing, and recourse was had to a mercury valve which was attached to the vertical section of the pipe above the blower. This valve consists of a glass Y tube, one arm of which was attached to the air-pipe and the other connected to the residual-analysis apparatus. To the stem of the Y a glass bulb filled with mercury was attached by means of a piece of rubber tubing. By raising this bulb, mercury rises in the stem of the Y tube and closes the connection between the two arms of the Y. On lowering the valve a free passage is obtained for the air.

An ordinary one-inch "angle" valve was placed in the pipe as it descends from the ceiling to aid in testing the air-circuit from time to time. This valve, as well as that in the return air-pipe, is shown in figure 5, near the ceiling.

THE ROTARY BLOWER.

Considerable difficulty has been experienced in obtaining a suitable apparatus for maintaining the ventilating current of air in the system. An attempt was made to use the Blakeslee mercury pump used in the earlier type of respiration apparatus,[1] but the possible danger of mercury vapor in the air prevented its use in a closed circuit. Several other forms of mechanical pumps were devised, built, and tested, but were ultimately discarded in favor of a rotary blower. A blower was obtained in the market, and after undergoing modification was adapted to the specific purpose of maintaining a ventilating current of air for this apparatus. The advantages of a rotary blower over a pump are numerous. In the first place, the current of air is very much more constant, since with the pump there is more or less intermittent motion; but more important than any other is the fact that it is possible to immerse the rotary blower in oil and thus minimize and detect leakage of air.

The blower and the receptacle containing cylinder oil in which the blower is immersed, together with the air-pipes leading to and from the blower, are shown in figure 9.

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, p. 31.

The blower consists of a cylinder A, perforated laterally by the openings *a* and *b* for the entrance and exit of the air current. Inside the cylinder and arranged eccentrically with it is a revolving drum B, bearing on its axis the rod F which carries at each end a piston, G and G¹. The piston G has a tight connection with the rod, while G¹ is cushioned on the springs H. As the drum B is revolved the rod slides so that the pistons press against the inner face of the cylinder and prevent a backward escape of air, and the current entering through *a* is forced out through *b* into the absorber system.

The box in which the blower is placed is made of cast iron and provided with stuffing-boxes through which the shaft or axis of the revolving drum B and the pipes *a* and *b* pass. Any leakage of air in the blower is instantly detected by the bubbles of air in the thick cylinder oil. The shaft is oiled by unscrewing two long rods, which are tapped into oil-holes on each side of the blower. Leather washers on the rods insure tightness when screwed down. To avoid escape of air the blower is oiled only when at rest.

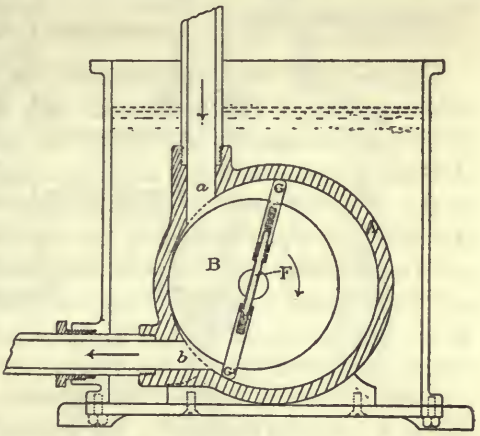

FIG. 9.—Rotary Blower. Air enters at *a*, is forced about the Drum B by Sliding Pistons G and G¹, and is driven out at *b*.

In order that no oil may be drawn into the absorbing system a trap is provided, as shown in figure 10. The tube *t* is prolonged into the blind passage *s s*. The oil collects in the bottom of this tube, and by removing the plug *h* may be drawn off from time to time. It is impossible to eliminate the use of a small amount of lubricating oil from a blower of this type, but we have found that the amount of oil mechanically carried forward by the air current is extremely small and is practically all collected in the trap. Furthermore, before reëntering the chamber the air passes through strong sulphuric acid, by which any hydrocarbons would be absorbed. On the other hand, the partial reduction of sulphuric acid to sulphurous acid as a result of the absorption of hydrocarbons would do little harm, because of the absorption of this gas by the soda lime.

The efficiency of the blower was tested by connecting it with a gas-meter for several weeks. It was found that the amount of air forced through the meter was almost directly proportional to the speed of

the blower; consequently the meter was deemed unnecessary and was removed.

For simplicity and efficiency, it is very much to be doubted if an apparatus could be devised which would materially improve the conditions now obtained with this simple form of blower. While the pressure of the air is, under the conditions here used, but 35 mm. of mercury, tests have shown that the blower would give still greater pressures in case they were necessary.

By means of a small counter-shaft attached to the ceiling of the calorimeter laboratory, it is possible to start and stop the blower without disturbing the other machinery.

MERCURY VALVES.

Inasmuch as the experimental day is generally subdivided into twelve periods of two hours each, it is necessary to provide means for diverting the main air current at the end of each experimental period through a second series of absorbers, and thus provide for the weighing of the water and carbon dioxide absorbed by the first set. Accordingly, the main air-pipe conducting the air from the blower to the absorbers and that leading from the absorber system to the respiration chamber are divided, and a system of valves is employed to cut off the air-circuit at the beginning and end of each of the absorber systems. The two valves at the end nearest the blower are shown in figure 3, and figure 4 shows the two valves at the opposite end. A closer view of these valves is given in figure 18. By opening the valve at each end of one set of absorbers and closing both corresponding valves on the other set, air can be caused to traverse either system as desired.

The requirements for these valves are such as to demand a special form of construction. At the point where the air enters the absorbing system it is under an increased pressure of 40 to 50 mm. of mercury. At the other end, *i. e.*, where the air leaves the absorbing system, it is at atmospheric pressure. While the problem of a valve at the exit end of the system is simple, that of devising a suitable one for the other end presented certain difficulties which were overcome only after considerable time. It is necessary that this valve should be sufficiently tight to withstand without a leak an increased pressure of 40 to 50 mm. of mercury while the ventilating current of air is passing through it. On the other hand, for a period of at least two hours the valve must be capable of being closed absolutely with atmospheric pressure on one side of the closure and an increased pressure of 40 mm. of mercury on the other. Furthermore, the valve must be of sufficient size to permit the passage of 75 liters of air per minute through it without a marked

resistance. No valve that we could find on the market would be guaranteed by its manufacturers to meet these conditions. The form of valve finally used is shown in figure 10.

The valve consists of a mechanical closure which is subsequently bathed in mercury, thereby giving a mercury seal. Air from the blower enters the tube *t*, passes around the annular space *s* to the valves, through the annular space *a* of the open valve, up through the vertical tube *b*, and then to the absorbers at *d*. Figure 10 shows the valves as in actual operation, one being open, the other closed.

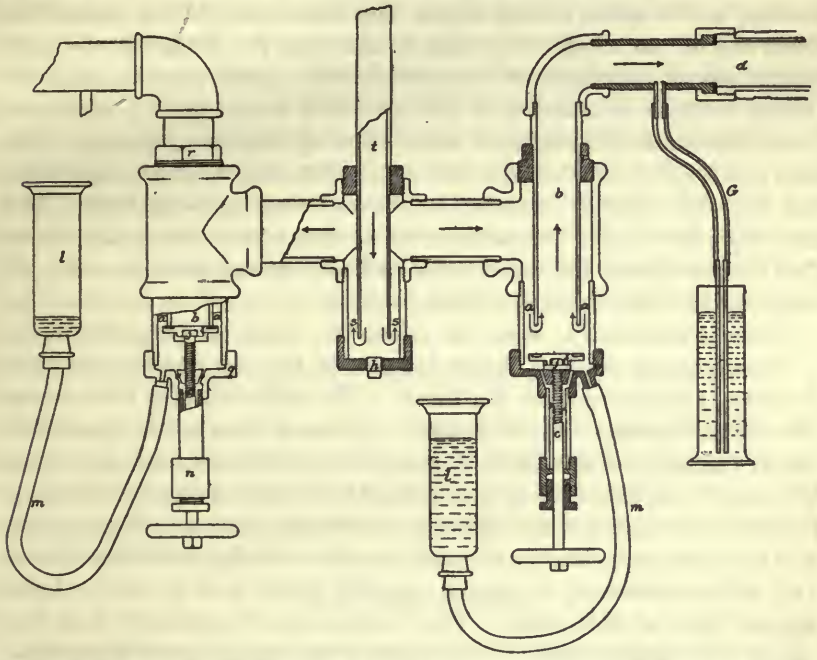

FIG. 10.—Mercury Valves. By raising the mercury reservoir the mechanical closure made by the valve against end of tube *b* can be bathed in mercury. Direction of air current indicated by arrows. The valve at right is open, that at left closed. Tube G is inserted in mercury and is used for testing the system.

To close the valve, the lower end of the tube *b* is shut off mechanically by pressing an iron disk, in which a fiber gasket *g* is inserted, firmly against its edges by means of the screw and spindle *c*. The closure is then made complete by immersion in mercury. The glass reservoir *l* is so raised that mercury can flow through the rubber tube *m* into the annular space *a* until the level desired is reached.

To prevent leakage of air along the spindle, it is caused to traverse a length of pipe, the lower end of which is closed with a stuffing-box and gland *n*, and the annular space between the spindle and the

inner walls of the pipe is filled with mercury which flows down from above through the small holes *o* and *o*[1]. This column of mercury is approximately 100 mm. long, and its pressure, increased by the 50 mm. pressure of the air current, tends to force the mercury against the packing at the bottom and thus prevent the entrance of air. The valve is constructed of a 2-inch T, which is galvanized on the outside to fill possible blow-holes in the iron. Before galvanizing, the ends of the T were plugged to prevent the zinc entering the inner part and subsequently forming an amalgam. A reducer, *r*, is fitted in the top, and a short 2-inch nipple inserted in the lower part. The lower end of the nipple is covered with a cap, *q*. This cap was made from a special casting, and is provided with a small pipe to which the rubber tube *m* is attached. The ball and socket joint *j* minimizes lateral motion and consequent destruction of the fiber gasket *g*. The pipe *b*, which is screwed into the reducer *r*, has its lower end trued and the edges slightly rounded to prevent cutting the gasket. As is seen in figure 10, the connections from this pipe to both the blower and the absorbers are made with ordinary steam fittings. All the metal work of the valve is of iron or steel.

When it is desired to open the valve, the reservoir *l* is lowered, and by reason of the pitch of the under side of the cap *q* every particle of mercury is drained out of the valve. The valve wheel is then turned and the mechanical closure opened. There is then a free passage for the air through the side tube, around the annular space, and up through the tube *b*. When the valve is opened the only chances for a leak are around the coupling *d* and through the stuffing-box *n*. The coupling *d* is the same as is used at all other junctions of the absorbing system, and when connected is always specially tested (see p. 32) to insure against leak at this point. The tendency of the mercury is to press out of the stuffing-box *n*; consequently no leak has ever been found. When the valve is closed one of the chances for leak is shifted from the coupling *d* to the closure of the pipe *b*, for after removal of the water-absorber attached at *d* the air in the annular space *a a* is at a pressure of from 30 to 50 mm., while that in *b* is at atmospheric pressure. Because of the mechanical closure on gasket *g* and the mercury seal, no air can pass from *a* to *b*.

It sometimes happens that the gasket *g* becomes worn or cut, or that a particle of dust gets in between *g* and the pipe *b*, thereby preventing a tight mechanical closure. Under these conditions, unless the column of mercury above the level of *g* is sufficiently high, there may be a slight leakage of gas down through the mercury into the inside of tube *b*. This condition is, however, seldom present, and suitable tests for such a leakage have been devised.

The details of manipulation in changing from one absorber system to the other are somewhat important. The first step is to open the valve at the exit end of the new absorber system. This operation, of course, is not carried out until the absorber system has been tested and coupled up, as described on page 32. Inasmuch as there is no tension in the pipe leading from the absorber system to the chamber, this preliminary step does not affect the volume of air. At one-half minute before the end of the experimental period the reading of the pointer on pan No. 1[1] is recorded, pan No. 2 being in general kept empty. At 10 seconds before the end of the experimental period the blower is stopped. The mercury reservoir on the valve connected with the new absorber system is then lowered, and at the exact end of the experimental period the reading of the pointer on pan No. 1 is again recorded. As soon as this is done the wheel on the valve connecting with the new absorber system is opened, and the wheel on the valve connected with the old absorber system is simultaneously closed. The mercury reservoir is then raised to seal the closed valve and the blower is started. The valve at the rear or exit end of the old absorber system is still open, but inasmuch as the air is under no pressure this valve may be closed at leisure.

APPARATUS FOR THE DETERMINATION OF WATER.

The water vapor eliminated by the subject through the lungs and skin is removed from the chamber in two ways—part of it is condensed within the chamber and collected as drip, but the major part is carried out in the air current as water vapor and removed from the air by dehydration by sulphuric acid.

Collection of Drip.

Condensation of water vapor within the chamber is due to the method of absorbing and removing the heat eliminated by the subject, as explained on page 125. The apparatus for collecting the drip may be seen in figure 33, on page 124.

The temperature of the water in the heat-absorbing system is sometimes below the dew-point of the air of the chamber. It frequently happens, therefore, especially when the subject is working hard and there is a large quantity of water vapor in the air, that the surface of the heat absorber becomes covered with condensed moisture and the water drips from it. This water is collected in the aluminum shields (*Sd* in fig. 33) used to regulate the rate of heat absorption, which are purposely made water-tight.

[1] For a description of the pans see page 39.

The cold air which settles in the bottom of the aluminum shields cools them so noticeably that frequently they, too, begin to condense water on the outside. To collect this water another trough, or, more properly speaking, gutter (*Dt* in fig. 33), is attached to the bottom of each shield to conduct the water dripping from the aluminum trough to a proper container (*Dc* in fig. 33).

The shields do not encompass the heat-absorber pipes at the corners, as may be seen in figure 33. It was frequently found, however, that the copper pipe became coated with moisture and the water thus condensed dropped to the floor of the chamber. To collect this moisture the drip-cans into which the water from the troughs is emptied are suspended from the copper pipe at the corners and are of such shape that they catch any water that drips from the pipe. The water may be drained from these cups into bottles and weighed.

To determine the total quantity of water thus condensed it is necessary to know how much remains on the surface of the heat absorbers not collected as drip. For this purpose provision is made for weighing the whole heat-absorbing system, as explained elsewhere.

Removal of Water Vapor from the Air Current.

The problem here is the removal of a large amount of water vapor from an air current flowing at the rate of 75 liters per minute. For this purpose the air is caused to pass through concentrated sulphuric acid in a specially devised container. From numerous preliminary experiments it was learned that none of the common solid absorbents for water, such as calcium chloride and phosphorus pentoxide, could be relied upon to remove water from a large air current as completely as does the acid.

Description of the Water-Absorbers.

The difficulty with using sulphuric acid as the absorbent is that it is next to impossible to obtain a satisfactory container for it other than glass, and it was feared that the large size of the absorber would make a glass vessel so unwieldy that it would be readily broken. A large number of experiments were made testing the resistant powers of copper, aluminum, hard rubber, gold-plated copper, and various enameled wares. As the result of these tests it was found that enameled iron resisted the action of the strong sulphuric acid admirably, and a set of absorbers made from this material was in use for over a year. It was, however, impracticable to construct a form of absorber from this material of fewer than two parts, and equally impossible to join the two parts so as to prevent permanently leakage of air. Consequently the use of enameled ware was abandoned.

Recourse was then had to earthenware absorbers, the parts of which, by means of heavy glazing, could be tightly joined together. This type of absorber, while by no means all that could be desired, has given fair results and is still in use.[1] The external appearance of the water absorber is shown at the right in figure 11.

The absorber is 300 mm. high, 285 mm. in diameter, and contains about 14.5 liters. There are three openings in the top—two 40 mm. in diameter for the entrance and exit of the air current, and a smaller one of 15 mm., which is used for emptying and recharging the absorber with acid. When the absorber is in use this opening is closed by a well-vaselined rubber stopper, and the larger openings are connected by couplings to the remainder of the absorber system. For convenience handles are put on each side of the absorber, each being perforated in the center to admit of the attachment of hooks for supporting the absorber during weighing. Each can is numbered with enamel paint.

The interior construction of the absorber is shown at the left in figure 11. The tube through which the air enters extends nearly to the bottom of the can and has four openings or slots in its lower edge. A circular disk not seen in the figure, 160 mm. in diameter, having a rim 30 mm. deep, with a large number of holes in its edge, is fastened 30 mm. above the lower end of the extension tube. A larger disk 240 mm. in diameter, having a still deeper rim also provided with holes in its periphery, is attached to the central tube 35 mm. above the first disk. Acid is poured into the can until the whole flaring end of the extension tube is immersed in acid, about 5.5 kg. being sufficient for this purpose. Air descending through the entrance tube first passes through the four openings in the end of the tube and, bubbling through the acid, collects under the first disk; it then passes out through the small holes in the periphery and, bubbling through sulphuric acid the second time, enters the second chamber, where it collects under the second or larger disk. It then passes through the openings in the edge of the larger disk and bubbles a third time through the acid to the surface, whence it escapes through the second large opening in the top of the can. To prevent spattering and escape of acid fumes through this opening it is protected by a perforated earthenware cup filled with a layer of pumice stone and a layer of asbestos. A thimble of wire gauze is then fitted into the opening to prevent any of this material from sifting out when the can is turned over, as in emptying.

It is thus seen that the air bubbles through acid three times, and as the bubbles are subdivided by the holes in the periphery of the disks, the

[1] We are indebted to the Charles Graham Chemical Pottery Works of Brooklyn, New York, for much assistance in obtaining these absorbers.

dehydration is very complete, even though the depth of acid through which the air passes is not great.

The absorbers are constructed to withstand increased pressure, and consequently in testing for tightness a water manometer is attached and air forced in. If a leak is indicated by the manometer it can be located by either coating the joints with soap solution or immersing the whole absorber in a vessel of water and noting any escape of air in the form of bubbles.

For connecting the absorbers to each other and to the valve, metal couplings are used, but the desired flexibility of the parts is secured by means of a specially made elbow of rubber.[1] The simple form of coupling shown in figure 11, when used with a soft rubber gasket 2 mm. thick, has invariably resulted in a perfectly tight closure.

Durability of the water-absorbers.—When the absorbers were first obtained they gave excellent satisfaction in every way. After about three months' use, however, it was noted that the acid had penetrated the earthenware and was collecting in drops on the outside of the absorber. As a result of a number of tests it was found that after thoroughly washing the absorbers to free them from acid and then drying at 100° in a water-oven until thoroughly dry, boiling-hot paraffin could be forced into the porous material and thus prevent leaking. The hot dry absorber was removed from the water-oven, a pint of boiling paraffin poured into it and well shaken about so as to insure contact with all portions of the interior, and then the excess of paraffin poured out. The openings in the top of the absorber were then carefully corked and a pressure of 10 or 15 pounds applied by forcing air into the absorber with a bicycle pump. As the absorber cooled, the paraffin solidified, filling the porous portions of the absorber. This treatment has thus far given excellent satisfaction.

Efficiency of the water-absorbers.—The greater the efficiency of the water-absorbers the fewer required in series and the longer they can be used. It was found that with a current of air passing at the rate of 75 liters per minute an absorber freshly charged with sulphuric acid would remove 500 grams of water vapor from the air current before allowing any water vapor to pass through unabsorbed. As the system is now arranged, one absorber is used to remove the water from the air current and another to collect the water taken up by the air current in its passage through the carbon-dioxide absorbers. In practice, a record is kept of the weight of each absorber, and when a gain of 400 grams

[1] These elbows were furnished upon specifications by the Davol Rubber Co., Providence, Rhode Island.

To face page 26.

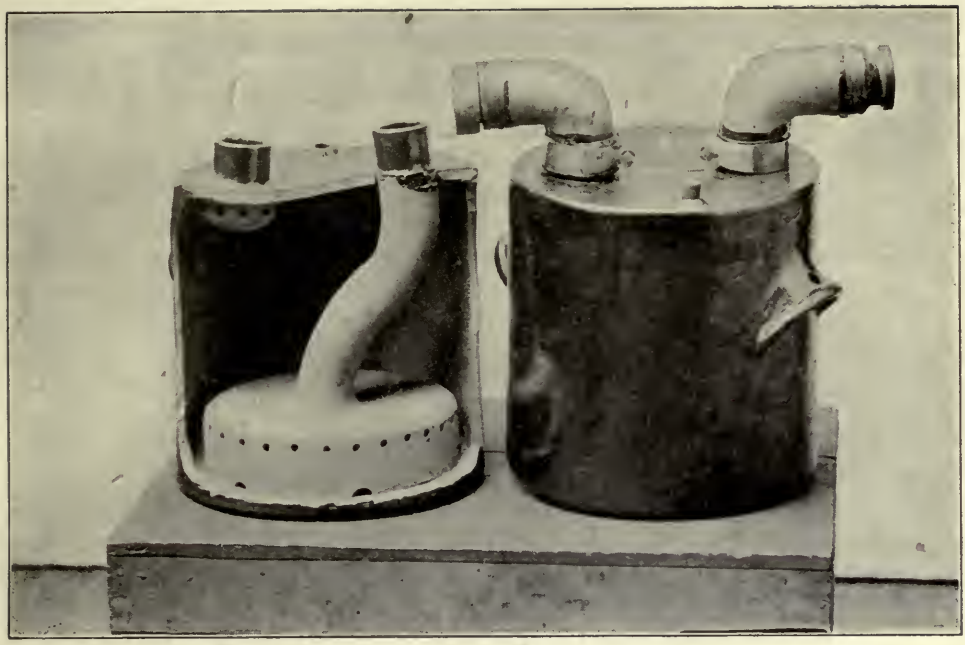

FIG. 11.—Water-Absorbers. At the right is a complete Absorber with rubber elbows and connections. At the left is represented the interior of an Absorber, showing the method for breaking up air-bubbles as the air passes through the acid, the device for preventing the escape of acid through outgoing air-pipe, and the opening by means of which the Absorber is filled and emptied.

FIG. 12.—A Carbon-Dioxide Absorber showing Cylinder Cap, Collars, Wire-gauze Disks, and Cakes of spent Soda Lime.

is noted, *i. e.*, 100 grams less than tests have shown to be absolutely safe, the spent acid is removed and replaced by a fresh supply.

Supply of sulphuric acid.—With this form of absorber for the removal of water vapor from the air the use of considerable quantities of sulphuric acid is necessary. It has been found that the ordinary grades of concentrated sulphuric acid, specific gravity 1.84, are admirably adapted for this work. The acid is purchased in carboys and consequently the expense for this reagent is small.

APPARATUS FOR THE DETERMINATION OF CARBON DIOXIDE.

As the air leaves the first water-absorber it is perfectly dry, but still contains carbon dioxide and is somewhat deficient in oxygen. The next step in the process of purification is the removal of the carbon dioxide. For a number of years prior to the introduction of the closed-circuit system soda lime of special preparation was used in this laboratory for removing carbon dioxide from the air samples taken for analysis. The success attending its use for this purpose was such as to suggest it as a means for removing the total quantity of carbon dioxide from the main ventilating air current. From the area of the ordinary U tube, described on page 45, the rate and length of time of flow through it, and the length and weight of the layer of soda lime, it was calculated that a soda-lime container with a diameter of approximately 150 mm. and a length of approximately 380 mm. would be as efficient in removing carbon dioxide from an air current with a rate of 75 liters per minute (the usual rate of ventilation) as was the U tube in removing carbon dioxide from the air current with a rate of 2 liters per minute. After a number of experiments an absorber was devised which in its present form is shown in figure 12 and in cross-section in figure 13.

Description of the Carbon-Dioxide Absorbers.

The absorbers are constructed of seamless drawn brass tubing 150 mm. internal diameter, 380 mm. long, and with walls 1.5 mm. thick. One end consists of a brass disk to which a 64 mm. length of brass tube is permanently soldered and the joints stiffened by being well banked with solder. The other end is detachable and consists of a similar brass disk somewhat larger in diameter (157 mm.), which can be drawn up against a rubber gasket fitting against the face of a shoulder on the end of the main tube, so that by means of the large collar C (fig. 13) the opening can be tightly closed. All parts are heavily plated internally and externally with silver, which has been found to stand the action of the soda lime indefinitely. For convenience each can is lettered with blue enamel.

In order to facilitate the passage of the air current through the soda lime and prevent channeling, a number of wire-gauze disks about 148 mm. in diameter and 8 mm. in thickness (*d*, *d*, *d*, in fig. 13) are inserted in each cylinder so as to divide it into compartments. In filling the cylinder the detachable cover is removed and a square of wire gauze is inserted in the opposite end. A layer of cotton, d^1, about 10 mm. thick is then inserted and a cover of wire gauze is placed above it, these precautions being taken to prevent any of the soda lime from sifting out. For the same reason a small thimble of wire gauze, T (also shown in the extreme left of figure 13), is inserted in each end of the cylinder. The cylinder is then filled with soda lime for about one-fourth of its depth, one of the wire-gauze disks inserted, a second layer of soda lime of equal thickness introduced, another disk added, a third layer of soda lime, and then a disk, and finally a fourth layer of soda lime. A square of wire gauze, S, is then put in, the rubber gasket and cover set in place, and the collar screwed down tightly.

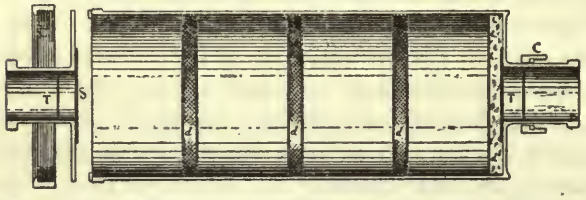

FIG. 13.—Cross-section of Carbon-Dioxide Absorber. Arrangement in Cylinder, when Absorber is filled with Soda Lime, of Wire-gauze Disks *d*, *d*, *d*, Thimbles T, T, and Square S, with layer of cotton d^1, are here shown.

Vise for tightening absorbers.—It is absolutely essential that this joint be tight, and as it is not safe to rely on the hands alone for this closure, we resort to the use of a clamp and vise devised by our mechanician, Mr. S. C. Dinsmore, and shown in figure 14.

This device consists of two blocks of wood which offer a good surface to grip the smooth cylinder. By means of two metal screws on the top of the vise the two jaws are brought together and the cylinder firmly held without distorting it. A wooden clamp which is readily adjustable is then placed about the large collar C (see fig. 13), and by means of this the end and the cap can be screwed down tightly against the rubber gasket.

Before removing the cylinder from the vise the tightness of closure is tested by means of a water manometer and air-pump. With proper precautions no difficulty is experienced in securing a tight joint. The cylinders are weighed on the large balance shown in figure 21, being suspended from one end of the balance beam by two loops of wire fitting over the small tubes in both ends of the can. When charged with soda lime they weigh approximately from 9.3 to 9.5 kg.

Six of these soda-lime cans are always on the absorber-system table, three of them connected ready for use. The same form of coupling, *i. e.*, that shown at right of figure 13, is used throughout the whole absorber system, *i. e.*, on the water-absorber cans and on the valves at both ends of the absorber system. The cans not in use are closed at both ends with rubber stoppers and all extra cans are placed on a rack fastened to the wall. (See fig. 1.)

Removal of spent soda lime from the can.—After an absorber has become exhausted, *i. e.*, when no further increase in weight is observed, the can is placed in the vise and the collar started one or two turns of the thread by means of the clamp. The can is then carried to some convenient place, the collar unscrewed with the hand, and the top removed. When the can is inverted the soda lime generally slips out of the can without any difficulty. The spent soda lime is of much lighter color than the fresh, and is usually found to have agglomerated into the form of cakes such as are shown at the right of figure 12. To insure the free removal of the spent soda lime the cans are occasionally given a thorough washing.

Preparation of soda lime.—The use of a partially moist soda lime for the absorption of carbon dioxide seems to have been first adopted by Haldane[1]; but as our method of preparing soda lime is markedly different from that used by Haldane, and tests that we have made indicate that its efficiency as an absorbing agent is considerably greater than that of the earlier preparation, a description of the method of its preparation is given herewith.

One kilogram of commercial caustic soda, preferably in the form of fine powder, is dissolved in 750 cc. of water in an iron dish. We have found a round-bottomed iron kettle admirably adapted to this purpose. When the caustic soda has all dissolved, or by stirring with an iron poker can be held in suspension, and while the liquid is still hot from the action of the soda and water, one kilogram of pulverized fresh quicklime is poured into the solution with constant and rapid stirring. The lime should all be added before the expiration of 10 seconds. The stirring should be continuous and the lime held in suspension as much as possible. In a few seconds the lime begins to slack in the soda solution and the mass in the iron dish becomes very hot, large quantities of steam escaping. Care should be taken to avoid the spattering of drops of hot alkali. Rubber gloves should be worn, and the operation conducted in a well-ventilated room or in the open air.

[1] Journ. Physiol. (1892), **13**, p. 422.

While the mixture is cooling the stirring is continued and the larger lumps broken into smaller bits as much as possible. It is then transferred to a shallow pan and broken into small particles with a large iron pestle. Before being used the material is sifted through wire gauze with a mesh 4 mm. square, the larger particles being reduced by means of a pestle to a size that will pass through the sieve.

When properly made the soda lime is sufficiently moist to appear distinctly damp, no dust being visible, and yet not so damp that it will "cake" when being crushed with the pestle. In color it is white with a slight yellowish tinge. The finished product is stored in galvanized-iron ash-barrels with the top hermetically sealed by a tin cover waxed at the edges.

The caustic soda is purchased in cans varying in weight from 5 to 25 pounds, and as fast as a can is opened it is emptied into a large glass jar, which can be tightly closed. The requisite quantity for each batch is weighed out into a porcelain evaporating dish on scales weighing to within one or two grams. As a matter of fact, the observance of the exact proportions is not strictly necessary, and probably the weights taken vary from 10 to 20 grams from those given above.

The pulverized quicklime is best obtained by taking a barrel of the best quality of fresh lime, pulverizing it with a pestle, and storing it in an iron ash-barrel, which can be carefully closed at the top. The lime in this condition is ready to be weighed and added directly to the strong lye. It is important that the lime used be very fresh, and each barrel should be tested to make sure that the material slacks freely.

If the lime is not of standard strength, or if the proportions of the soda and lime are not carefully maintained, the mixture is likely to be too moist and form pasty lumps. In some instances it is possible to utilize such a product by mixing with it some especially dry soda lime, though as a rule the product would better be rejected and another lot of lime used. With due precautions and care, however, the manufacture proceeds smoothly and with minimum waste of material. A ton or more of this soda lime has been made in this laboratory in the past three years, and the method and finished product have been all that could be desired.

Efficiency of the carbon-dioxide absorbers.—In the absorption of carbon dioxide by soda lime the reaction may be considered as resulting in the formation of calcium carbonate and sodium carbonate from calcium oxide and sodium hydroxide. Assuming that the soda lime is a mixture of equal parts by weight of sodium hydroxide and calcium oxide, a soda-lime can containing 6 kilos of soda lime should, theoretically, absorb not far from 4,000 grams of carbon dioxide. In practice, how-

ever, the actual efficiency falls far short of these figures, and under the most favorable conditions only about 400 grams can be absorbed. While this efficiency is very far from the theoretical, it is none the less remarkably good, considering the conditions under which the absorption takes place, *i. e.*, a solid absorbent limited to surface absorption only, and indicates that the apparatus is well adapted for the absorption of a relatively large amount of carbon dioxide from a rapidly moving current of air.

The efficiency of the absorber has been found to depend very largely upon the rate of evolution of carbon dioxide. In the alcohol check experiments and in rest experiments with men, where the rate of evolution of carbon dioxide is fairly constant and does not exceed 50 to 60 grams per hour, the soda lime is more completely exhausted than in work experiments with men, where the amount of carbon dioxide may rise to 200 grams per hour. With this large quantity of carbon dioxide passing through the absorber system, the reaction between the soda lime and the carbon dioxide is so intense that the cans become very much heated. The soda lime seems to fuse or cake on the edges, and the interior of each section of soda lime is thereby partially protected from the action of the carbon dioxide. Under such conditions it is found that each can will not, as a rule, take up much more than from 100 to 125 grams of carbon dioxide before it is necessary to change. Furthermore, all three cans in the system, shown in figure 5, during a two-hour period when the man is at hard work, take up approximately the same amount and all become heated. While it is possible to use these partially exhausted cans during the night period, when the subject is at rest and the rate of evolution of carbon dioxide at a minimum, it is not found safe to use such a partially exhausted can during a second work period; consequently the can is opened and the soda lime removed. It is found on removing the different sections of the soda lime that instead of adhering in a solid white cake, as is the case when the soda lime is completely exhausted (see fig. 12), it crumbles and falls apart, except where the partial fusion or caking has taken place. By picking out the larger lumps of the partially fused material[1] the major portion of the unused material can be saved and used to refill the cans. In this way the efficiency of the soda lime is not impaired, and the total amount of carbon dioxide absorbed by a given weight of soda lime need not, under such manipulation, fall much below the maximum amount under the most favorable conditions.

[1] By "partially fused" it must not be understood that the temperature of the soda lime rises to anything like the fusing point of soda lime, but that there is an appearance not unlike fusion.

TESTING THE WATER AND CARBON-DIOXIDE ABSORBER SYSTEM.

In a closed-circuit apparatus every precaution must be taken to guard against leakage of air; hence the absorber system is frequently subjected to the most rigid tests for tightness.

Each water-absorber is tested, immediately after being weighed, in the following manner: A one-holed rubber stopper fitted with a Y tube is inserted in the coupling of the water-absorber at the end through which the air leaves the can. One arm of the Y is connected with a water manometer capable of indicating pressures up to 4 feet of water, and the other arm is connected by means of a length of rubber tubing to a bicycle pump for obtaining an increased air-pressure. A solid-rubber stopper is used to insure a tight closure of the other coupling on the absorber. By means of the bicycle pump the desired pressure is put on the absorber, and the screw pinchcock on the rubber tube between the pump and the manometer is then tightly closed. After a preliminary fluctuation in pressure, which lasts for a moment or two, a piece of paper is slipped between the glass arm of the manometer and the wooden support at such a point that its lower edge just coincides with the bottom of the meniscus. A leakage of air from the absorber is accompanied by a fall of water in the manometer. No leakage should be apparent at the end of from three to five minutes. At the conclusion of the test the manometer is disconnected and the pressure released.

An extended experience shows that after the removable ends of the carbon-dioxide absorbers are well screwed on a leak rarely occurs at this point; consequently it is not necessary to test each individual absorber after weighing.

The water-absorbers are then coupled with the three carbon-dioxide absorbers as in use and the system as a whole is tested to prove not only the tightness of the individual absorbers themselves, but also of all the couplings. In this test a solid-rubber stopper is used to close the couplings on the exit end of the last water-absorber, and the Y tube of the manometer is connected with the side tube G, figure 10, attached just beyond the mercury valve. Pressure is then put on the system by means of the bicycle pump and the tightness of closure tested, as for the separate cans. By the use of this method of testing, leaks in this portion of the apparatus have been practically eliminated.

MAINTENANCE OF THE SUPPLY OF OXYGEN.

To replace the oxygen consumed by the subject, as well as to maintain a constant volume inside the system, supplies of oxygen are admitted from time to time. The oxygen used for the purpose is a commercial product, the so-called "commercial oxygen" manufactured by

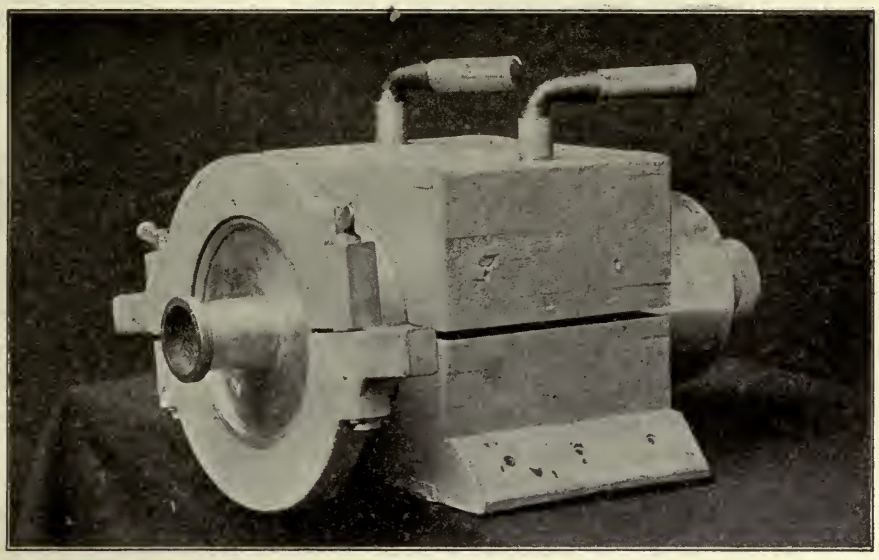

FIG. 14.—Vise for tightening Carbon-Dioxide Absorbers. Top of Absorber is held in a wooden vise clamp by two handles; Collar held in special clamp.

FIG. 15.—An Oxygen Cylinder with Valve, Rubber Pressure Bag, and Purifying Attachments. On opening valve oxygen escapes through the metal tube through the purifying attachments. If the pressure is excessive, excess of gas enters bag.

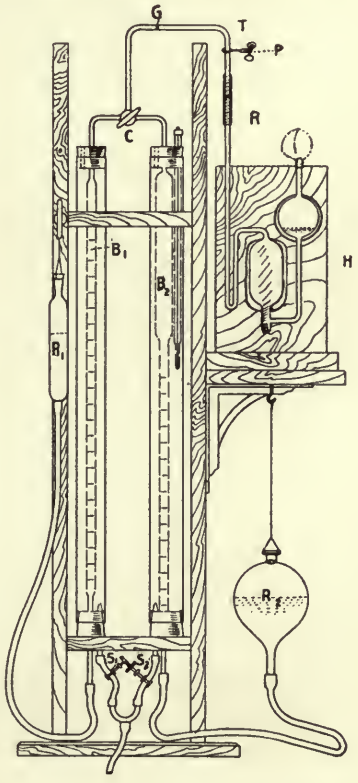

FIG. 16.—Apparatus for Analysis of Oxygen and Air. Two water-jacketed burrettes, B_1 and B_2, each with water reservoirs, R_1 and R_2, are connected by the 3-way stopcock C. Pipette H is connected through a capillary (T) with the apparatus.

the S. S. White Dental Manufacturing Company, of Philadelphia. This oxygen has been in use for some years in this laboratory in connection with the bomb calorimeter[1] and the carbon and hydrogen determinations.[2]

It contains, besides oxygen, from 2.5 to 8 per cent of nitrogen and small quantities of carbon dioxide and water vapor, but no appreciable quantities of hydrogen or gaseous hydrocarbons. In preparing it for use it is necessary only to remove the carbon dioxide and water and determine quantitatively the percentage of nitrogen.

The oxygen is contained in steel bottles or cylinders (fig. 15) 61 cm. high, 11 cm. in diameter, weighing (exclusive of purifying apparatus), when charged with 283 liters of oxygen at a pressure of 2,000 pounds to the square inch, about 7 kg.

A metal yoke is securely fastened to the valve with a screw clamp and leather washer, and a brass T tube conducts the oxygen into a rubber gas-bag[3] and through the side outlet to the purifying device. The use of the bag is imperative, for the pressure in the cylinder is so high that however carefully the valve is opened the gas escapes so suddenly that the connections are liable to be disturbed unless an overflow for the surplus gas is provided.

The gas then enters a large U tube fastened to the side of the cylinder by means of two rubber bands. The U tube is filled with soda lime, such as is used in the carbon-dioxide absorbers in the main system. To prevent any particles of soda lime from being carried mechanically out of the U tube, a tuft of cotton batting is placed at the exit end. In its passage through the soda lime the gas is completely freed from carbon dioxide. It still retains the moisture it originally contained, and some that it has taken from the moist soda lime. To remove the moisture, the gas is next passed through a drying tube of special construction, filled with pumice stone drenched with sulphuric acid. A bulb at the lower end allows for the accumulation of spent acid. By an actual test it has been found that such a tube will remove all the water vapor from the oxygen in at least ten cylinders before it needs refilling.

As a matter of fact, when the bulb at the lower end becomes filled with spent acid, the tube is removed, inclined so as to drain out the

[1] Jour. Am. Chem. Soc. (1903), **25**, p. 569.
[2] Benedict, Elementary Organic Analysis, p. 4.
[3] The bags are made for us by the Davol Rubber Company, of Providence, Rhode Island. They are extra heavy wall, of pure rubber, and will withstand considerable tension without noticeable leak. It is estimated that a bag 21 cm. long (measured, when folded) will, as a rule, readily take care of 2 or 3 liters of oxygen without loss. It is seldom, however, that an excessive amount of gas enters the bag, as the adjustment can usually be readily made by means of the valve.

acid, and several portions of concentrated acid poured in at the top, each successive portion being allowed to drain out before the next is added. Obviously such replenishment of acid is made only when the purifying system is to be changed from an empty cylinder to a new one, and, as pointed out above, at least ten cylinders can be used with each charge of acid. The replenishment of the soda lime in the U tube is made only when the reagent becomes exhausted, as is readily noted by the whitening effect on the reagent. (See p. 29.)

By attaching the purifying device to the cylinder itself and noting the loss in weight in the system as a whole, the weight of gas used can be obtained, since it corresponds to the amount of oxygen and nitrogen leaving the cylinder. The quantity of oxygen consumed in the course of 24 hours by a subject, varying as it does from 350 to 1,500 liters, can be best determined in this way.

By means of the balance described on page 57 it is possible to note the loss in weight of an oxygen cylinder to within 10 mg. As 10 cc. of oxygen weigh but 14 mg., it is thus seen that 283 liters (the contents of one cylinder) can be measured with an accuracy far beyond that of any gas-meter with which we are familiar. In all of the work with the respiration calorimeter this method of measuring oxygen is constantly used.

In weighing, the cylinder is suspended on a wire from the balance-arm by two loops of wire, one around the valve end of the cylinder and the other, a much larger loop, around the bottom of the cylinder. The manipulation of the cylinder and its adjustment on the balance require a little care on the part of the assistant, but in spite of the use of glass tubes for absorbers there has been as yet no loss by breakage during weighing.

Analysis of Oxygen.

Since the gas in the cylinder contains nitrogen as well as oxygen, and the amount of oxygen admitted to the system is estimated from the loss in weight of the cylinders, it is obviously necessary to analyze the gas and determine the percentage of nitrogen. As has been stated, the amount of nitrogen generally present is not far from 2.5 to 8 per cent. There is also a small amount of carbon dioxide, but this is removed by the soda-lime U tube attached to the cylinder. Of the three standard methods for absorbing oxygen, *i. e.*, the use of potassium pyrogallate, phosphorus, and explosion with hydrogen, the first is most readily adapted to the analysis of nearly pure oxygen. The method of analysis consists, therefore, of measuring a known volume of commercial oxygen free from carbon dioxide, absorbing the oxygen by potassium pyrogal-

late, and measuring the residual nitrogen. The form of apparatus is shown in figure 16.

The apparatus consists essentially of two burettes, water-jacketed to secure more constant temperature, and connected by a 3-way cock, which in turn is joined to the regular Hempel gas-pipette. The 3-way cock and glass connections are made of capillary glass tubing.

Each fresh cylinder of oxygen is connected by a metal yoke from its valve with a T tube, one arm of which dips under a little water and the other arm of which is connected with a soda-lime U tube and thence with the capillary tube T leading to the burettes. Before connecting with this capillary tube, however, the oxygen is allowed to flow for several minutes through the soda-lime tube with just enough pressure not to bubble through the water of the escape. The burette B_2 and capillary tube T have been previously filled with water by opening the 3-way cock C and raising the reservoir R_2, thus expelling the air from the apparatus into the room and leaving the burette B_2 and the tube T filled with water. The stopcock C is then closed and the reservoir R_2 lowered and hung at such a level that the water in the burette will drop to about the 100 cc. mark when the stopcock C is opened. The soda-lime U tube is connected with the capillary tube T, the oxygen meanwhile bubbling through the escape, the stopcock C slowly opened, and oxygen drawn into the burette, the bubbling ceasing or nearly ceasing while the burette fills. When the level of the water in B_2 is the same as that in R_2 the stopcock C is closed and the current of gas through the soda-lime tube stopped by closing the valve on the cylinder. After allowing the water to drain down the side of the burette B_2 for a definite length of time (five minutes), the reservoir R_2 is held immediately behind the burette B_2 in such a manner that the level of water in both is the same. The readings of the volume of gas in the burette B_2 are then recorded. By means of gentle suction with the mouth the capillary tube and a portion of the rubber tube R which is attached to a Hempel pipette containing a solution of potassium pyrogallate are filled with the pyrogallate solution and the rubber tube tightly closed by means of a pinchcock P. The section of the rubber tube above the pinchcock is then completely filled with water and attached to the capillary tube T. The connection with the cylinder first being broken, the pinchcock is then opened, slipped on the glass capillary tube T, the stopcock C turned in such a manner as to connect the burette B_2 directly with the Hempel pipette, and by raising the reservoir R_2 the oxygen is transferred to the pipette. The last traces of gas can be removed from the burette and both capillary tubes by forcing through them water

from the reservoir R_2. When the last traces of gas have left the capillary on the pipette the stopcock C and the pinchcock are closed.

The pipette is then shaken in the hand for five minutes, at the end of which time, as has been shown by repeated tests, the absorption of oxygen is complete.

After filling the upper part of the rubber tube R with water the pipette is connected with the capillary tube T. On opening the stopcock C in such a manner as to connect the capillary tube T with the burette B_1 previously filled with water, and by lowering the reservoir R_1, the unabsorbed gas can be drawn over into burette B_1. R_1 is lowered sufficiently to cause the reagent in the pipette to rise in the capillary, completely fill the rubber tube R and pass along the capillary T, to a graduation G, when the stopcock C is closed. After waiting about three minutes for the water on the walls of burette B_1 to settle, the reading of the level of water in B_1 is made by holding the reservoir R_1 immediately back of the burette in such a manner that the levels in both tubes are the same.

Both burettes B_1 and B_2 are so graduated that they can be read accurately to 0.01 cc. The small burette B_1 is graduated from 0 to 20 cc. The large burette B_2 is graduated only above 90 cc., but from 90 to 100 cc. it is graduated in 0.05 cc.

In computing the actual volumes of gas used it is necessary to take into consideration the volume of the space in the connection between the stopcock C and the two burettes, as well as that of the capillary extension-tube T. Before being used for gas analyses, both burettes were calibrated very accurately by filling with mercury. It was thus found that to the reading obtained on burette B_2 there must be added a constant 0.51 cc. for the volume of gas in the connections between the burette proper and the end of the tube T, and to the volume as read on burette B_1 there must be added a constant 0.34 cc. for the volume of gas in the connections between the burette proper and the graduation mark G on the capillary tube T.

In the analyses it is assumed in the first place that the difference in time between the beginning and end of an analysis is so short that no difference in barometric pressure will occur that need be taken into consideration. It is furthermore assumed that in general, in the analysis of oxygen, the relations between the volumes of nitrogen and of the oxygen as originally measured are such that no fluctuations in temperature ordinarily experienced will affect materially the percentage of nitrogen in the sample of oxygen being analyzed. Consequently the volume of gas plus the correction 0.51 cc. as measured on burette B_2 and the volume of nitrogen as corrected with the constant 0.34 cc. as

measured on B_1 are compared directly in order to determine the percentage. The analyses are always made in duplicate, and the figures, it is found, are in general sufficiently accurate to warrant calculation to the second or even third decimal place.

It may be said of this apparatus that it might easily be made more convenient and accurate. Designs for an improved form are now under consideration. Inasmuch, however, as the apparatus gives excellent service, it has not seemed advisable to delay other work for the inevitable period of experimentation that must always accompany the introduction of a new form of apparatus. Furthermore, it is readily seen that owing to the small percentage of nitrogen there might be a considerable error in measuring the absolute volume of oxygen taken for a sample without noticeable effect upon the final results.

Preparation of the reagents.—Inasmuch as large quantities of potassium pyrogallate solution are used for the numerous oxygen analyses, as well as in air analyses to be described beyond, incidental to a metabolism experiment, we have found it advisable to prepare stock solutions of potassium hydroxide and of pyrogallic acid that can be mixed in the proper proportions as desired.

The potassium hydroxide solution was formerly prepared by dissolving 2,400 grams of stick potassium hydroxide in 1,600 cc. of water. This method, however, proved needlessly expensive, and moreover demanded that special precautions be taken to make sure that the "stick potash" had not been purified with alcohol, since, as Hempel[1] points out, the presence of small quantities of alcohol may be a serious source of error. It was found that a grade of commercial caustic potash, sold by the Roessler & Hasslacher Chemical Company, of New York, and costing about 7 cents per pound, could be substituted to good advantage. Our present practice is to dissolve 2,400 grams of this potash in 1,750 cc. of water and filter the solution when sufficiently cool through glass wool.

In preparing the solution of pyrogallic acid 100 grams of the acid are dissolved in 300 cc. of water, the mixture of acid and water being well shaken until there is complete solution.

These stock solutions are generally made up several days before they are needed for use.

The proportions in which the acid solution and the potassium hydroxide solution are mixed are 7 cc. of the pyrogallic-acid solution to 44 cc. of the potassium hydroxide solution. Two sizes of pipettes are regularly used. The larger pipette requires 28 cc. of the acid and 176 cc. of the alkali to fill it, the smaller 21 cc. of acid and 132 cc. of alkali. The acid is placed in the pipette, a portion of the alkali added, and the

[1] Hempel, Gas Analysis, 1892, p. 115.

mixture shaken. The remainder of the potassium hydroxide is then added, and after thorough mixing the reagent is allowed to cool to room temperature. The resultant effect of mixing the two solutions and of the heat generated is generally a slight evolution of gas, which usually remains in the form of small bubbles on the surface of the reagent. Before being used for an analysis these bubbles are withdrawn by connecting a 10 cc. pipette with the rubber tube R, figure 16, and drawing the froth into the pipette.

It has been found advisable on mixing up fresh reagent to shake it well and, if possible, allow it to stand some time before use. The quantity of reagent in the small pipette, *i. e.*, 155 cc., suffices for five oxygen analyses, in which 100 cc. of gas are taken for each sample. Thus the absorbing constant of this reagent is not far from 2.5.

The usual precautions are taken to prevent the deterioration of the reagent, such as keeping both ends of the pipette closed when not in use. The open end of the reservoir on the pipette is closed with a rubber bag.

Converting percentage by volume to percentage by weight.—As the amount of oxygen and nitrogen admitted from each cylinder into the ventilating air current is determined by weight rather than by volume, it is necessary to convert the percentage composition by volume to that by weight. The percentage is calculated in the following manner:

Weight of 1 liter of nitrogen = 1.25668 grams.[1]
Weight of 1 liter of oxygen = 1.42853 grams.

Example: In cylinder No. 31089 analysis showed 5.13 per cent of nitrogen by volume.

	Grams.
100 liters of gas contains 5.13 liters of N =	6.43
100 liters of gas contains 94.87 liters of O =	135.53
100 liters of gas weighs.....	141.96

6.43 ÷ 1.4196 = 4.541 per cent of nitrogen by weight.

Computation of percentage of nitrogen by weight by using factors.—The percentage of nitrogen in oxygen seldom falls below 2 per cent or exceeds 6 per cent, but the fluctuations are too great to rely on the constancy of composition of a lot of cylinders, even if shipped from the factory at the same time; consequently it becomes necessary to analyze each cylinder. After a few determinations it was found that instead of carrying out the somewhat elaborate calculations just referred to, a factor could be used in calculating directly the percentage by weight from the percentage by volume. Thus, for all samples of oxygen containing

[1] See page 82.

nitrogen in percentages below 2.50, the calculation of the percentage composition by weight can be very accurately made by multiplying the volume percentage by the factor 0.882. For all volume percentages between 2.50 and 3.80 the factor in use is 0.883. For higher percentages the factor is increased 0.001 for every 0.95 per cent of increase in the nitrogen content. At present we rely wholly on this method.

In order to minimize the actual amount of work during the progress of an experiment, the cylinders of oxygen are analyzed and the percentage composition by volume and weight determined several days before the experiment begins.

THE TENSION EQUALIZERS.

The volume of the air inside the closed circuit is subject to continued fluctuations as a result of changes in temperature, barometric pressure, oxygen consumption, and water and carbon-dioxide absorption. In order to maintain at all times atmospheric pressure inside the respiration apparatus, and thereby reduce to a minimum the danger of rupturing the comparatively thin chamber walls and the liability of leakages throughout the system, a compensating device was arranged, which is shown in figure 17.

The device consists of two pans, connected with the main air-pipe and covered at the top with flexible rubber diaphragms, which by their expansion allow for considerable variation in the total volume of the circuit. The diaphragms are made of pure gum, molded to fit the inner surface of the pan, and so formed as to lap over the edge. A stout rubber band is snapped over the edge of the pan so as to hold the edge of the rubber diaphragm closely against the rim of the pan, making a very tight closure. A hard rubber disk of a diameter a few millimeters less than that of the inside bottom of the pan is cemented to the top of the diaphragm by means of fish glue. Three holes at equal distance in the periphery of this disk provide for three loops of wire which meet at a point directly above the center of the disk and are there fastened to a small ring. The weight of the diaphragm and disk, distributed as it is over the whole system, exerts comparatively slight pressure. In order to eliminate pressure entirely, however, the weight is counterbalanced by suspending the diaphragm on a fine, flexible steel wire running over the rim of a bicycle wheel, the edge of which is so placed that the wire hangs perfectly plumb and without lateral strain or pull. On the opposite side of the rim of the wheel a similar flexible wire is attached, the lower end of which is weighted with a counterpoise containing shot. The bicycle wheel, having ball bearings, is extremely sensitive, and it is possible to adjust the weight of shot in the counter-

poise so as to compensate for practically all the weight of the rubber diaphragm. It is evident that the higher the diaphragm is raised the greater the proportion of its weight that is suspended, as more of the rubber diaphragm is then suspended from the central rubber disk and less from the edge of the pan, though as a matter of fact the slight variations in weight, amounting to but a few grams for the different positions of the diaphragm, are distributed over so large an area that it is impossible to note any difference in fluctuation of the water manometer. In practice the counterpoise is so adjusted that the rubber diaphragm remains in a position about half way between the top and the bottom when all connections are open.

Under these conditions it is assumed that the pressure on the whole respiration system, when the blower is not in operation, is atmospheric, except in the carbon-dioxide and water absorbers, as explained on page 73. The resistance of the length of pipe between the pans and the respiration chamber is sufficient to cause the pans to rise rather than fall when the blower is running and the pipe is open, but under all conditions of passing air through the system it has been found practically impossible to detect any differences in pressure in the chamber proper, since the pans so perfectly compensate for variations in barometric pressure and other changes in volume.

It will be noticed that the pans are connected with the air-pipe between the pump and the respiration chamber. The air in the pans has therefore been freed from carbon dioxide and water. There is as yet no evidence to indicate that carbon dioxide enters through the rubber diaphragm in measurable amounts. It has been found, however, that appreciable quantities of water vapor may be admitted into the system in this way. To guard against this an enameled-ware dish, half filled with concentrated sulphuric acid, is placed in the bottom of each pan. As the result of a number of tests it was found that when this precaution was taken no weighable quantities of water vapor enter the closed air-circuit through the pans, whatever diffuses through the rubber being apparently retained by the sulphuric acid. To prevent the rubber diaphragm from coming into contact with the acid, the dish containing the latter is covered with a wire gauze.

The volume of air in each pan consists of two portions, one of which is constant, the other variable. The constant volume comprises that portion contained when the rubber diaphragm is at its lowest point, *i. e.*, resting on the gauze cover to the sulphuric-acid dish. The fluctuating volume is limited by the highest position of the diaphragm. The two pans allow for fluctuations in volume of about 29 liters.

Calibration of the pans.—In order to know accurately the actual volume of air in the system as a whole, it is necessary to take into consideration the fluctuating volume of air in the pans, and consequently a calibration showing the volume of air inclosed by the rubber diaphragms at different positions is essential. By calculations based upon measurements of dimension it is possible to determine the volume of air in the pans when both diaphragms are down.

By means of the valve in the main air-pipe leading to the chamber (see fig. 17) and the mercury valves at the exit end of the absorber system, the section of the circuit to which the pans are attached may be sealed off. Furthermore, by means of a lead weight attached to a hook from which the rubber disk is hung, one of the pans may be kept empty. It is thus seen that if air is admitted at any point in this portion of the ventilating air-pipe under these conditions the rubber diaphragm on the other pan will become inflated.

There is no condition in which both pans need to be read when only partly filled, and in practice one can be kept either full or empty. It is necessary, therefore, to calibrate completely but one of the pans, and this has been done only with that shown in the foreground of figure 17. It is sufficient for the other pan to determine the actual amount of air contained when full, and in order to facilitate reading and insure accuracy it is customary either to place a weight on the disk and so expel all air from the pan or to attach the weight to the outer end of one of the bicycle spokes on the opposite side of the wheel to insure filling. That there shall always be a rise and fall through exactly the same distance, two screws are inserted in the rim of the wheel at such a point that when the pan is weighed empty a screw strikes against the fork, and thus relieves the extra weight. Similarly, a screw placed in the bicycle rim on the other side of the fork prevents the weight from raising the rubber diaphragm beyond a definite point. Between these two points, therefore, it is necessary to know the volume of air required to fill the diaphragm. This was found by forcing room air through the Elster meter, then through sulphuric acid to remove all moisture, and finally into the system until the rubber diaphragm had reached its highest point. This was easily detected, for at the moment the screw in the rim of the bicycle wheel touches the fork during the upward movement of the diaphragm an electrical contact is made, causing a bell to ring. From the readings of the meter, including its temperature and the pressure on the manometer, and the readings of the barometer and thermometer, the volume of dry air thus added to the system was readily computed. This amount, plus the constant volume of air contained in the pan below the bottom of the diaphragm when in its lowest

position, obviously gave the entire content of the pan when filled. In calibrating the other pan the procedure was identical with that outlined above, save that the pan was calibrated for intermediate positions of the diaphragm. These were determined by means of a pointer attached to the bicycle wheel. As the diaphragm rises or falls the wheel turns, and the pointer travels over a graduated arc reading to millimeters. In the calibration, as the dial on the meter passed each half-liter mark, the reading of this pointer was taken. The actual volume of air was then determined for each point on the scale. These points were subsequently plotted on a curve, and as a result it is only necessary to adjust one pan so that it is either full or empty, and to read the pointer on the other in order to estimate very exactly, that is, probably within 0.1 liter, the actual volume of air in the two pans.

In the course of a year's experimenting the sulphuric acid in the enamel dishes inside the pans will gradually absorb moisture and consequently increase in volume. This increase in volume is, however, negligible.

POSSIBILITY OF NOXIOUS GASES IN THE SYSTEM.

An anticipated objection to the use of the closed circuit was the possibility of introducing noxious gases into the apparatus. It is readily conceivable that relatively small amounts of sulphuric-acid vapor, or mercury vapor, for example, would be extremely injurious to the health of the subject. Since the air current comes in contact with sulphuric acid in the absorbers and to a less extent with mercury vapor in the valves, it was especially necessary to determine carefully the extent to which these substances might be carried into the system.

Acid fumes carried over by air current.—Reference has already been made to the pumice-stone traps on the exit tube leading from the water-absorbers. These serve to diminish the possibility that acid will be carried along mechanically. As an additional safeguard, a layer of cotton, kept in place by a wire-gauze thimble such as is used in the carbon-dioxide absorbers, is inserted in the rubber tube connecting the last water-absorber with the air-pipe leading back to the chamber. As a result of practical experience it has been found that this cotton serves to retain any acid fumes in the air current.

Mercury vapor in the air.—Owing to the marked susceptibility of certain individuals to the toxic properties of minute quantities of mercury vapor, care was necessary to obviate all danger of poisoning. As has been described, the mercury valve (fig. 10) depends upon mercury to effect a tight closure. To be sure, the construction of this valve is such that when it is open and air is passing through it all of the

mercury is drained out of the valve into the reservoir. Nevertheless, it is conceivable that a few globules might adhere to the metal work and the mercury gradually find its way into the air current. In the first set of valves, however, it is highly probable that any mercury vapor passing through the absorber system would be absorbed, and consequently there remains only the possibility of the vaporization of mercury from the valves beyond the absorbers.

Since the volume of air confined in the system is used over and over again, it might at first glance be considered an ideal place for the accumulation of mercury vapor. Two circumstances militate against this assumption. In the first place, the air is continually being withdrawn from the chamber, and any mercury vapor remaining in it would be absorbed along with the water in the water-absorbers. Secondly, the air traverses a relatively long metal pipe galvanized inside, so that the tendency for amalgamation would be very great. Likewise the copper walls of the chamber would tend to retain the mercury. As a matter of fact, in none of the experiments thus far made, in which different subjects have remained in the chamber for periods varying from 1 to 13 days, have indications of mercurial poisoning ever been noted, and it seems probable that no appreciable quantity of mercury vapor enters the respiration chamber.

Proportion of water vapor in the air.—Since the ventilating current of air enters the respiration chamber absolutely dry, the possible effect of such dry air on the mucous membranes of the throat and nose is of importance, especially in long-continued experiments. In the immediate vicinity of the pipe which conducts the air into the chamber, unquestionably the air is extremely dry. In the course of a very short time, however, diffusion produces a uniformity in the composition of the air in the chamber which is probably pretty evenly distributed throughout the whole volume.

The total volume of air in the chamber is not far from 5,000 liters, and if saturated with water vapor at 20° C. it would contain about 85 grams of water vapor. Generally the amount of water vapor present in the residual air is not far from 40 grams, although at times it may be as low as 25 grams. Obviously, then, there is only about 50 per cent saturation under ordinary conditions, and at times as low as 30 per cent. This is not unduly dry air, and yet experience has shown that it is capable of producing certain physical effects that can be attributed only to excessively dry air. The subjects very frequently complain of being rather cooler than when in the air of the laboratory. This is explained by the fact that there is much more rapid vaporization of water from the lungs and skin and consequently a low-

ering of temperature. On one or two occasions, when the subject has slept, contrary to the advice of the experimenters, with his head near the pipe conducting the air into the chamber, slight disturbances of the respiratory tract have been experienced, but when sleeping with the head at the other end of the chamber no such disturbances have occurred.

APPARATUS FOR THE ANALYSIS OF THE RESIDUAL AIR.

For purposes of calculation it is necessary to know the carbon-dioxide and water content of the closed volume of air at the end of each experimental period. While any one of the numerous methods depending on the use of a solution of barium hydroxide and phenolphthalein might be used for the determination of carbon dioxide, and consequently only a very small volume of gas required, none of the methods of hygrometry as ordinarily employed will give the water content of the air with sufficient accuracy. It is therefore necessary to determine the water by the absolute method, that is, by aspirating a large quantity of air through some water absorbent and actually weighing the water vapor thus removed. The arrangements for this operation are illustrated in figure 18.

A 10-liter sample is withdrawn from the air-pipe between the respiration chamber and the blower through the mercury valve described on page 18. The water vapor and carbon dioxide are removed by conducting the sample through sulphuric acid and soda lime, respectively, the volume of air withdrawn being accurately measured by a gas-meter. After leaving the meter the air enters the water-pump, where the suction required to draw the air through the tubes and the meter is obtained. A device for separating the air and water leaving this pump makes it possible to return the air sample to the ventilating air current between the pans and the respiration chamber.

Theoretically the sample of air should be drawn at exactly the end of the different experimental periods. In such case, however, it would necessitate the complete withdrawal of 10 liters of air from the system and introduce serious complications in the calculations. By means of the system of U tubes described beyond, it is found that air may be drawn through these tubes at the rate of 2 or even 3 liters in one minute and all the carbon dioxide and water be quantitatively absorbed. At this rate the air can be drawn with sufficient rapidity to furnish results that agree with those from a 10-liter sample drawn at one instant. By returning the air to the system no loss occurs.

The requirements for absorbents for water vapor and carbon dioxide that will effect the complete removal of these substances from an air

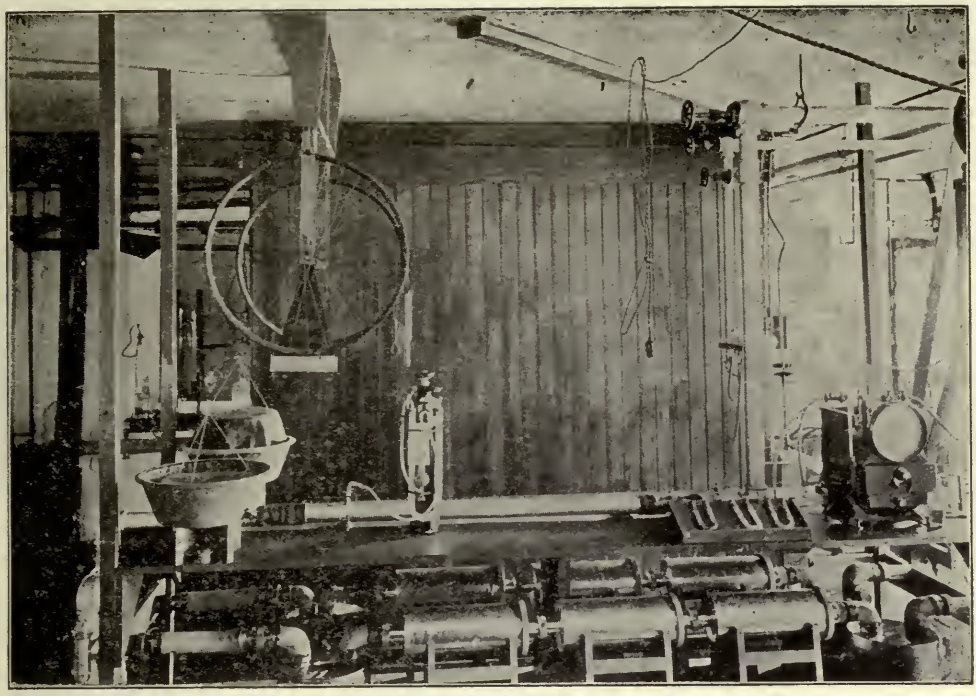

FIG. 17.—Pans for Equalizing Pressure. Two painted tin pans with rubber diaphragms which fit their interior are attached to connecting air-pipe. Weight of diaphragms is equipoised by lead shot suspended from a bicycle wheel. Variations in position of height of diaphragm are read on the graduated arc beneath bicycle wheel.

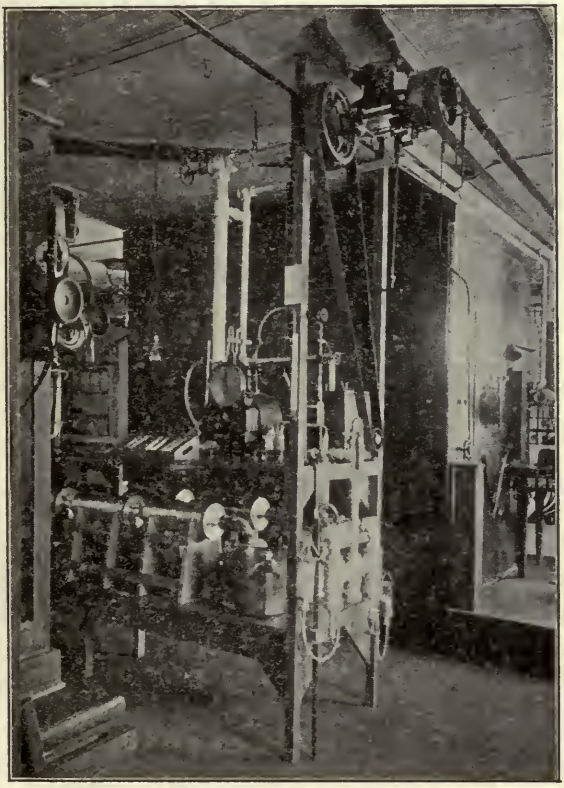

FIG. 18.—Apparatus for Analysis of Residual Air. U tubes on top shelf of table are connected with Elster meter. Glass water-pump and air-separating chamber immediately to right of center posts. Sulphuric-acid drying bottle at right of Elster meter.

current flowing at the rate of 2 to 3 liters a minute are met by using pumice stone drenched with sulphuric acid to absorb the water vapor and the specially prepared soda lime (see p. 29) to absorb the carbon dioxide. These absorbents are held in glass U tubes.

Apparatus for Absorption of Water.

The pumice stone is broken into pieces approximately 5 mm. in diameter, the finer dust carefully sifted out, and each arm of the U tubes filled to within 10 mm. of the top. About 10 cc. of commercial concentrated sulphuric acid is slowly poured over the pumice stone in both arms of the tube, care being taken not to add so much acid as to completely close the bend at the bottom of the U and thus retard the free passage of gas. One-hole rubber stoppers provided with small glass elbows are fitted in each arm of the U and a small label with the number of the tube is placed on one arm. All connections are made in such manner that the air leaves the U tube from the arm on which the label is placed. This precaution is necessary, because as the moist air enters the U tube the sulphuric acid with which it first comes into contact takes up the water vapor from it, and consequently becomes somewhat diluted. If during a subsequent use of this tube the air were allowed to enter the other arm and pass out over the dilute acid on the pumice stone, experience has shown that the removal of water would not be complete, since the very dry air would take up water from the dilute acid.

Owing to the presence of chlorides in the pumice stone, the addition of sulphuric acid is liable to produce a slight evolution of hydrochloric-acid gas, and consequently, when the U tubes are freshly filled, it is desirable to draw dry air through them for a few minutes, thus removing the hydrochloric-acid gas. This precaution is also taken with the U tubes used for the oxygen purification, described on page 33. In this case it is of even greater importance, as otherwise the hydrochloric-acid gas would enter the main air current.

The U tubes are 130 mm. long, 60 mm. wide, measured on the outside, and 15 mm. in diameter. They weigh, when fitted with rubber stoppers, glass elbows, pumice stone, and acid, not far from 70 grams. When not in actual use the glass elbows are closed by short pieces of rubber tubing fitted with glass plugs.

Efficiency of absorption.—It has been found by repeated experiment that a U tube filled as above described can be safely relied upon to absorb one gram of water vapor. In the ordinary usage to which the tubes are subjected in this laboratory, it is nearly always possible to predict the gain in weight during an analysis. Thus if it is expected

that a tube will gain in weight 0.12 gram, it can have already increased in weight 0.88 gram with safety. If, however, the anticipated increase in weight will make a total gain of more than one gram, the tube is refilled before use.

Apparatus for Carbon-Dioxide Absorption.

For the removal of carbon dioxide, U tubes similar in size to those used for water absorption are employed. Each tube is filled to within 10 mm. of the top with soda lime, the particles of which are not so fine as to obstruct the flow of gas. The ends of the tube are then closed with rubber stoppers and glass elbows, as described above.

Efficiency of absorption.—In spite of the remarkable absorptive power of soda lime for carbon dioxide, it is not advisable to use a soda-lime U tube for more than one or two analyses, depending upon the amount of carbon dioxide absorbed. As a rule, it is not safe to use a U tube in which the whitening effect, due to the formation of carbonate, extends more than half the length of the tube.

In practice, the sample of air is drawn through a sulphuric-acid U tube, a soda-lime U tube, and a second sulphuric-acid U tube. Any moisture escaping from the damp soda lime is retained by this second sulphuric-acid U tube, the quantity thus absorbed being approximately 1 mg. for every liter of air passing through the soda lime.

The Elster Meter.

For measuring samples of air for residual analysis, a meter made by S. Elster, of Berlin, has been used. The meter is shown in figure 18, just to the right of the U tubes.

This meter is very sensitive, and measures volumes up to 10 liters, each liter being graduated to 2 cc. Attached to it is a water manometer. Experiments show that the extreme variation in tension in different parts of the meter when air is freely drawn through it amounts to less than 5 mm. of water. This difference holds regardless of the rate at which the air is drawn through the meter. The meter is provided with a spirit level and leveling screws. The case of the meter is filled with water, the excess being drawn off through an overflow. Since the air enters the meter dry and leaves it moist, water is removed from the meter during the progress of the experiments. As used at present about 4.5 grams of water are evaporated during the course of 24 hours; consequently water is added from time to time in order to keep a constant level.

In general, 10 liters of air are drawn for each residual analysis, the meter being read before drawing the sample and after the manometer has settled to zero at the close.

The vaporization of water in the meter results in a slight lowering of the temperature of the water in the meter as the air passes through it. The thermometer is read in the middle of each residual sample, *i. e.*, when 5 liters of air have passed through the meter. This is assumed to give the average temperature of the 10 liters.

Calibration of Elster meter.—The Elster meter was calibrated by passing a known weight of oxygen from a cylinder through the meter and comparing the volume as calculated from this weight with the volume recorded by the meter after making due corrections in the latter for temperature, tension of aqueous vapor, barometer, etc. In order to have the conditions under which the gas is measured correspond as nearly as possible to those under which residual analyses are taken, provision was made for maintaining during the test a diminished pressure in the meter amounting to 198 mm. of water. This diminished tension is that ordinarily experienced when conducting a residual analysis, and is a measure of the resistance of the tubing, U tubes, and meter.

In conducting the test the apparatus was connected ready for use, the oxygen cylinder weighed, and the barometer reading taken. At the end of every 10 liters the temperature of the meter was recorded. The barometer was read periodically, but it was found that the fluctuations were very slight, and, in general, the average of the readings at the beginning and end could be used. After about 100 liters of air (apparent volume as measured by the meter) had passed through the meter the cylinder was weighed and the calculation of volume from weight was made.

From a number of such tests it was found that to obtain the true reading from the meter under the conditions of the experiment the logarithmic factor .98895[1] should be added to the logarithm of the apparent volume.

Test for Saturation of Air Passing Through the Elster Meter.

In drawing through the Elster meter the air used for the residual analyses, it is assumed that, coming in contact, as it does, with a large volume of water in its passage through the meter, it becomes saturated with water vapor at the temperature of the meter. It was necessary to verify this assumption, especially as in the calculations the volume of air passing through the meter is multiplied by a large factor and so must be known with great accuracy. To test this point, 20.103 liters of air, as measured by the meter, were forced through the meter at a tem-

[1] For convenience in calculations the characteristics of the logarithms of the factors are neglected.

perature of 17.89° and then through a weighed U tube containing pumice stone and sulphuric acid.

Air saturated with water vapor at 760 mm. and 17.89° contains 0.01513[1] gram of water per liter.

In this test the air when passed through the meter contained 0.3055 gram of water vapor in 20.103 liters apparent volume or 20.42 liters corrected volume. This corresponds to 0.3055 ÷ 20.42 = 0.01496 gram of water vapor per liter—an agreement inside of the error of experimentation. It is assumed, therefore, that the air passing through the meter is saturated with water vapor.

Apparatus for Drawing Sample.

Obviously, with the closed circuit, it would be undesirable to remove from the system so large a sample as 10 liters of air at the end of every two hours. By means of the apparatus shown in figure 19, it is possible to draw as large a sample of air as is desired through the U tubes, remove from it carbon dioxide and water vapor, and return it to the system dry, free from carbon dioxide, and diminished in volume only by the volume of the carbon dioxide and water vapor removed by the absorbents.

The apparatus consists of a glass suction-pump A, a separating chamber B, in which the air and the water used for aspiration are separated, and the drying chamber D, in which the water vapor taken up by the dry air from the water-pump is removed before the air is returned again to the system. The sample of air after leaving the U tubes passes through the Elster meter (see fig. 18) and then enters the suction-pump at the tube *a*. As the air and water issue from the glass extension tube they strike against the side of the separating chamber B. The water flows through the overflow *c* into the drain *d*. The air passes out through the enlarged tube *e*, bubbles through concentrated sulphuric acid in the drying chamber D, and finally passes through the small tube *f* back into the air system. It has been found by repeated experiment that 10 liters of air saturated with water vapor at the temperature of the laboratory, *i. e.*, 20°, passing through the drying chamber in three or four minutes, will be completely freed from water vapor. The acid in the chamber is replenished from time to time by removing the central stopper and withdrawing the acid by suction.

Two valves, w_3 and w_4, are used to admit water to the suction-pump. The valve w_4 is permanently adjusted so that the supply of water passing through the pump will be that best fitted for drawing the sample

[1] Smithsonian Meteorological Tables (1897), p. 133.

of air through the U tubes and meter at a proper rate of flow, while the water is ordinarily turned on and off by the valve w_3. At t a glass T tube is inserted for the rejection of air (see p. 77), to the stem of which a rubber tube dipping into a small vial containing water is attached. The rubber tube is ordinarily closed with a screw pinchcock, the tightness of the closure being proved by the absence of bubbling of water in the small vial.

The water used for actuating the suction-pump enters at m and passes into the large chamber F, which serves as a trap. This chamber consists of 2-inch gas-pipe with a cap at each end. To prevent sediment from clogging the fine jet of the water-pump, the supply of water for the pump itself is drawn from a point somewhat above the bottom of the trap. The sediment in the water collects below this point, and can be drawn off through the valve w_2, which is always opened a moment or two before starting the suction-pump. To prevent the entrance of air in the water current, a

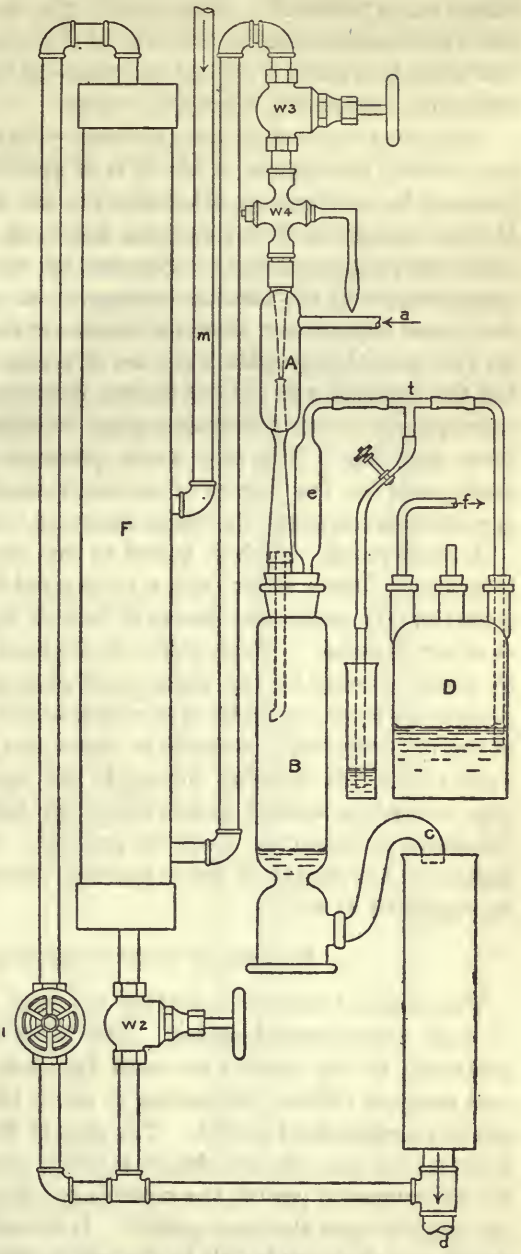

FIG. 19.—Apparatus for Drawing Sample of Air for Residual Analysis. A glass suction-pump A draws air from the Elster meter and delivers it, together with the water used for aspiration, into separating chamber B. The water flows off through overflow through pipe d and the air passes through exit tube t into drying chamber D.

valve, w_1, is provided. Any air that may have been brought along by the water current will accumulate in the upper part of the chamber F, and when this valve is opened will pass out into the drain, the chamber becoming completely filled with water.

Apparatus for constant water pressure.—In using a water suction-pump for drawing the sample of air, it is of great importance that the water pressure be constant, as otherwise the air will be drawn through the U tubes and meter with a varying degree of rapidity, and consequently under varying tension as measured by the water manometer. The measurement of the absolute volume of air passing through the meter is of great importance, since its relation to the larger volume of residual air (10 : 5,000) necessitates the use of a very large factor when computing the residual amounts of carbon dioxide and water in the system; consequently every precaution must be taken to secure the most uniform sampling. The city water pressure was found to be entirely inadequate for the degree of accuracy required for this work, and a special water system, shown in figure 20, was installed.

A force-pump, which is belted to the line shaft in the calorimeter laboratory, draws water from a galvanized-iron pail, which is supplied from the city main, and forces it into an upright boiler, which serves as an air-chamber. The boiler is filled about half full of water, the level of which is noted by the glass water-gage at the side, and then compressed air from a cylinder is admitted to the boiler until the manometer at the top indicates a pressure of about 100 pounds. The water withdrawn from this chamber for use in the suction-pump is taken from a pipe extending several inches above the bottom of the boiler, so as to eliminate sediment as much as possible. By means of the valve w_4, figure 19, the supply of water passing through the suction-pump may be regulated at will.

Process of Taking Residual Samples.

The residual analysis is started at about 10 minutes before the end of each experimental period. Ten liters of air (apparent volume as measured by the meter) are used for each determination. A duplicate analysis follows, beginning at about three minutes before the end of the experimental period. The rate of flow of air through the meter is such that the second sample is about one-half taken at the end of the experimental period, the remaining 5 liters of air being taken during the beginning of the next period. It is assumed that the average composition of the sample will be that of the air at the moment of changing from one period to another. The differences in results by the two samples are usually insignificant, in which case the second series of

results is invariably used in the calculations. Occasionally, though rarely, wide discrepancies in the two analyses will appear. Under these conditions a third analysis is made and the figures agreeing most closely are used. In such cases the error is almost always directly traceable.

SAMPLING THE AIR FOR THE DETERMINATION OF OXYGEN.

Of the four constituents of the ventilating current of air, carbon dioxide, water vapor, nitrogen, and oxygen, the amounts of the first two in the residual air are determined by the apparatus described above. In order to know accurately the amount of oxygen in the air, a determination of this element is necessary.

The actual determination of oxygen in the air current, by absorption by potassium pyrogallate, is usually made once each 24 hours, the sample being generally drawn at the close of the experimental period ending at 7 a. m.

It is of great importance to obtain a sample of air in which the percentage of oxygen shall represent accurately that in the respiration chamber. Formerly the air was sampled after it had passed through the blower and absorbing system, and it was assumed to be

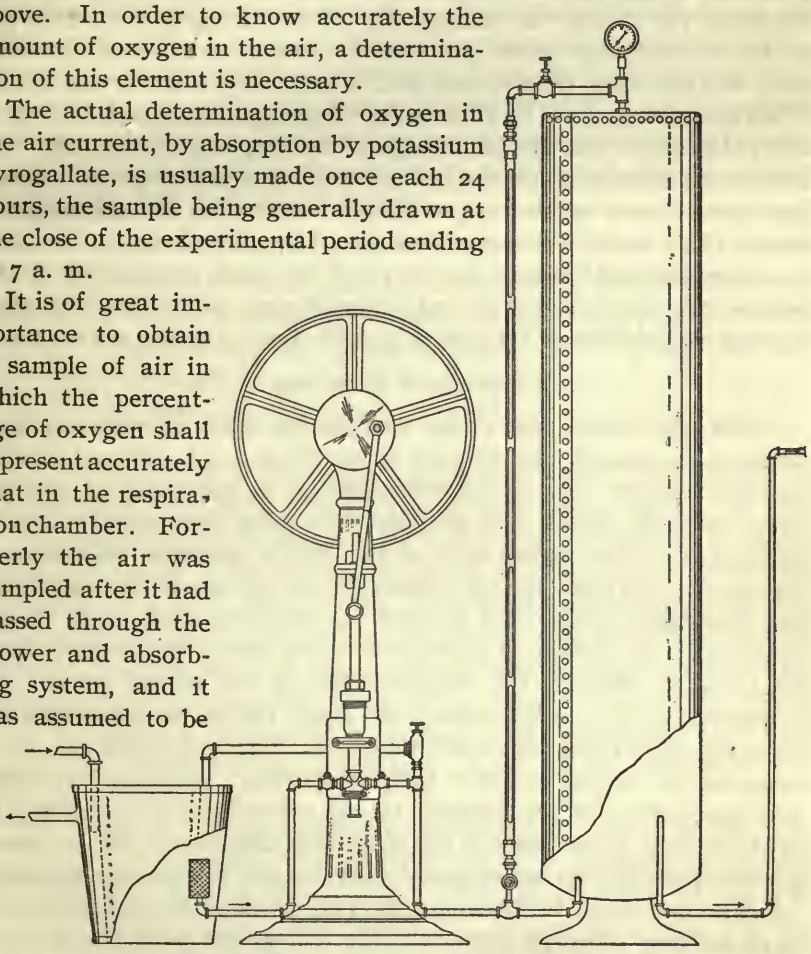

FIG. 20.—Water-Pressure System. Water from reservoir at left is forced by pump into the large air-tank at right. The release valve immediately to right of pump returns the water to reservoir in case pressure in tank exceeds 100 pounds. Water is drawn from tank for suction-pump used for drawing residual samples.

free from carbon dioxide when taken under these conditions. It was found, however, that at the time when the air sample is usually taken, *i. e.*, immediately after the end of the experimental period, the air in the main ventilating pipe leaving the absorbers is a mixture of purified air from the respiration chamber and normal air from the laboratory contained in the carbon-dioxide and water absorbers that had just been put into use, and, since the percentage of oxygen in the normal air is somewhat larger than that in the air from the chamber, the proportion of oxygen in the sample would of course be too large. If the taking of the sample was delayed for several minutes, *i. e.*, until the air in the absorbing system had been thoroughly swept out, this difficulty was no longer experienced, but, as any delay in taking the sample of air was accompanied by a gradually varying percentage of oxygen, it was evident that this method of taking the sample was erroneous. To avoid these difficulties, the air that has been through the residual U tubes and meter is now utilized as the sample. Inasmuch as this sample is always taken during the second residual, *i. e.*, after the air in the meter has been thoroughly swept out by air of the same composition as the sample, the air thus collected probably represents better than any other the true composition of the carbon-dioxide free air inside the chamber.

Method of Sampling.

It has been found that if the analyses are made immediately after drawing the sample the air may be collected in an ordinary rubber foot-ball bladder. In taking the sample it is customary to slip the rubber neck of the bag over the glass tube connecting with the T tube (*t*, fig. 19). The rubber neck of the bag is provided with a screw pinchcock. On opening this pinchcock and the one above, air rushes into the bladder rather than through the sulphuric acid in the drying bottle until the tension on the rubber bag is sufficiently great to force the air again through the sulphuric acid in the drying bottle. By squeezing the bag together with the hands the air can be discharged again into the drying bottle and thence into the main air-pipe. In so doing there is no gain or loss of air to the system. Care must be taken, however, to see that the pressure on the rubber bag is not enough to force the level of the water in the separating chamber B (fig. 19) down to such a point that air can escape along with water through the overflow.

It has been found by repeated tests that the amount of air contained by an ordinary foot-ball bladder under the tension here used is about 0.80 liter, and this quantity of air is removed from the main air-circuit. A correction for this amount is made in the data for the experimental period from 7 a. m. to 9 a. m., in making which it is customary to assume that this volume of air consists of one-fifth of oxygen and four-

fifths nitrogen, since the actual composition rarely varies sufficiently to make any material difference in the calculation.

After the sample is taken, both pinchcocks are closed, the rubber bag removed, and the glass tube again dipped in water to insure tight closure.

In the alkaline pyrogallate method of determining oxygen it is absolutely essential that the air sample be free from carbon dioxide. In the procedure outlined above the sample is taken after the air has passed through the three U tubes for the residual analysis, and consequently should be free from carbon dioxide. We have frequently tested the efficiency of these U tubes for removing completely the carbon dioxide from an air current and have found them to be remarkably satisfactory. Furthermore, it is to be remembered that the amount of residual carbon dioxide is usually low, and absorption is presumably correspondingly complete. It is therefore reasonable to assume that the air sample is absolutely free from carbon dioxide.

The Analysis of Air.

The desirability of exact analysis of air during the progress of an experiment with the respiration apparatus has been emphasized on page 12. The methods and apparatus used thus far in this work are essentially those outlined previously for analyzing oxygen, and reference is made in the following description to the illustration previously given (fig. 16).

But in the analysis of air certain refinements of the method described are necessary. The chief of these is an accurate observation of changes in temperature of the gas between the time of the first and final readings. While a variation in temperature of several tenths of a degree could not have any appreciable effect on the small volume of residual nitrogen obtained in the analyses of oxygen, in air analyses, where the residual nitrogen amounts to about 80 cc., fluctuations in temperature will be accompanied by marked fluctuations in the residual volume. Furthermore, fluctuations in barometric pressure, although seldom occurring during the actual process of analysis, might affect perceptibly the percentage of nitrogen.

The important rôle played by temperature fluctuations necessitates the use of a thermometer graduated in tenths of a degree centigrade, and read with a reading glass to 0.01°. This thermometer is placed in the water-jacket surrounding burette B_2. To insure a more equable temperature of the gas in the burettes, provision is made for stirring the water in the water-jackets. A slow stream of air is forced through two fine jets at the bottom of the water-jackets, openings in the corks in the top allowing for the free escape of air. As the air bubbles through the long column of water, the water is very completely stirred.

By means of the screw pinchcocks s_1 s_2 the amount of air bubbling through the water can be regulated at will. Some difficulty was experienced in getting an air pressure sufficient to force air through such a long column of water, but compressed air from a cylinder was eventually found satisfactory. The air is first saturated with water vapor by bubbling through water in a gas-washing bottle, thus diminishing the cooling effect in the water-jackets due to the evaporation of water. In case there is clogging of the tubes and consequent increased pressure, a mercury trap provides a safety escape.

Inasmuch as the percentage of oxygen in the carbon-dioxide free air from the respiration chamber is seldom less than 17 to 18 per cent, the graduations on burette B_2, which extend only from 90 to 100 cc., do not permit of reading directly the volume of unabsorbed gas when drawn from the pipette back into B_2. This volume may be as great as 83 cc. or as small as 78 cc. To overcome this difficulty, we have adopted the plan of driving a definite volume of nitrogen from the burette B_1, through the 3-way stopcock C, into burette B_2, in order to depress the level of the water in B_2 to such a point that it can be read on the graduations from 90 to 100 cc. In general, about 10 to 14 cc. of nitrogen are thus expelled from the burette B_1. At the beginning of an analysis the burette B_1 is nearly filled with pure nitrogen, obtained either from a previous analysis of air or from the gas above the reagent in the Hempel pipette.

Having filled the burette B_1 with nitrogen, the neck of the rubber bag used to collect the sample of air to be analyzed is slipped over the end of the capillary tube T. On opening the stopcock C the air is drawn into the burette B_2 until the water level in the burette is the same as that in the reservoir R_2. The stopcock C is then closed, the screw pinchcock on the neck of the rubber bag closed, and the bag removed. Theoretically, it is better to leave the bag on until just before reading the volume, but the difference in composition of the room air and the small sample in the open portion of the tube is so slight that practically no difference in results is to be expected. After allowing the water in burette B_2 to drain down the customary time, readings are taken of the volume in the burette, of the thermometer, and of the barometer. The gas is then driven over through the stopcock C into the Hempel pipette described for oxygen analysis (p. 37), all the gas in the capillary tubes being forced out by the pressure of the water in the elevated reservoir R_2. After closing the stopcock C and the pinchcock P on the pipette, the air is shaken vigorously with the reagent for five minutes. The residual unabsorbed gas is then returned to the burette B_2, and by lowering the reservoir R_2 the reagent is drawn up through the rubber connection R and along the capillary

to the mark G. The volume of gas thus returned to the burette must be supplemented by a volume to be delivered from the burette B_1 before the gas can be read on B_2. The reservoir R_1 is lowered until the level of the liquid in R_1 and B_1 are the same. The reading on B_1 is then carefully noted. On raising R_1 and carefully opening stopcock C pure nitrogen can be driven over into B_2. It is necessary, however, that in this case the reservoir R_2 should be at or about the level shown in figure 16. As soon as sufficient nitrogen has been forced into B_2 to bring the water level well on the graduated portion of the burette the stopcock C is closed. After again adjusting the water levels in R_1 and B_1, the reading of the gas remaining in B_1 is made and the difference in volume subtracted from the final reading on B_2. The final readings of volume and temperature are, of course, not taken until the water has settled and drained down the sides of the burette.

A specimen analysis of a sample of the air taken from the respiration chamber is given below as illustrating the methods of analysis. The sample of air was drawn at 7 a. m. on April 29, 1904. The reading on B_2 was 99.25 cc. + 0.51 = 99.76 cc. The initial temperature was 18.64; the corrected barometer reading was 753.29 mm. After absorbing the oxygen the gas was run back into B_2 and nitrogen from B_1 added to this volume. The first reading on B_1 was 19.00, the second 5.47, indicating that 13.53 cc. of nitrogen had been added to the volume of the gas in B_2. The final reading on B_2 was 93.89. On deducting the 13.53 cc. of nitrogen that were added from B_1, the corrected volume of gas measured in B_2 was 80.36. There still remained, however, the constant volume 0.34, which should be added for the gas remaining in the stopcock and connection to graduation point G. The final result, then, is 80.36 + 0.34 = 80.70. The change in temperature amounted to 0.09°, the initial temperature being 18.64° and the final 18.73°. In increasing its temperature the gas has expanded and the tension of aqueous vapor has increased slightly; consequently it is necessary to take into consideration its effect on the tension of the gas in the burette. The tension of aqueous vapor at 18.64° is equal to 15.96 mm. of mercury. This, subtracted from the barometric reading, 753.29, gives the reduced pressure as 737.33 mm.

The tension of aqueous vapor at 18.73° is 16.05 mm. As there was no noticeable change in the barometric pressure, this tension is deducted from the original barometric pressure, *i. e.*, 753.29, and the resulting pressure is equal to 753.29 — 16.05 = 737.24 mm. Therefore 99.76 cc. of *air* at 18.64° and 737.33 mm. pressure yield 80.70 cc. of *nitrogen* at 18.73° and 737.24 mm.

On reducing both these gas volumes to standard conditions of temperature and pressure we find that this particular sample of air contains

80.856 per cent of nitrogen. A duplicate analysis gave 80.854 per cent of nitrogen. It is only fair to state that such an agreement is exceptional rather than the rule. In general, however, the agreement is within 0.03 to 0.05 per cent.

During the process of each analysis a small quantity of water is unavoidably forced into the pipette, and consequently, while 155 cc. of reagent will absorb nearly 500 cc. of oxygen in oxygen analyses, it will absorb only 150 cc. of oxygen in the air analyses. It seems reasonable to suppose that this diminished efficiency is due, in part at least, to the gradual dilution of the reagent by the introduction of water. Experience has led to the renewing of the solution after eight analyses of air.

It can be readily seen that this method of analysis, depending as it does on so many readings of burettes, thermometers, barometer, etc., is open to serious objections when used for the most accurate work.[1] However, a series of analyses of samples of outdoor air taken on successive days indicated extremely close agreement, such as to lead us to believe that the method is as accurate as we can expect, in the absence of a constant-temperature room and the services of an expert gas analyst, whose whole time can be devoted to this kind of work.

ACCESSORY APPARATUS.

Aside from the elaborate respiration apparatus proper, certain incidental apparatus is necessary, such as balances for obtaining the weights of gases absorbed by the residual U tubes, of the carbon dioxide and water in the absorbers, and of the oxygen, a barometer, and thermometers for determining the temperature of the air, both in the respiration chamber and in the exterior portions of the air-circuit. Other incidental apparatus, which has, however, more to do with the measurements of heat than of the respiratory products, will be described hereafter in connection with the discussion of heat measurements.

BALANCES.

Analytical.—For weighing the residual U tubes and all general analytical work in the laboratory, in connection with experiments with the respiration calorimeter, short-beam analytical balances of standard types are used.

Balance for weighing the carbon-dioxide and water absorbers and oxygen cylinders.—The quantitative determination of the total carbon dioxide, water, and oxygen in the air current necessitates the use of a balance at

[1] At the moment of writing there is being installed in this laboratory the form of air-analysis apparatus used by Zuntz in his work on the respiratory exchange.

once sufficiently strong to stand the weight of the individual members of the absorbing system and of the oxygen cylinders and at the same time sufficiently sensitive to note a slight increase in weight with great accuracy. The heaviest individual members of the absorbing system are the water-absorbers, which weigh, after the absorption of one-half kilogram of water, not far from 16 to 18 kg. The balance now in use for this purpose was obtained from the firm of Dr. Robert Muencke, of Berlin, through the Bausch & Lomb Optical Company, of Rochester, New York. It is shown in figure 21.

The water and carbon-dioxide absorbers and oxygen cylinders are too large to be placed directly upon the balance-pan for weighing; consequently the balance is so mounted that it is possible to suspend each separate member on a wire fastened to one arm of the balance. As is shown in figure 21, the balance is mounted on a heavy shelf fastened securely to the brick wall. The left-hand hanger of the balance has been removed and is replaced by a phosphor-bronze wire which extends through a hole in the bottom of the balance-case, and is provided with hooks or loops for suspending the objects to be weighed.

Since changes in weight are here desired, rather than absolute weight, the larger part of the weight of these objects is balanced with lead counterpoises. The glass front of the balance-case can be raised and the counterpoises added or removed as desired.

To prevent the effect of air currents along the floor, the lower part of the balance, *i. e.*, the portion beneath the shelf, is inclosed as a closet. The framework, however, does not come in contact with the shelf, there being a small air gap between to eliminate the transmission of vibration from the floor to the shelf. The front of the closet consists of two doors, one of which is removed in figure 21. To provide illumination a glass window is placed in the left-hand side, and the whole interior is painted white. On dark days or during the night an electric light is inserted.

A small piece of plate glass is set in the shelf immediately in front of the balance in such a way that the upper surface of the glass is just flush with the top of the shelf. After the doors of the closet have been closed it is possible for the assistant to look through this glass and see that the object to be weighed is freely suspended.

The phosphor-bronze wire by which the objects are suspended is permanently fastened to the hanger on the left-hand balance-arm. The lower end is provided with a swivel, to which two wires with small hooks on the end are attached. These hooks can be conveniently attached to the handles of the water-absorbers. (See fig. 11.)

In weighing these heavy objects it was found much more convenient to place them first on a small platform which could be raised sufficiently

to allow the hooks from the suspension wire to be readily slipped under the handles of the absorber. By means of the wooden lever at the left-hand side of the weighing closet, the movable platform on which the absorber is placed can then be lowered slowly, thus gradually shifting the weight to the wires. When the wooden handle is in an upright position, the movable platform or elevator is at its lowest point, and the object to be weighed swings freely above it. A simple clutch holds the lever firmly when it is sustaining the weight of the absorber, and all that is necessary to release the clutch is to push the handle forward a short distance.

The bracket-arm fastened to the lever has two chains attached to its outer end; these travel through pulleys in the top of the closet and are so adjusted that both sides of the elevator are lowered to the same distance and simultaneously, thus making an even up-and-down motion. The details of this apparatus are shown in figure 21.

After weighing, the lever at the left of the balance is pushed forward, thus taking the weight off the wire. The hooks can then be unfastened and the absorber readily withdrawn.

For weighing the carbon-dioxide absorbers, two copper loops act as extensions to the steel hooks. A similar device serves for suspending the oxygen cylinders.

One of the most striking features of this balance is its great capacity and extreme sensitiveness. In weighing the water-absorbers, some of which weigh fully 18 kg., we have the greatest test on the sensitiveness of the balance, and it is found that these absorbers may be weighed so delicately that a difference of 20 mg. is readily detected—a degree of accuracy far beyond the ordinary requirements.

A balance of the same type, but with one-half the capacity, *i. e.*, 10 kg. in each pan, is employed for weighing food, feces, urine, and miscellaneous small articles used in connection with experiments on man. This balance is so accurate and so sensitive that it can be used for adjusting large weights, and by a method of double weighing we have standardized with it all of our weights over 200 grams, and determined the actual weight of the different counterpoises used on the water-meter (see p. 126) and large balance.

WEIGHTS.

The accuracy of the determination of the balance of intake and output of matter with the respiration calorimeter obviously depends on the accurate weighing of the factors of income and outgo. The materials of the income are weighed usually on a sensitive balance with one set of weights, the samples for analyses weighed on an analytical balance with

To face page 58.

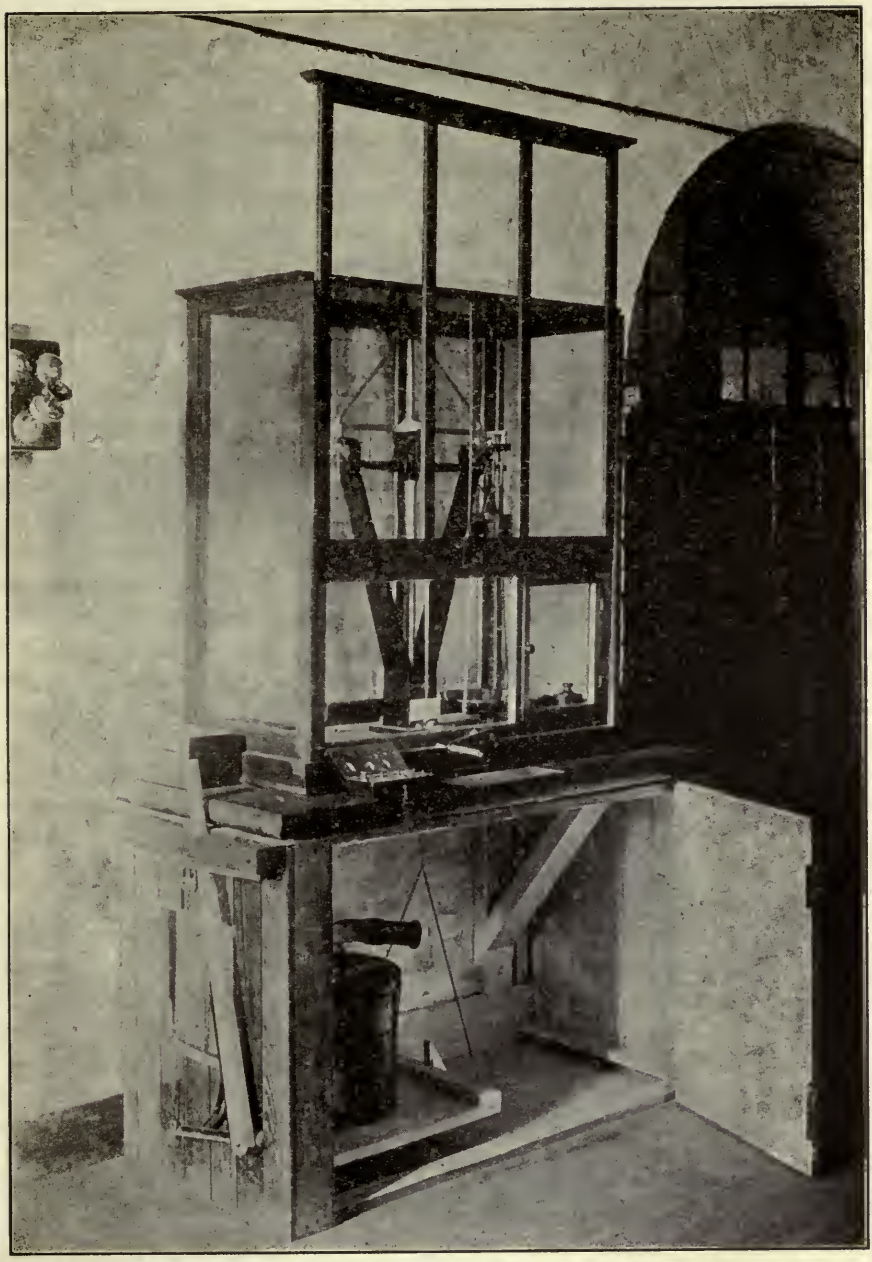

FIG. 21.—Balance for Weighing Absorbers and Oxygen Cylinders. The absorbers are suspended on a wire from left-hand arm of balance, and lead counterpoises are used on right side. Doors inclose weighing chamber and prevent drafts. The lever on outside at the left actuates the elevator, which raises or lowers the absorbers in weighing chamber.

a second set of weights, and the water, carbon dioxide, and oxygen weighed on a third balance with a third set of weights.

Other weighings entering into the complete balance of energy, as well as of matter, are the weights of water used to bring away the heat from the apparatus, and in the bomb calorimeter for measuring the energy of income, and the weights used on a platform balance (fig. 46) for weighing a man. With such a system of balances and weights, it is obviously necessary that all weights should be on some standard basis. We have imported from Germany a set of gold-plated weights ranging from 1 mg. to 1 kg., and all of our different sets of weights have been carefully calibrated with this set, which is used only for a standard. Consequently all weights used in the experimenting with the respiration calorimeter are reduced to the same basis. The weights, as well as the sensitiveness and accuracy of the balances, are tested periodically every six months and proper adjustments made.

The individual weights of the standard set have been compared with each other frequently in all possible combinations, and the agreement is in all cases very close. There has been no comparison with any absolute standard, as practically all of our work depends upon differences in weight rather than absolute weight. We have, however, no reason to doubt the accuracy of the standard weights as furnished us, for when compared with numerous new sets of analytical weights no noticeable differences have been found. Apparently the analytical weights, though from several manufacturers, must have been referred to standards agreeing very closely with each other.

With the larger weights used for weighing food and the absorbing apparatus of the respiration chamber, the adjustment was found to be much more readily made if the handle or top of the weight screwed into the base. Accordingly a number of sets of weights were made in the mechanical laboratory of Wesleyan University on this plan, and consequently the work of delicate adjustment is reduced to a minimum.

For calibrating the larger weights, 200 grams and over, the balances described on page 58 were used, after making all due precautions and interchanging weights from one pan to the other.

All the weighings and measurements are made at the same level in the calorimeter room, which has an elevation of 48.8 meters above sea level. The latitude of Middletown is 41° 34′. It has been found that to correct all weighings to standard gravity, *i. e.*, latitude 45°, would involve a large amount of unnecessary labor. The actual correction is only about three parts in 10,000, representing a degree of refinement that is far removed from many of the operations in connection

with the experimental work with the respiration calorimeter. For this reason, where it is necessary to make comparisons of weights and volumes of gases, the relations are calculated for the latitude and elevation of the calorimeter laboratory. For similar reasons, weights are not reduced to vacuum.

THE BAROMETER.

With the volume of air confined in the apparatus, amounting to about 5,000 liters, slight variations in barometric pressure will make relatively large variations in the apparent volume of the air in the system. A variation in barometric pressure of 1 mm. of mercury, or 1 part in 760, is accompanied by a variation amounting to about 7 liters in the apparent volume of air. Consequently it is necessary that the barometric pressure be known as accurately as possible.

Through the kindness of Mr. Willis L. Moore, chief of the Weather Bureau of the United States Department of Agriculture, at Washington, a barometer was loaned for use in connection with these experiments. The barometer was brought to Middletown by Prof. Charles F. Marvin, of the instrument division of the Weather Bureau, who personally superintended its installation. This instrument is of the Fortin type, capable of being read with a vernier to 0.001 inch. It is mounted with two white backgrounds, consisting of two sheets of paper, behind which two incandescent lamps are placed. When the lamps are lighted a brilliantly illuminated field gives excellent opportunity for adjusting the vernier at the top. The box in which the barometer is hung is firmly supported on two uprights extending from the floor to the ceiling of the laboratory. The relative position of the barometer to the rest of the apparatus is shown in figure 1.

Tables giving corrections for the barometer and for the attached thermometer were furnished by the U. S. Weather Bureau, and before being brought to Middletown the instrument was carefully adjusted under Professor Marvin's supervision. Its accuracy is all that could be desired.

The correction for the scale errors and capillarity of this instrument amounts to + 0.002 inch and the correction for local gravity at the latitude of Middletown, 41° 34′, is — 0.009 inch, making the total correction — 0.007. As will be noted later, however, it is found to simplify calculations if the corrections for gravity are not applied, and in practice the correction used is + 002 inch.

The thermometer attached to the barometer has only insignificant corrections for that portion of the scale on which readings are usually

made, and, as it need be read only to the nearest half degree, no corrections are made. Consequently to facilitate in the calculations, reference is made to tables giving the true correction to be deducted in every case from the actual reading of the barometer and for every half inch difference in the height of the barometer and for every half degree difference in the temperature. The correction as recorded on this table is the standard temperature correction for reducing the mercury column minus the scale error and capillarity correction of this special barometer (0.002 inch), as mentioned above. To facilitate the calculations, the corrected reading of the barometer is converted by means of a table to the metric reading in one-hundredths of a millimeter.

OBSERVATION OF TEMPERATURE.

The total air in the closed circuit may be considered as being made up of two portions. The larger portion, amounting to about 5,000 liters, is that in the respiration chamber proper; the remaining portion, of about 62 liters, is that contained in the air-pipe, absorbing system, pump, and pans. (See p. 70.)

The air in the chamber is maintained at a fairly constant temperature as a result of the heat-regulation devices described elsewhere (p. 124). The temperature is recorded quite accurately by means of the electrical resistance thermometers (p. 135).[1] These thermometers are assumed to give the temperature of the air within 0.01°. In addition, a mercury thermometer, graduated to tenths of degrees, is suspended in the chamber near the window as a guide to the actual temperature expressed in degrees centigrade.

The air outside the chamber is subject to a number of temperature fluctuations. As has been described, the calorimeter laboratory is heated by steam-pipes suspended near the top of the room. Consequently a very great difference in temperature exists between the air at the level of the absorbing system and that of the pipes conducting the air to and from the chamber. To obtain the temperature of these portions of the system, we rely upon other mercurial thermometers. One is attached to the outside of the chamber, so as to hang just in front of the window. A second thermometer is suspended near the pans, so that the bulb is on a level with the horizontal air-tube. A third thermometer, the bulb of which is immersed in the water in the Elster meter, gives the temperature of the air sample. These thermometers are designated respectively as T, T_1, and T_m. The first two

[1] For a discussion of the significance of the temperature measurements by these thermometers, see page 91.

thermometers are graduated in degrees and read to tenths of a degree. That used in the Elster meter is read to hundredths of a degree. As the temperatures at which they are used rarely exceed 25°, it was found expedient to calibrate them, together with a number of others used for incidental work, such as in the specific gravity of alcohol, etc., simultaneously with the water thermometers, and a table of corrections for each thermometer in use in the laboratory was thus obtained under conditions exactly similar to those described for the water thermometers. (See p. 133.) All temperatures read by observers are subject to these corrections before use in the calculations.

In regard to the temperature observations on that portion of the air-circuit outside of the respiration chamber, it is found that under certain conditions of experimenting, especially those in which large quantities of carbon dioxide are being absorbed, the temperature of the carbon-dioxide absorbers is considerably increased. In one experiment the bulb of a thermometer was placed on the exterior of the absorber, the bulb covered with a piece of hair felt, and the temperature noted. A temperature of 47.5° was observed during this experiment, and an observation on another day gave a temperature of 53.3°.

As stated previously (p. 31), all three carbon-dioxide absorbers during a work experiment become more or less heated, although usually the excessive heat is confined to one absorber. In consideration of the lack of more data, it has been assumed that, while the carbon dioxide was being absorbed from the air current during a period in which the subject was engaged in excessive muscular exercise, one-half of the air in the soda-lime absorbers reached a temperature of 50°, the rest remaining at 20°. It has been computed that about 0.4 liter of air is thereby added to the system at each change in the absorbing system after a period of heavy work. In an alcohol check experiment, or in a rest experiment, the rise in temperature is so slight that no correction is necessary.

In the first water-absorber there is always a slight rise in temperature above the initial temperature. The amount of water absorbed in the course of a two-hour period is too small, however, to cause any great increase in temperature, and consequently it is not considered in the calculations.

CALCULATION OF RESULTS.

The ultimate object of the respiration apparatus and the accessory appliances is to obtain an accurate measure of the respiratory products, *i. e.*, the carbon dioxide and water vapor eliminated and the oxygen consumed. The data obtained with the apparatus are the weights of carbon dioxide and water absorbed in the absorbing system, the weight of oxygen supplied to the ventilating current of air, and the incidental physical measurements, such as the temperatures of the different masses of air comprising the system, and the barometric pressure. If the variations in composition of the residual amounts of air were entirely neglected, the total carbon-dioxide and water output and oxygen intake could be determined readily by noting the increase in weight of the absorbers and the loss in weight of the oxygen cylinders. For convenience in calculation, the data obtained from the absorbers and oxygen cylinders, and also the data regarding the residual analyses, together with the temperature observations and positions of the rubber diaphragms on the pans, are recorded on a special blank, a specimen of which is given on the following page.

AMOUNT OF WATER ABSORBED.

Assuming that there are no changes in the amount of moisture in the residual air, the amount of water vapor eliminated per period corresponds to the gain in weight of the first water-absorber.

By reference to the blank, it will be seen that in the experiment here used the absorber, which was No. 5, weighed at the start, aside from the weight of the counterpoises, 3,296.0 grams. At the end of the period, which in this particular instance was of two hours' duration and ended at 7 a. m., April 9, 1905, the absorber, when removed from the system, weighed 3,350.8 grams, the increase in weight during this two-hour period being, therefore, 54.8 grams. While this may be taken as an estimate of the weight of water absorbed during this period, there are two corrections to be applied independent of any correction for the variation in composition of the residual air. In the first place, a small amount of water is actually absorbed in the U tubes used for residual analysis, and thus removed from the ventilating air current. In this instance the amount of water in the two tubes was 0.11 gram. Furthermore, as was explained on page 26, owing to the transudation of acid through the absorbers during the time that these particular data were obtained, they were absorbing a small amount of water from the external air of the laboratory, which has been very closely determined to be 0.20 gram per two-hour period, and consequently the increase in weight of this absorber is too large by 0.20 gram. The corrected weight of water absorbed during this period, accordingly, is 54.71 grams.

Calculations for Carbon Dioxide, Water, and Oxygen. No. 16.

7.00 a. m., April 9, 1905. Residual at end of 12th period. Metabolism expt. No. 77.

First Residual.		Second Residual.		Oxygen.	
	9.958 liters.		10.016 liters.	Cylinder No. 32888	Log. % N. = 1.5838
T_m,	= 20.69	T_m,	= 20.68	Weight on 1846.00	" O + N. = 6.7006
Cor.	= —.24	Cor.	= —.24	" off 1799.22	" gms. N. = 8.2844
Cor. T_m,	= 20.45	Cor. T_m,	= 20.44		90078
Water Man.	= 149	Water Man.	= 167	Grams O. + N. 46.78	" liters N. = 7.2922
	10.30		11.77	" N. .67	
	.66		.51	" O. 46.11	Liters N. .54
	Hg = 10.96		Hg = 12.28		
H_2SO_4	72.3788	$\frac{1}{2}H_2SO_4$	72.6625	Cylinder No.	Log. % N. =
No. 9	72.3249	No. 2	72.6071	Weight on	" O + N. =
Weight H_2O	.0539	Weight H_2O =	.0554	" off	" gms. N. =
S. L.	78.9948	S. L.	73.3793	Grams O. + N.	90078
N	78.9696	E	73.3507	" N.	" liters N. =
	.0252		.0286	" O.	Liters N.
H_2SO_4	67.7512	H_2SO_4	76.6298	Cylinder No.	Log. % N. =
No. 19	67.7342	No. 13	76.6143	Weight on	" O + N. =
	.0170		.0155	" off	" gms. N. =
S. L.	.0252	S. L.	.0286	Grams O. + N.	90078
Total CO_2	.0422	Total CO_2	.0441	" N.	" liters N. =
				" O.	Liters N.
T_0 = 20.79		Pan No. 1 = 575	= 11.2	Cylinder No.	Log. % N. =
T_1 = 20.0	= 20.0	Pan No. 2 = empty	= 2.5	Weight on	" O + N. =
			13.7	" off	" gms. N. =
				Grams O. + N.	90078
				" N.	" liters N. =
				" O.	Liters N.

CO_2 & H_2O				Grams Oxygen	Liters Nitrogen
H_2SO_4 No 5	End	3350.8	H_2O total. 54.8		
	Start	3296.0	.11		
		54.8	Cor. — .20	46.11 Cylinder	.54 Total.
			54.71	—.04 Corrections	
S. L. S	End	2422.7	.7	46.07 Total.	
	Start	2416.2	38.297		
		6.5	= —.04 liters air displaced		
S. L. I.	End	2740.9	CO_2 total. 6.5		
	Start	2722.1	18.8		
		18.8	2.5		
			16.3		
S. L. I	End	2284.7	.09		
	Start	2282.2	Cor. — .20		
		2.5	43.99		
S. L.	End		Resp. loss		
	Start		CO_2 = 43.99		
			H_2O = 54.71		
H_2SO_4 No. 6	End	3525.0	Sum = 98.70		
	Start	3508.7	Less O = 46.07		
		16.3	Diff = 52.63		
			= .05 L.		

Air Rejected at.....M.

.....liters

T_m, = Log. L.

Cor. = Cor.

Cor. T_m, = Temp.

Pressure

Water Man. = O. + N. = L.

Log. % N.

N. — . . . . = L.

Hg . . = O . . . . . L.

e @ T_m, =

Sum . =

Barometer =

Difference =

AMOUNT OF CARBON DIOXIDE ABSORBED.

The weight of carbon dioxide absorbed was determined by noting the increase in weight of each of the three soda-lime cylinders S, L, and I and the water-absorber No. 6, through which the air passed after leaving the soda-lime cylinders. Soda-lime cylinder S weighed at the start 2,416.2 grams more than the counterpoise. At the end of two hours it was observed that the weight had increased by 6.5 grams. Similarly, cylinder L had increased in weight 18.8 grams and cylinder I 2.5 grams, while water-absorber No. 6 had increased in weight 16.3 grams. To find the total weight of carbon dioxide during this period, therefore, the increases in weight of these four parts of the carbon-dioxide absorbing system were added together, the amount of carbon dioxide absorbed in the two residual analyses, *i. e.*, 0.09 gram, added, and the usual correction of 0.20 gram for the increase in weight of absorber No. 6 subtracted. It is thus seen that the total weight of carbon dioxide absorbed during this period was 43.99 grams. It will be noted on the blank that space is left for a fourth soda-lime cylinder. Frequently, in experiments in which there is an excessive amount of carbon dioxide absorbed, it becomes necessary to stop the air current for a moment or two and replace an exhausted soda-lime cylinder with a fresh one.

AMOUNT OF OXYGEN ADMITTED.

The calculation of the weight of oxygen admitted to the chamber is carried out on the upper right-hand side of the blank. To avoid errors and to aid in referring to the cylinder, the cylinder number is first recorded. The weight of the cylinder over and above the counterpoise at the beginning of the period and the weight under the same conditions at the end are recorded immediately beneath this. The difference, which represents the loss in weight of the cylinder, is the weight of the oxygen plus the nitrogen, for, owing to the purifying attachments on the cylinder itself, the gas issuing from the rubber tube consists only of oxygen and nitrogen. It becomes necessary, therefore, to calculate the amount of nitrogen admitted with this oxygen, and this is done by adding the logarithm of the percentage of nitrogen of this particular cylinder, as determined by the analysis (see p. 34), to the logarithm of the weight of oxygen and nitrogen admitted. The sum of these logarithms is the logarithm of the weight of nitrogen, which, in this instance, amounted to 0.67 gram, and, since the weight of the oxygen plus the nitrogen was 46.78 grams, the true weight of oxygen admitted during this period was 46.11 grams.

For purposes of calculation, to be explained beyond (p. 88), it is desirable to know the volume of nitrogen admitted to the chamber,

and consequently at this point the calculation converting the weight in grams of nitrogen to liters is made. This calculation is based on the relations between the weights and volumes of gases as discussed on page 82, and is here simplified by adding the logarithmic factor .90078 to the logarithm of the weight of nitrogen in grams. It is thus seen that the volume of nitrogen admitted with the oxygen in this case was 0.54 liter. On the blank a space is left for several calculations of this nature, as it frequently happens that more than one cylinder of oxygen is used during an experimental period. The oxygen is always admitted as long as it will flow from the cylinder, and even in ordinary rest experiments it is rare that the last of a cylinder of oxygen is coincident with the end of an experimental period. During excessively hard-work experiments, several cylinders may be used. In case more than one cylinder is used, the weights of oxygen and liters of nitrogen are footed up at the bottom. Furthermore, a slight constant correction, amounting to —0.04 gram of oxygen (see p. 74), is made for certain alterations in volume, due either to interchange of air through the food aperture or opening and closing of mercury valves, which correction, for the sake of convenience, is made on this sheet. During this period we find that the total amount of oxygen admitted is 46.07 grams.

It is thus seen that, when no reference is made to the variations in composition of the residual air, the amount of carbon dioxide and water eliminated per given period and the amount of oxygen absorbed may be determined from the weights of water and carbon dioxide taken up by the absorbing system and the weight of oxygen admitted from the steel cylinder, with due allowance for the accompanying weight of nitrogen.

RESIDUAL ANALYTICAL DATA.

The data for the two residual analyses are likewise recorded side by side on this sheet. They include the amount of air passing through the meter, the temperature of the meter, correction for the thermometer used in the meter, pressure on the meter expressed in millimeters of water as read on the manometer, its conversion to millimeters of mercury, and the gains in weight of the U tubes used for analysis. Beneath the record of these data are placed the temperature records and the position of the pans. When the thermometer has a correction, the corrected temperature is placed at the right of that observed. In this instance the thermometer had a zero correction. Pan No. 2 was empty, and in this position it is assumed that 2.5 liters of air are inclosed by this pan, diaphragm, and pipes. (See p. 41.) The pointer on the wheel of pan No. 1 stood at the graduation 575, and from a previously prepared table it is found that at this position the rubber diaphragm, pan, and

pipe inclosed 11.2 liters of air, thus making a sum total of 13.7 in the tension equalizing system.

DATA FOR THE REJECTION OF AIR.

As the amount of nitrogen in the system gradually accumulates during an experiment, by reason of the fact that the admission of oxygen is unavoidably accompanied by an admission of nitrogen, it becomes necessary from time to time to reject a considerable volume of air, varying from 30 to 70 liters, by drawing it through the Elster meter, and to replace it with oxygen. The calculations by which the exact amount of air thus rejected is determined are made in the lower right-hand corner of this sheet. Here are recorded the time at which the air is rejected, the number of liters passing through the meter, the thermometer reading and correction for the thermometer in the meter, the water manometer, with its equivalent in mercury, the tension of aqueous vapor at the temperature of the meter, and the barometer reading. It is thus possible to calculate the corrected volume of oxygen and nitrogen rejected. The proportions of oxygen and nitrogen in this corrected volume are obtained from the analysis of air taken immediately before the air is rejected. (See p. 77.)

CORRECTIONS FOR VARIATIONS IN VOLUME AND COMPOSITION OF RESIDUAL AIR.

Necessity for Residual Analyses.

The amounts of carbon dioxide and water eliminated and oxygen absorbed as determined by the gains in weight of the absorbing system and the loss in weight of the oxygen cylinder, with due corrections for nitrogen, give, on the whole, a general approximation of the amounts of carbon dioxide and water eliminated and oxygen absorbed by the subject; but in this calculation, as has been pointed out, no notice is taken of the alterations in composition of the residual volume of air. The chief factors influencing such variations are muscular activity of the subject with its consequent fluctuations in carbon-dioxide and water production and oxygen absorption, rapidity of ventilation, and barometric pressure.

The fluctuations in the amounts of carbon dioxide and water are in the main of a temporary nature. There may be variations of over 100 grams of carbon dioxide and 20 grams of water vapor in the amounts of these gases in the air in different periods of the day, as, for example, at the beginning and cessation of hard muscular work; but with approximately uniform muscular activity for the whole period the residual amounts of these gases are almost invariably the same from day to day

at the end of each experimental day, *i. e.*, 7. a. m., after an eight-hour sleep.

On the other hand, in the case of oxygen there is present in the system from the very beginning not far from 1,000 liters of oxygen, which store can be drawn upon by the subject, and, indeed, is drawn upon to a very considerable extent. It is of course immaterial to the subject whether he uses oxygen from the steel cylinder in which the oxygen is duly weighed, or oxygen from the large store in the residual air. Obviously, when taken from this second source, provision must be made for noting the amount thus used. If, furthermore, we are to obtain data regarding the exact quantities of carbon dioxide and water vapor used in short periods, the fluctuations in the amounts of these materials in the air current must likewise be determined, and our analyses of residual air should include determinations of water and carbon dioxide as well as oxygen.

Possibility of Leakage.

From a consideration of the construction of the whole apparatus, it is seen that it is practically impossible for carbon dioxide to leak into or out of the air-circuit; for if there were a leak into the system, a very large number of liters of room air would have to enter to affect materially the weight of carbon dioxide, inasmuch as there are only 4 parts of carbon dioxide per 10,000 of air. Similarly, a very considerable leakage of air out of the system would be necessary before any noticeable amount of carbon dioxide would have escaped. With reference to the water vapor, much the same can be said, although the percentage of water vapor in the air of the calorimeter laboratory is much greater than the percentage of carbon dioxide. There is, moreover, a possibility (although in all of our experience it has never yet occurred) that water from the cooling current of water used to bring away the heat may leak into the system through the connections with the heat-absorbers (see p. 123); but, for all practical purposes, we may consider that the construction of the apparatus is such as to make it impossible for any appreciable amounts of carbon dioxide or water vapor to leak into or out of the system.

In the case of oxygen and nitrogen, however, it is of fundamental importance that there be no leakage of these gases into or out of the system. The precautions taken to secure thorough closure of the system have already been discussed in considerable detail. The residual analyses give, as is shown on page 88, data for determining any gain or loss of nitrogen to the residual air, and consequently, as a leakage of air in either direction would result in a marked disturbance of the amount of nitrogen remaining in the chamber, the residual analysis is

frequently of great assistance in indicating such leakage. Furthermore, the residual analysis is used to measure the amount of leak. This point, as well as the general significance of leaks of either oxygen or nitrogen, will be taken up more in detail beyond.

Factors Used in the Calculation of the Residual Analyses.

The chief factors necessary in the calculations of the residual amounts of carbon dioxide, water vapor, oxygen, and nitrogen in the ventilating air current are the volumes of the gases in the various parts of the system, the composition of the different portions of air, the volume of the sample taken for analysis, the weights of carbon dioxide and water in the sample drawn through the meter, and the volume percentage of oxygen and nitrogen found by the gasometric analysis.

Volumes of Air in Air-Circuit.

The volume of the residual air in the different parts of the chamber, pipes, absorbing apparatus, and pans is calculated with considerable accuracy from measurements of dimension, especially for those parts of the system in which the air volumes are not liable to fluctuate.

Volume in Chamber.

The respiration chamber is 19.27 decimeters high, 12.17 decimeters wide, and 21.38 decimeters long. The corners of the floor and ceiling are rounded, the radius of curvature being 1.27 decimeters. From these data the volume of the chamber proper is computed to be 4,987.0 liters. A recess in the wall provides for the window, and as this does not set flush with the inner wall, its volume must be added to that of the rest of the chamber. The recess is 7.24 decimeters high, 5.20 decimeters wide, and 0.57 decimeter deep. Its volume consequently equals 21.4 liters, which, added to the volume of the chamber, 4,987.0 liters, equals 5,008.4 liters.

A certain amount of material in the apparatus can be considered permanent fixtures, such as the absorbing system, the air-pipe and metal work (other than the metal of the walls), the telephone and batteries, and various smaller pieces of apparatus that are in regular use. The volume occupied by these permanent fixtures is determined by measurement of their dimensions or by calculating the volume by means of the specific gravity when the weight is known. The volumes thus obtained are as follows, in liters: Heat-absorbing system, 5.94; air-pipes and metal work, 1.0; switch, 0.3; telephone and battery, 2.0; making a total of 9.24 liters to be deducted from the apparent volume, 5,008.4 liters, in all calculations.

VOLUME OF AIR IN THE AIR-PIPE FROM THE CHAMBER, MERCURY VALVES, AND BLOWER.

The ventilating air-pipes consist of ordinary iron gas-pipe galvanized inside and out, and vary considerably in length as well as diameter. From measurements of the length and internal diameter their volume was computed, as were also the volumes of the accessory members of the air system, such as the blower, mercury valves, and rubber connections. From these data it is calculated that the air between the chamber and the level of the acid in the first water-absorber occupies a volume of 6.55 liters.

VOLUME OF AIR IN WATER-ABSORBERS.

The content of the water-absorbers was estimated by filling them to the top of the exit tube with water and noting the amount required. For one absorber this was found to be 14.38 liters, for the other 14.69 liters, or an average of 14.54 liters. The rubber tubes which serve to connect the absorbers increase the volume to 15.16 liters each. Of this, 0.93 liter is contained in the entrance tube reaching to the bottom of the absorber, or 14.23 liters for the remainder of the absorber.

From this figure must be deducted the volume occupied by the sulphuric acid. This is originally 3 liters, leaving as the air volume 11.23 liters.

VOLUME OF AIR IN CARBON-DIOXIDE ABSORBERS.

The volume of air in the soda-lime cylinders was calculated by observations upon the contraction in the volume of air under a known pressure. Three soda-lime cylinders were connected in series in the usual way. In one end of the system a water manometer was placed and the other end connected with a bottle, the volume of which was determined by weighing it when empty and when full of water. When a known amount of water was poured into the bottle through a long funnel-tube, the air in the bottle and in the three absorbers became compressed, the pressure being measured by the manometer. From the volume of water poured into the bottle, the reading on the manometer, and the barometric pressure, the volume of air in the system could be calculated. Inasmuch as the experiments were all made in a very few minutes, no difference in temperature was taken into consideration in the calculations.

From three determinations, in which varying quantities of water were used, the total volume of air in the three absorbers varied from 10.128 to 10.486 liters, averaging 10.28 liters as the volume of air in the three soda-lime cylinders. Since the apparatus for the absorption

of carbon dioxide includes a water-absorber in addition to the three soda-lime cylinders, the volume of air in this absorber and connections, *i. e.*, 14.60 liters, must be taken into consideration.

VOLUME OF REMAINDER OF AIR SYSTEM.

The volumes of the mercury valves at the exit end of the absorbing system and the pipes back to the calorimeter are computed as before. This volume is equal to 41.08 liters. The volume of the pans is a fluctuating one, and consequently considered under the head of fluctuating volumes.

VOLUME OF OBJECTS IN THE CHAMBER NOT PERMANENT.

The apparent volume of air in the respiration chamber (p. 69) of 5,008.4 liters is diminished by the volume of the objects in the calorimeter. This may affect the calculation of results in two ways. In the first place, the total volume of air in the system is diminished by the presence of articles inside the calorimeter chamber. In an alcohol check experiment (see p. 96) this reduction in volume of the air is a constant one, there being no change from the beginning to the end of the experiment, since neither the window nor the food aperture is opened during that time, and the volume of alcohol inside is the same at the beginning and the end of each experimental period. Under such conditions, therefore, the only influence of the presence of material inside the chamber is that of diminishing the apparent volume of air. When a metabolism experiment with man is in progress, however, there may be very material differences in the apparent volume of air in the system, due to the fact that the quantity of material in the chamber is constantly varying by passage into or out of the food aperture. (See p. 75.) Under these conditions a second influence may be exerted by the presence of material inside the chamber, *i. e.*, a fluctuation in the actual volume of gas present.

VOLUME IN AN ALCOHOL CHECK EXPERIMENT.

In alcohol check experiments, the volume of the air in the chamber is increased as the inner door of the food aperture remains open, thus adding 4.63 liters of air, the volume of the food aperture, to the system. In addition to the volume of the permanent fixtures, 9.24 liters, it is necessary to deduct the following volumes, in liters : Lamp, 0.2 (see fig. 22) ; alcohol in lamp, 0.4 ; three iron stands for holding the lamp and mirror, 0.95—a total of 1.55 liters. The total volume of air in the system under these conditions is therefore $5{,}008.4 + 4.63 - (1.55 + 9.24) = 5{,}002.24$ liters.

It frequently happens that other fixtures, such as the metal bed, are left in the chamber when making the alcohol check experiments. Under these conditions, their volumes also must be deducted.

VOLUME IN EXPERIMENTS WITH MAN.

In metabolism experiments with man, the alcohol lamp and iron stands are removed. The food aperture is closed, and consequently its volume is not added to that of the chamber. A number of additional articles are, however, taken into the chamber before the experiment begins. Among these may be enumerated the bed, table, chair, bedding, weighing fixtures, books, papers, dishes, urine jars, feces cans, and, in work experiments, the ergometer. By far the greatest correction, however, is that for the volume of the subject himself.

The specific gravity of the body is not far from 1.00, and we have been in the custom of assuming that the weight of the subject and clothing represented the volume in liters displaced by the man when entering the calorimeter chamber. The corrections for the furniture are computed by means of the weight and specific gravity of the various materials. These volumes are, in liters, as follows: Bed, 3.66; table, 0.51; chair, with weighing attachments, 5.61, and ergometer, when included, 14.00.

A similar procedure is followed in the calculation of volumes of books, papers, and incidental articles.

Fluctuations in the Air Volume.

While the apparent volumes of air in the different sections of the closed system are those given in the preceding calculations, there are several fluctuating factors that must be taken into consideration.

VOLUME IN THE PANS.

The most noticeable and important fluctuation in volume is that specially provided for in the construction of the pans. Sudden fluctuations in temperature are not uncommon, especially in the change from rest to hard work, or vice versa, and as the air in the chamber can be considered as comparable to that in the bulb of an immense air thermometer, some provision for expansion or contraction must be made if the pressure is to remain constant. Furthermore, variations in barometric pressure are accompanied by very material alterations in the volume of the confined air.

As was pointed out on page 41, fluctuations in the volume of the air in the pans can be determined with considerable accuracy from readings on the millimeter scale and the corresponding table of calibrations.

COMPRESSION OF AIR IN ABSORBING SYSTEM.

A second fluctuation in volume is due to the fact that, as air is forced through the absorbing system, the increased pressure required causes portions of the air to be somewhat compressed. The chief resistance to the passage of the air is furnished by the layer of sulphuric acid in the two water-absorbers. When the acid in the absorbers is fresh, *i. e.*, when 3.5 kilos of acid of the specific gravity of 1.84 is in each, the pressure is not far from 35 mm. of mercury. The resistance of the soda lime in the carbon-dioxide absorbers to the passage of the air has been found by actual experiment to be relatively insignificant.

The actual measurement of air in the system is made, however, at the period of changing from one absorbing system to the other, *i. e.*, at the end of each experimental period. Under these conditions, therefore, since the air in all other parts of the circulating system is at atmospheric pressure, we have to do only with the air in the first water-absorber and the three carbon-dioxide absorbers. When the blower is stopped the compressed air leaks back through the blower into the system, and the pressure on that portion of the air confined between the blower and the level of the sulphuric acid in the entrance pipe of the first water-absorber becomes atmospheric. Since the exhaust tube from the last water-absorber connects directly through the main air-pipe to the chamber, the air above the acid in this absorber is likewise at atmospheric pressure. The air above the sulphuric acid in the first water-absorber, as well as the air in the three carbon-dioxide absorbers and that small portion confined in the entrance pipe of the last water-absorber, remains, however, under a somewhat increased pressure. Consequently, in order to obtain the true volume of air in that portion of the absorbing system under increased pressure, it was formerly necessary to correct the volume for the increased pressure. By a simple process of calculation it was found that the difference in the volume of the air confined in this portion of the absorber system at atmospheric pressure and under the slightly increased pressure amounted to not far from 0.4 liter. There was therefore a discharge of air from the system as a whole amounting to 0.4 liter every time the absorbing system was changed.

As a verification of the calculations, provision was made to allow the compressed air to escape through the Elster meter, the amount escaping being thus measured accurately. This was found to be almost invariably 0.4 liter.

In the more recent experiments, when the plan for testing the absorbing system described on page 32 was put in operation, this correction for the air contained in the absorbers at the end of this period has

not been applied, since, in the very process of testing, the air in the first water-absorber and the three carbon-dioxide absorbers was left in somewhat compressed form after the test, and obviously the true volume of air in this portion of the system was the same at the beginning as at the end of each period.

CORRECTION FOR MERCURY VALVE.

In the manipulation of the mercury valve[1] at the end of each experimental period, a certain amount of air is rejected from the system, since, by the raising of the mercury reservoir, air in the annular space is forced back into the last water-absorber, and when this is uncoupled escapes into the room air. The volume of air thus rejected has been determined very accurately to be 0.13 liter, and this is a constant correction to be applied for every period. The correction is applied on the blank for the calculation of the residual amounts of nitrogen, oxygen, carbon dioxide, and water vapor, as shown on page 84.

INCREASE IN VOLUME OF THE WATER-ABSORBERS.

As the water vapor is absorbed, the volume of the acid in the absorber gradually increases, and consequently the volume of air decreases. As this volume of air is practically driven into the air system, a correction for it is necessary. The specific gravity of concentrated sulphuric acid is 1.84, and as water is absorbed the specific gravity becomes lower. There is, however, a contraction in volume which must be allowed for in the calculations. It has been computed that approximately 0.7 of the weight of the water absorbed when expressed in cubic centimeters corresponds to the increase inside the water-absorbers, and consequently it is customary to multiply the number of grams of water absorbed by 0.7, the product equaling the volume of air in cubic centimeters forced out of the water-absorbers. This correction is always in one direction, and hence a cumulative one, and, though small, is made. On the blank in which the data for the weights of the absorbing system are recorded, the amount of this correction is calculated by multiplying the weight of water collected in the first water-absorber by 0.7, *e. g.*, as illustrated on page 64, $54.71 \times 0.7 = 38.297 = 0.04$ liter. That is to say, 0.04 liter of air was expelled from the water-absorber during this particular period.

FLUCTUATIONS IN VOLUME OF THE CARBON-DIOXIDE ABSORBERS.

That there is an actual difference between the volumes of the sodium hydroxide and calcium hydroxide at the beginning and those of the sodium carbonate and calcium carbonate at the end is highly probable,

[1] For construction of valve and diagram, see page 21.

as can be inferred from the slight difference in their specific gravities. The effect of such difference would be to drive air from the carbon-dioxide absorbers into the closed circuit by virtue of the increased volume of the absorbent. That the increase in volume would be sufficiently large to affect our results is, however, very questionable, and owing to the lack of data we have made no correction for it.

In addition to the possible difference in volumes of the reagent at the beginning and end of the period, there is a loss of water from the carbon-dioxide absorbers corresponding to the amount taken up by the air and absorbed by the last water-absorber. Inasmuch as the quantity rarely exceeds 50 grams per two-hour period, it has been assumed for purposes of calculation that it is the equivalent of distilling 50 grams of water occupying a volume of 50 cc. from the three carbon-dioxide absorbers into the water-absorber, where the 50 cc. become reduced in volume by the contraction taking place when mixed with sulphuric acid to $50 \times 0.7 = 35$ cc. Thus, even in maximum cases, there is a difference in volume due to absorption of water in the last water-absorber of only 15 cc. In the work so far this amount has been entirely neglected.

It is thus seen that no correction is applied at present for any possible changes in the air volume of the carbon-dioxide absorbers.

INTERCHANGE OF AIR THROUGH FOOD APERTURE.

The double door on the food aperture (see fig. 8) makes it possible to put into the chamber or remove from the chamber food and excreta, and the vessels in which they are contained, without causing any great change in the air admitted to or removed from the chamber during this process. When the inner door is closed and the outer door is open, it is assumed that the air in the food aperture has the composition of that of the laboratory. On the other hand, when the outer door is closed and the inner door open, it is assumed that the air in the food aperture has the composition of the air inside of the chamber. It is possible, however, that while air ordinarily diffuses quite rapidly, the composition of air in the food aperture does not change as rapidly or as completely as the above assumptions would imply.

We have assumed that laboratory air contains 20 per cent of oxygen and 80 per cent of nitrogen, not allowing for a small quantity of water vapor and carbon dioxide. The composition of the air in the chamber is always very different from that of the air in the laboratory, the difference being most pronounced as to the carbon dioxide present, as this may be anywhere from 12 to 60 times the normal amount. The percentage of oxygen is in general lower than normal, at times being as low as 17 per cent, though ordinarily it is not far from 19.5 to 20

per cent. If we assume for an average percentage of air inside the chamber 19 per cent of oxygen, 1 per cent of carbon dioxide, and 80 per cent of nitrogen, it follows that every time the food aperture is open there is an admission of oxygen to the system and a loss of carbon dioxide, with no very great change in the amount of nitrogen. The actual variations in the amounts thus admitted and removed have as yet not been taken into consideration, though during heavy-work experiments, when as much as 0.04 gram of carbon dioxide is collected in the 10-liter air sample used for residual analysis, as much as 0.02 gram of carbon dioxide may be lost from the system every time the food aperture is open. In experiments it is sometimes opened as often as 20 times per day, and it is thus seen that under these circumstances a not inconsiderable amount of carbon dioxide may be lost from the system. The amount of oxygen thus admitted is of less consequence, though the desirability of certainty as to its amount would suggest that more attention might be paid to this correction.

Another important correction in connection with the opening and closing of the food aperture is the displacement of air by the various articles of food, excreta, and dishes passed into and out of the chamber. If we consider the volume of air in the respiration chamber as 5,000 liters, then obviously, if a liter of water or metal or glass is passed into the food aperture, the total volume of air is reduced to 4,999 liters. On the contrary, if a liter of urine or of drip water or a volume of glass and metal equivalent to 1 liter is passed out of the chamber, the volume of air is increased to 5,001 liters.

It is therefore of considerable importance that the volume of this interchange through the food aperture be known, not merely from day to day, but from period to period. To aid in determining this interchange, a schedule has been prepared, the so-called "food aperture sheet," in which entries are made of all material entering and leaving the chamber. On this sheet are recorded the time at which the food aperture is opened, the nature and weight of the containers and their contents, and the temperature when not that of the chamber.

The temperature records are more numerous for materials entering the chamber than for those leaving it, since the attempt is made to have all articles in the chamber remain there until they have acquired the chamber temperature.

In calculating the volume of air displaced by the different materials entering and leaving the food aperture, it is necessary to take into account not only the weight but also the specific gravity. For the materials entering the chamber, *i. e.*, the food, drink, and containers, the following specific gravities are used: For glass, porcelain, etc., 2.6;

for sugar, carbohydrates, bread, crackers, cereals, etc., 1.5 ; for books, papers, underclothes, etc., 1.0 ; for milk, cream, butter, drinking water, cereal coffee, beef tea, 1.0. The specific gravity of both urine and feces is taken as 1.0.

The calculations of volume are made by dividing the weight of material by the specific gravity. Thus, inasmuch as the interchange through the food aperture should be known for each experimental period, it is our custom to add together the weights of all the glass entering the food aperture during the period in question and then divide the total weight by the specific gravity, 2.6. In a similar manner the total weight of sugar, carbohydrates, bread, cereals, etc., is found and this value divided by the specific gravity, 1.5. The volume of the materials leaving the respiration chamber during this same experimental period is likewise found, and the difference between the two volumes, *i. e.*, the volume of the material entering the chamber and the volume of the material leaving the chamber, is taken as representing the volume of air either removed from or added to the air in the closed circuit. If the volume of material entering the chamber is larger than the volume of material leaving it, this difference in volume is subtracted from the air in the system, and if, on the other hand, the volume of material leaving the chamber is greater than that entering the chamber, the volume of air equivalent to this difference is added to the total volume of air in the system. This correction in volume is made for every experimental period. (See blank on p. 84.)

ADDITION OF NITROGEN WITH THE OXYGEN.

As oxygen is admitted to the system, there is a continuous addition of nitrogen which accumulates in the ventilating air-circuit. The amount thus admitted is calculated very exactly, as has been shown on page 34. The application of this correction in the volumes will be discussed when the total amount of nitrogen in the system is considered. (See p. 88.)

THE REJECTION OF AIR.

Since the amount of nitrogen in the closed air-circuit accumulates as a result of its admission as an impurity in the oxygen, it becomes necessary to reject air from time to time, replacing it with pure oxygen, *i. e.*, oxygen containing from 2.5 to 8 per cent nitrogen, to keep up the normal percentage of oxygen in the main air current. In order to know exactly the proportions of oxygen and nitrogen rejected, it is desirable, theoretically at least, to make an analysis of a sample of the air rejected. In practice, however, we have been in the habit of re-

jecting when necessary a considerable quantity of air (30 to 70 liters) immediately after the beginning of the experimental period at 7 a. m., thereby making use of the data obtained from the analysis of the air at 7 a. m. in determining the composition and amount of the oxygen and nitrogen rejected.

Under these conditions the analysis of air at 7 a. m. holds good for the first portion of air rejected, but, in order to keep up the normal volume of air in the system and thus not draw the rubber diaphragms on the pans down too tightly, it soon becomes necessary to admit oxygen into the main air-pipe and thereby alter the composition. To delay this step as much as possible, and so diminish its effect on the composition of the air rejected, we allow the temperature inside the chamber to rise somewhat, as is its tendency when the subject is moving around vigorously, as at this time of day, and thus utilize the expansion of the air to keep the pans partially filled even when considerable air is being rejected. Under these conditions, while it is probably true that the percentage of oxygen in the last portion of the air rejected is somewhat higher than that in the first portion, we have customarily assumed that the analysis of air at 7 o'clock represents so nearly the actual composition of the air that no correction is necessary.

In rejecting air, the petcock on the entrance pipe of the Elster meter, through which the air sample is usually drawn, is closed, and the petcock connecting the entrance pipe of the meter with the main air-pipe at a point between the pans and the inlet for oxygen is opened. The screw pinchcock on the T tube, through which the air sample for oxygen analysis is taken, is opened, thus permitting free exit of the air leaving the suction-pump. The air is rejected as soon as possible after the end of the second residual analysis. Inasmuch as there is but little resistance between the main air-pipe and the meter, the gas passes through the meter very rapidly, and consequently 50 to 60 liters of air can be rejected in about 15 minutes. The manometer indicates a slightly diminished pressure, amounting to not far from 20 mm. of water, which, together with the temperature of the meter, is read when half the air is rejected.

From the volume of air as measured by the meter, the temperature of the meter, the manometer reading, and the barometric pressure, it is possible to calculate exactly the volume and weight of oxygen and nitrogen rejected.

Occasionally, especially when a sudden fall in barometric pressure has, by virtue of the expansion of the gases in the closed system, so retarded the admission of oxygen that the percentage of oxygen has fallen considerably below normal, it has been necessary to reject air

at other hours of the day than at 7 a. m. Under these conditions it is customary to make an analysis of a sample taken in the middle of the process of rejection.

Since the air is rejected after it has left the absorbing system, it is assumed that it is free from carbon dioxide and water vapor. Save in very rare instances in which large quantities of carbon dioxide are being absorbed by the soda lime and the cylinders have become very much heated as a result of the absorption, we have never found carbon dioxide in the air current leaving the absorbers. The efficiency of the last water-absorber, provided it has not gained in weight over 400 grams, is such as to preclude the possibility of the presence of any weighable amount of water. It is therefore assumed that nothing but nitrogen and oxygen are rejected, no account being taken of the possible presence of argon or other gases not absorbed by potassium pyrogallate, sulphuric acid, and soda lime. The small quantities of marsh gas resulting from putrefactive changes in the intestinal tract have also been disregarded. That these are considerable in man is not at all well established.

RESPIRATORY LOSS.

As the food is eaten, digested, and oxidized, *i. e.*, converted into gaseous products, the volume of solids in the chamber is constantly diminished and the volume of gas increased. In a similar manner, if, in a fasting experiment, the subject draws upon his body material, it is assumed that the volume of his body is diminished. These fluctuations have been a rather elusive object of search. Perhaps the most accurate estimate is obtained by adding together for each period the weight of water vaporized and of carbon dioxide eliminated and subtracting from it the weight of oxygen consumed. This figure, here termed the "respiratory loss," represents what the subject loses in weight during the period, exclusive of the water which may have been vaporized in perspiration and recondensed on the heat-absorbers inside. No account of this is taken, since in all probability it occupies the same volume in the absorbers that it did within the subject. This respiratory loss gives an estimate of the amount of substance changed from solids to gas during a given period. It is assumed that each gram of material occupied 1 cc. and the volume of air in the chamber should be increased by this amount in calculating the residual amount at the end of each period.

As a matter of fact, in the calculations of the last few experiments, instead of using the weight of the total amount of carbon dioxide eliminated during a given period, we have used the value obtained by

weighing the carbon-dioxide absorbers. No notice was therefore taken of the change in the amount of residual carbon dioxide. Theoretically, of course, this should be taken into consideration, although the ultimate result in 24 hours is compensating and no error finally results. In the first morning period, *i. e.*, from 7 a. m. to 9 a. m., the amount of carbon dioxide collected in the absorbers, especially in a work experiment, is considerably less than that actually eliminated. On the other hand, in the later periods of the day the amount of carbon dioxide thus absorbed is more than that actually eliminated during a given period.

A similar criticism applies to the use without correction of the weight of oxygen admitted for the variations in the residual amount of oxygen. As regards water vapor, no changes in residual amounts that could materially affect this calculation are possible.

In general, however, the actual correction for respiratory loss is not very large, and, while the residual amounts of carbon dioxide and oxygen should theoretically be taken into consideration in the calculation, it would be rather difficult and somewhat costly to carry through a preliminary calculation to determine the total amount of residual carbon dioxide and then recalculate the experiment, allowing exactly for the respiratory loss.

Subdivision of Air Volumes.

In calculating the true volume of gases in the different parts of the system, it is necessary to take into consideration the apparent volume as shown in the preceding section of this report, the barometric pressure, and the temperature. Of these three factors, the apparent volumes are determined by measurement, and the barometric pressure is that of the atmosphere, since the volumes of gas are measured when the blower is stopped, and due corrections are made for that small proportion of the total air which is confined in the first water-absorber and the carbon-dioxide absorbers. The temperature measurements are made in two places—first, that of the large volume of air in the respiration chamber, and second, that of the exterior portions of the apparatus. For calculating the true volume of air, four subdivisions of the air volume are made on the basis of differences in composition or temperature as follows:

I. The volume of air in the chamber.

II. The air in the pipe from the chamber to the absorbing system, including the blower and the entrance pipe of the first water-absorber.

III. The volume of air from the bottom of the first water-absorber to the entrance end of the second carbon-dioxide absorber.

IV. The volume of air in the remaining carbon-dioxide absorbers, second water-absorber, and pipe from the absorber back to the chamber. To this is also added the fluctuating volume of the air in the pans.

Volume I is measured at T_c, the temperature of the chamber; volumes II, III, and IV are measured at T, the temperature registered by a mercury thermometer near the pans.

As a result of the removal of carbon dioxide and water vapor and the admission of oxygen, the air in the different parts of the air-circuit is of varying composition, and consequently, in any calculation in which the total residual amounts of carbon dioxide, water vapor, oxygen, and nitrogen are to be determined, the composition of the different parts must be taken into consideration.

It is assumed that all the water vapor in the air current is absorbed by the first water-absorber during the passage of the air current through the acid, so that there is no moisture in the air above the acid in the water-absorber. It is further assumed that, in general, by the time the air current has passed through the first carbon-dioxide absorber its carbon-dioxide content has been reduced to zero. A second subdivision may therefore be made of the air volumes, based solely upon the variations in composition of different parts of the system.

The first two sections of the subdivision outlined above, *i. e.*, I and II, are alike, save as regards the temperature measurements. They differ from sections III and IV in that they contain water vapor in addition to the carbon dioxide, oxygen, and nitrogen. The volume of air containing water vapor, therefore, is the sum of I and II, and may be designated V_1. The air in the third section above, *i. e.*, III, though free from water, contains carbon dioxide in addition to oxygen and nitrogen, and consequently the total volume of air containing carbon dioxide is I+II+III. This volume is designated as V_2. The sum of the four subdivisions obviously includes the total volume of air in the system, and represents the volume of carbon dioxide, water vapor, oxygen, and nitrogen. This is designated as V_3.

COMPOSITION GRADIENT OF AIR IN CLOSED CIRCUIT.

In the preceding discussion it is assumed that the air in the various sections of the air-circuit has a uniform composition in each individual section.

Considering the closed volume of air absolutely independent of the room air, as is the case, barring leakage, it is apparent that the air in the respiration chamber proper and in the outgoing air-pipe, up to the time that it first comes in contact with the acid in the first water-absorber, contains nitrogen, oxygen, carbon dioxide, and water vapor.

The air entering the respiration chamber is free from carbon dioxide and water, and contains a larger percentage of oxygen than that in the chamber itself. Theoretically, therefore, there will be a space about the tube conducting air into the chamber that will have varying proportions of the different constituents; practically, however, the slight differences at this point are neglected.

The distribution of the water vapor in the chamber is very uneven, for we have the moist surface of the skin of the subject and the very moist absorbing system in the upper part of the chamber, and consequently, with the tendency of moist air to rise, probably the upper half of the air in the chamber contains a greater amount of water than the lower half. That this difference in composition is sufficient to affect the results of experiments with man is very much to be doubted, and in alcohol check experiments the rate of evolution of water is so slow that in all probability natural diffusion produces a nearly uniform moisture content throughout the whole chamber. In all these calculations, therefore, it is assumed that each portion of air is of uniform composition.

DATA USED IN CALCULATING RELATION OF WEIGHTS AND VOLUMES OF GASES.

The atomic weights of hydrogen and oxygen employed in these computations are those derived by Morley,[1] as follows: Oxygen = 16; hydrogen = 1.00762. According to the same authority, the weight of 1 liter of oxygen at 45° latitude is 1.42900 grams. Corrected for gravity, this becomes, at Middletown, 1.42853 grams. From these data the weight of 1 liter of hydrogen is readily computed as 0.089964 gram, and water vapor as 0.80423 gram.

The atomic weight used for carbon is that given by Clarke[2] as 12.001. The weight of 1 liter of carbon dioxide is accordingly 1.96427 grams.

For the weights of a liter of nitrogen and air, data given by three observers, Von Jolly, Leduc, and Rayleigh,[3] for the weight of a liter of oxygen and nitrogen have been averaged. In this way the weight of 1 liter of nitrogen at Middletown has been computed as 1.25668 grams. Similarly the weight of a liter of dry air, which, according to Rayleigh and Ramsey,[3] contains 20.91 per cent by volume of oxygen and 79.09 per cent by volume of nitrogen, is taken as 1.29264 grams.

The figures obtained for the weight of 1 liter of water vapor are on the assumption that it is a perfect gas down to 0° and obeys the law of expansion and contraction due to pressure and temperature. Accord-

[1] Smithsonian Contributions to Knowledge (1895), **980**, p. 109.
[2] Smithsonian Misc. Coll. (1882), **27**, p. 56.
[3] Smithsonian Contributions to Knowledge (1896), **1033**, p. 14.

ing to Hirn, this is not strictly true. The coefficient of thermal expansion of perfect gases is taken as 0.00367, whereas Hirn[1] states that the coefficient of thermal expansion of water vapor is 0.00419 between 0° and 119°, the value seeming to diminish as the temperature rises and increasing numerically for lower temperatures. Perman,[2] however, concludes that the density of saturated aqueous vapor is probably only very slightly (if at all) above normal at temperatures up to 90°, and from the data at hand it seems reasonable to assume that water vapor at 20° behaves as a perfect gas, and that the weights of a liter of hydrogen and water vapor are directly proportional to their molecular weight.

CALCULATIONS OF RESIDUAL ANALYSIS.

In calculating the total amounts of carbon dioxide, water, oxygen, and nitrogen in the residual air of the system at the end of any given period, the volumes of the sample and the apparent volume of the whole air system are reduced to the same basis, *i. e.*, the standard conditions at 0° and 760 mm. pressure, thus simplifying the calculations greatly.

Reference has already been made to the process by which the residual samples are taken, and specimen data for such samples are shown in the upper left-hand corner of the record sheet previously explained (p. 64). There remain for consideration, first, the calculation of the true volume of gas in the sample and in the system, and second, from these corrected data the calculation of the amount of the various gases in the system.

These calculations are simplified as much as possible, and for convenience are recorded on a blank shown on page 84.

VOLUME OF THE SAMPLE.

The calculation for the samples for the residual analyses involves a reduction of the gas volume as measured by the meter to standard conditions of temperature and pressure, making a due allowance for the volume of water vapor and carbon dioxide absorbed by the reagents, thus giving the corrected volume of air withdrawn in the samples reduced to standard conditions. The calculations for the reduction of these volumes to standard conditions is made on the residual sheet (p. 84). Under the head "Air sample for analysis" is first entered the apparent volume of air which is passed through the meter. To the logarithm of this volume must be added the logarithm of the calibration correction

[1] Hirn : Recherches sur l'équivalent mechanique de la chaleur (1858).
[2] Proc. Roy. Soc. (1904), **72**, pp. 72–83.

RESIDUAL SHEET. No. 16.

Calculation of the Residual Amounts of Nitrogen, Oxygen, Carbon Dioxide, and Water Vapor Remaining in Chamber at 7 a. m., April 9, 1905.

Residual at end of 12th period. Metabolism experiment No. 77.

Volume of nitrogen in chamber at 5.00 a. m.	3574.14 liters.	
Nitrogen in air sample rejected, ...liters, ...% N.,	"	
Nitrogen rejected with absorbers,	—.10 "	
Nitrogen admitted with oxygen,	+.54 "	
No interchange through food aperture, in (+), or out (—),	"	
Nitrogen present at end of period,	3574.58 "	

OXYGEN CORRECTIONS.

.7) —.03 liters.
—.04 grams.

AIR SAMPLE FOR ANALYSIS.

Log. 10.016	l. .00069	
Correction,	.98895	
T ,	.96858	
Pressure	.97992	
	.93814 = 8.672 l.	
Wt. H_2O.		
.0554	74351	
Gms. to liters,	**09462**	
	83813 = .069 l.	
Wt. CO_2		
.0441	64444	
Gms. to liters,	**70680**	
	35124 = .022 l.	
	v_0 = 8.763 l.	

Log. = 94265
Colog. v_0 = 05735

Manometer =	12.28 mm	
e @ Tm, =	17.84 mm.	
Sum =	30.12 mm.	
Barometer =	755.78 mm.	
Difference =	725.66 mm.	

Barometer =	755.78 mm.
Tm =	20.44° C.
Tc =	20.79° C.
T1 =	20.0 °C.

APPARENT VOLUME OF AIR.

	4909.88 + .05	
I.		= 4909.93 l. @ Tc
II.		= 6.55 l. @ T1
	5, 14.60 — .04	
III.		= 14.56 l. @ T1
IV. = {41.08 / 13.7}		= 54.78 l. @ T1

Log. I.	= 69107	
Tc	= 96806	
Pressure	= 99758	
	65671 = 4536.40 l.	
Log. II.	= 81624	
T1	= 96924	
Pressure	= 99758	
	78306 = 6.07 l.	
	4542.47 l. = V_1	
Log. III.	= 16316	
T1	= 96924	
Pressure	= 99758	
	12998 = 13.49 l.	
	4555.96 l. = V_2	
Log. IV.	= 73862	
T1	= 96924	
Pressure	= 99758	
	70544 = 50.75 l.	
Total volume of air	= 4606.71 l. = V_3	
Volume $CO_2 + H_2O$	= 47.38 l.	
" O + N	= 4559.33 l.	
" N	3574.58 l.	
" O	984.75	

Log. wt. H_2O in residual		
.0554	= 74351	
Log V_1	= 65729	
Colog. v_0	= 05735	
	45815 = 28.72 gms. H_2O	
Gms. to liters	**09462**	
	(a) 55277 = 35.71 l. H_2O	
Log. wt. CO_2 in residual		
.0441	= 64444	
Log. V_2	= 65858	
Colog. v_0	= 05735	
	36037 = 22.93 gms. CO_2	
Gms. to liters	**70680**	
	(b) 06717 = 11.67 l. CO_2	
(a)	35.71 l.	
(b)	11.67 l.	
	47.38 = 1. $CO_2 + H_2O$	
Log. 984.75	= 99333	
" 4559.33	= 65890	
	33443	
By calculation	21.60%	
By analysis	21.62%	

for the Elster meter (see p. 47), the cologarithm of the correction corresponding to the temperature of the meter T_m, *i. e.*, $(1 + .00367\ T_m)$, and the logarithm corresponding to the corrected pressure. The pressure of the air in the meter during the process of taking the residual sample is affected by three factors—first, the atmospheric pressure; second, the tension of aqueous vapor at the temperature of the meter, and third, the tension of the air on the meter as measured by the water manometer. By referring to the data given for the water manometer on the blank (p. 64), it is found that in this instance the manometer when reduced to millimeters of mercury indicates 12.28 mm. The temperature of the meter was 20.44°, and the tension of aqueous vapor at this temperature indicated in the calculations by e equals 17.84 mm. The sum of these two pressures equals 30.12 mm., which must be deducted from the barometric pressure to give the corrected pressure on the air in the meter, namely, 725.66 mm. The logarithmic correction for this pressure, *i. e.*, $p \div 760$, is .97992. The true volume of air then drawn through the meter is 8.672 liters. This does not, however, represent the total volume of air withdrawn from the chamber in the sample, since there were 0.0554 gram of water and 0.0441 gram of carbon dioxide absorbed in the U tubes before the air entered the meter. By converting these weights to volume by means of the standard logarithmic factors, .09462 and .70680, we find there was withdrawn from the air system in the sample 0.069 liter of water vapor and 0.022 liter of carbon dioxide, thus showing that the total volume of air withdrawn in the process of taking a sample, v_0, was $8.672 + 0.069 + 0.022 = 8.763$ liters. The logarithm of this amount is .94265 and the cologarithm .05735. This is more clearly expressed algebraically as follows:

CALCULATION OF TRUE VOLUME OF SAMPLE FOR DETERMINATION OF CARBON DIOXIDE AND WATER.

v_0 = volume of air sample containing carbon dioxide and water vapor at 0° and 760 mm.
v = apparent volume of sample (*i. e.*, meter reading).
f = factor for correcting meter readings.
w = weight of water in sample.
w^1 = weight of carbon dioxide in sample.
$1.2434\ w$ = theoretical volume of water vapor at 0° and 760 mm.
$0.5091\ w^1$ = volume of carbon dioxide at 0° and 760 mm.
T_m = temperature of water (air) in meter.
e = tension of aqueous vapor at T_m (millimeters of mercury).
m = manometer reading, expressed in millimeters of mercury.

h = height of barometer (in millimeters), corrected to 0°.

$p = h - e - m.$

$$v_0 = \frac{v \times f}{1 + .00367\, T_m} \times \frac{p}{760} + 1.24334\, w + 0.5091\, w^1.$$

CALCULATION OF THE TRUE VOLUME OF AIR IN THE CLOSED AIR-CIRCUIT.

The apparent volumes of air in the different portions of the air-circuit are, as has been stated before, subject to fluctuations, the most noticeable of which is the variation in the quantity of air inclosed in the pans. Volume I, that portion of the air in the air-chamber and the air-pipe and blower and the first water-absorber (see p. 80), is subject to fluctuations which may normally occur inside the respiration chamber, such as interchange of air through the food aperture, respiratory loss, etc., in addition to the normal changes as affected by temperature and pressure. The record of the apparent volume of air is given at the right-hand side of the residual sheet (p. 84). In this particular instance the initial apparent volume of air in section I is 4,909.88 liters, to which a correction of + 0.05 is added for the respiratory loss,[1] thus making a total volume of 4,909.93 liters. This volume of gas is at a temperature (T_0) of 20.79° and at a barometric pressure of 755.78 mm. To reduce this volume to that under standard conditions of temperature and pressure the logarithm of the volume is added to the cologarithm of the correction for temperature and the logarithm for pressure, which are taken from tables prepared for convenience. The cologarithm of the correction for the temperature (T_0) 20.79° is .96806 and the logarithm for reducing the barometric pressure is .99758. On adding these three factors together it is found that the corrected volume under standard conditions is 4,536.40 liters. This calculation is carried out on the left-hand lower side of the sheet.

The apparent volume of air in section II, the air-pipe leading from the chamber, the blower, and entrance pipe to the first water-absorber is equal to 6.55 liters measured at a temperature (T_1) of 20.0° and under the same barometric pressure as I. To reduce this volume to standard conditions a similar process is carried out, the calculation being placed immediately beneath the first on the sheet, and we find that the volume 6.55, when reduced to standard conditions, becomes 6.07 liters. Since both these volumes contain water vapor, they are added together, their sum giving V_1, the volume of the air containing water vapor.

[1] For calculation of respiratory loss for this particular period, see the record sheet on page 64.

The air in section III is subject to a fluctuation as a result of the increase in volume in the first water-absorber, and consequently the initial volume in this particular case, 14.60, must be decreased by the volume of the water absorbed, 0.04,[1] yielding a volume of 14.56 liters. This volume is likewise reduced to standard conditions, and, since it contains carbon dioxide, the reduced volume, *i. e.*, 13.49, is added to the volume of V_1, giving 4,555.96 liters as the volume of air containing carbon dioxide, *i. e.*, V_2.

The air in section IV consists of the constant volume of 41.08 liters, which represents the volume of the air-pipes and the fluctuating volume inclosed in the pans. The amount so inclosed during this particular period is 13.7 liters,[2] making a sum total of 54.78 liters. The apparent volume of air in section IV is also reduced to standard conditions, and when so reduced it amounts to 50.75 liters, which, when added to V_2, equals 4,606.71 liters, or V_3, the total volume of air in the system.

Total Residual Water Vapor.

Since the amount of water vapor in the sample and the corrected volumes of both sample and residual air are known, the calculation of the total residual amount of water vapor is a simple matter. The computations are made on the right of the residual sheet. To the logarithm of the weight of water found in the air sample are added the cologarithm of the corrected volume of air withdrawn in the sample v_0 and the logarithm of the corrected volume V_1 of residual air containing water vapor. In the instance here cited there were 28.72 grams of water vapor in the air-circuit.

It is convenient to know not only the weight of water vapor in the air, but also the volume, and consequently the computation is carried a step farther by adding the logarithmic factor .09462 to the logarithm of the weight of water, thus indicating that 35.71 liters of water vapor were in the system.

Total Residual Carbon Dioxide.

The residual amount of carbon dioxide in the whole closed circuit is determined in a similar manner, *i. e.*, by adding together the logarithm of the weight of carbon dioxide found in the sample, the cologarithm of the corrected volume of air taken for a sample, v_0, and the logarithm of the total volume of air containing the carbon dioxide (V_2), *i. e.*, the

[1] The calculation for the amount of air displaced by the water absorbed is made on the sheet, page 64.

[2] For the calculation of this volume of air, see the record sheet, page 64.

corrected volume of air in the chamber and air-pipes up to the second soda-lime cylinder. The weight of carbon dioxide in the system at the end of the period cited was 22.93 grams. By the use of the logarithmic conversion factor .70680 this weight of carbon dioxide is found to correspond to 11.67 liters.

Oxygen and Nitrogen.

The residual volume of oxygen and nitrogen together is readily determined by deducting the volumes of water vapor and carbon dioxide from the total corrected volume of air in the system, V_3. By reference to page 84 it will be seen that the carbon dioxide and water occupied a volume of 47.38 liters. On deducting this volume from V_3, *i. e.*, 4,606.71 liters, the volume of the remaining gas, oxygen, and nitrogen is equal to 4,559.33 liters. What portion of this volume is nitrogen can be found by direct calculation.

The Nitrogen in the System.

The amount of nitrogen present in the system at the beginning of an experiment is determined directly by an analysis of the air, from which the oxygen is removed by means of potassium pyrogallate. From this analysis the composition of the air free from carbon dioxide is obtained, *i. e.*, the percentages of nitrogen and oxygen. From the apparent volume, the true volume of the gases in the system is calculated, and, with due allowance for the volume of carbon dioxide and water vapor, the initial volume of nitrogen present may be computed. This volume is commonly referred to as the base line. Nitrogen may enter the system in either one or both of the following ways: (1) With the oxygen in the steel cylinders; from 2.5 to 8 per cent of the contents of the cylinder is nitrogen. Inasmuch as each cylinder varies in composition and the amount of oxygen and nitrogen must be known for each cylinder, it is necessary to make an analysis before the cylinder is used. (See p. 34.) (2) In air admitted through the food aperture.

Nitrogen may leave the system either in small quantities through the food aperture by the interchange of material, through loss in changing absorbers, or in the sample removed for the determinations of oxygen, but more especially, however, in the large sample of air rejected from time to time.

In addition to these regular channels for the escape of nitrogen, any leakage of air out of the system through defects in the couplings or connections obviously carries with it a large amount of nitrogen. The discussion of this point will be deferred until later.

CALCULATIONS FOR NITROGEN.

It will be noted that at the top of the sheet (p. 84), the first space below the heading is arranged for the calculation of the amount of nitrogen. The amount of nitrogen in liters found, either by analysis or calculation, in the chamber at the beginning of the experimental period is first recorded. In case air has been rejected during the period, as explained on page 67, the number of liters of air, the percentage of nitrogen, and the number of liters of nitrogen thus lost are then deducted. The negative correction for the amount of the nitrogen removed with the absorbers and the positive correction for the amount admitted with the oxygen are then added, together with a correction for the interchange through the food aperture, if any, which may be either positive or negative, according to whether nitrogen was admitted or removed. On applying these corrections, the nitrogen present at the end of the period is found. This value may then be transferred to the next residual sheet under the heading "Volume of nitrogen in chamber at ----*m*.---- liters," and serves as the basis of new nitrogen calculations until a new analysis has been completed.

This method of calculation assumes that there is no free nitrogen eliminated from the body other than that entering and leaving the lungs in the free state; in other words, that there is no production of free nitrogen from food or body protein. That this is probably the case, all experimental evidence thus far seems to show, although the desirability of an absolute demonstration is obvious.

Furthermore, it is assumed that there is no unaccounted-for leakage of nitrogen into or out of the system. Indeed, as will be explained beyond, this calculation is used ultimately to detect a leak.

CALCULATION FOR TOTAL RESIDUAL OXYGEN.

From the total volume of oxygen and nitrogen determined by deducting the volumes of carbon dioxide and water from the total air volume, V_3, is deducted the volume of the nitrogen as computed at the head of each residual sheet. In this instance, the volume of oxygen plus nitrogen being 4,559.33, on deducting the computed residual nitrogen, 3,574.58, the volume of oxygen was computed to be 984.75 liters.

It is thus seen that if the corrected volume of air is known as well as the volume of nitrogen, carbon dioxide, and water vapor, the difference is obviously the volume of oxygen. Since no other gases are present in any considerable amounts, this method seems to suffice for

all practical purposes. It is seen that this method determines oxygen by difference, while usually the factor in air analyses that is determined by difference is the nitrogen.

The calculation may be expressed algebraically in the following way:

v_0 = volume of air sample.
V_1 = volume of air containing water = (I + II).
V_2 = volume of air containing CO_2 = (I + II + III).
V_3 = volume of air containing O + N = (I + II + III + IV).
a = total volume of water vapor.
b = total volume of carbon dioxide.
c = total volume of nitrogen.
d = total volume of oxygen.
W = total weight of water vapor in system; w = weight in air sample.
W^1 = total weight of CO_2 in system; w^1 = weight in air sample.

$$W = \frac{w \times V_1}{v_0} \qquad W^1 = \frac{w^1 \times V_2}{v_0}$$

$$a = \frac{1.2434\, w \times V_1}{v_0} \qquad b = \frac{.5091\, w^1 \times V_2}{v_0}$$

It was formerly assumed that at the beginning of the experiment

$$d = .2091\ (V_3 - a - b);\ c = .7909\ (V_3 - a - b).$$

These values for the amounts of oxygen and nitrogen were determined by assuming the composition of the air free from carbon dioxide and water vapor as 20.91 per cent oxygen and 79.09 per cent nitrogen. We now secure greater accuracy, however, by using the actual analysis of the carbon-dioxide and water free air as made at the beginning of an experiment, *i. e.*, at 7 a. m.

This consequently changes the factors used in the last two equations from 0.2091 and 0.7909 to those found by analysis. In calculating the composition of the air at the end of the first experimental period, c is determined from the record of the amount of nitrogen entering with the oxygen, lost or gained through interchange through the food aperture, rejected with the absorbers, and lost if a sample of air has been rejected. All of these corrections are applied to the original initial volume of nitrogen found by analysis.

Under these conditions, then, we have

$$d = V_3 - (a + b + c).$$

Accuracy of Calculations of the Residual Amount of Oxygen.

In calculating the volume of oxygen remaining in the apparatus at the end of each experimental period according to the method here described, it is seen that the sum of all the errors in the determinations of carbon dioxide and water, as well as the errors in the calculations of the different volumes in the apparatus and of the nitrogen admitted, affect directly the calculation of the amount of oxygen present. This is a serious defect in this method of calculation. With the present arrangements for sampling and analyzing the air, however, it is believed that the values obtained in a residual analysis represent very correctly the actual amounts of water vapor and carbon dioxide in the sample. Similarly it is probably true that the amount of nitrogen admitted to the chamber is known with sufficient accuracy. The main source of error therefore lies in the calculations of the different volumes in the apparatus, and of the factors affecting these calculations that of temperature is open to the most serious criticism.

Thermal Gradient Inside the Chamber.

Inasmuch as the computation of the true volume of the gas inside the respiration chamber depends in large measure upon a correct knowledge of the average temperature of the mass of gas, it is necessary to consider in detail the accuracy of its temperature measurements. While the electrical resistance thermometers, both for the air and for the copper wall, undoubtedly give a very accurate measure of the fluctuations in temperature of their environment, it nevertheless remains a fact that the inside of the respiration chamber contains a mass of air which is subjected in different parts to widely varying temperatures. In the case of the alcohol check experiments we have a thermal gradient extending from the high temperature of the alcohol flame down to the temperature of the incoming water of the heat-absorbing system. In this case great heat is concentrated at one point, while the cooling area, *i. e.*, the area of the absorbers, is quite extensive. In the case of experiments with man we have a body temperature, which on the surface is not far from 33°, affecting a relatively large area, and a cooling area similar to that during the alcohol check experiments. In severe work experiments we have the body more or less exposed and the temperature of the absorbing system cooled nearly to zero. It is therefore difficult to see how the electrical resistance thermometers, distributed as shown in figure 33, can in any way assume accurately the average temperature of the air in the whole chamber. During rest experiments and alcohol

check experiments the discrepancies are not so great as during work experiments with men, but it is clear that slight disturbances in either the heat-radiating surface or in the heat-absorbing surface will make considerable differences in the average temperature of the total volume of air.

With alcohol check experiments this factor is practically a constant one, and while the electrical resistance thermometers may not represent the average temperature in the system, at the same time, owing to the constancy of the thermal gradient, they probably record accurately any differences in temperature, and it is these alone which affect the volume of air.

In experiments with man the temperature factor could be eliminated were it possible to have the heat-radiating surface constant throughout the whole period. With variations in position, muscular activity, changes in clothing, bedding, etc., however, it is very difficult, if not indeed absolutely impossible, to measure the differences of the average temperature of the air at the beginning and end of each period. This is most noticeable in the case of work experiments, where in the morning at 7 a. m. the subject is lying quietly in bed asleep, and at the end of the period, 9 a. m., he is riding a bicycle ergometer at a high rate of speed. Again, at 11 o'clock at night the subject is sitting dressed, possibly reading or writing, and at 1 a. m. he is sound asleep, covered with bed-clothing. It is during these two periods, when the widest variation in bodily activity naturally takes place, that we find the greatest discrepancies in the measurement of the volume of oxygen. These discrepancies are indicated generally by abnormal values for the "respiratory quotient." (See p. 184.) In the particular experiment the results of which are presented in this report (p. 177) these discrepancies do not appear.

CONCLUSION REGARDING THE ACCURACY OF THE OXYGEN COMPUTATION.

This method of calculation is found to be far more practicable and on the whole more satisfactory at the present state of our experimentation than a method depending upon analyses of air at the end of each period; for the difficulties in securing proper temperature measurements of the large volume of air affect alike the calculation of the total residual oxygen whether the analysis of a sample is made by the most approved methods or whether the computation method is employed. It is therefore believed that the errors involved in the system of calculations as above outlined are certainly no greater than those that necessarily occur in using direct analyses of oxygen under present conditions.

CHECK ON THE COMPUTATION METHOD OF DETERMINING OXYGEN.

The method of computation outlined on pp. 86–90 gives the amounts of oxygen and nitrogen present in the air at the end of each period; consequently at the end of any experimental period we can calculate the percentage composition of air free from carbon dioxide and water in the system. If we make such a calculation at the end of a 24-hour period and then make an actual analysis of the air free from carbon dioxide and water at the end of this period, we can obviously compare the computed percentage of nitrogen and oxygen in the air with that actually found by analysis. If the sample for analysis is taken at 7 o'clock in the morning, *i. e.*, when the subject is asleep and the temperature condition (thermal gradient) inside the chamber is closely comparable to that of the day before, there is every reason to believe that the computed percentage composition and that actually found will be practically identical. Thus, in the actual experiment recorded on page 84, the percentage of oxygen as calculated was 21.60 and the analysis for that period gave 21.62. In fact, so uniform are these percentages that any difference in composition is ascribed to a leak of air into or out of the system.

In case an error has been introduced in some way, it may in many cases be accounted for by careful inspection of the various divisions of the calculations. When desirable, a new nitrogen "base line" may be determined by using the results of the chemical analysis, after which the calculations are made as before. The increase or decrease in the amount of nitrogen in the new base line is that which has leaked into or out of the system.

COMPUTATION OF TOTAL CARBON-DIOXIDE AND WATER OUTPUT AND OXYGEN INTAKE.

Having considered in detail the methods of calculating the residual amounts of carbon dioxide, water, and oxygen in the air, it is evident that it is possible to use the data obtained by such calculations to compute the total output of carbon dioxide and water and intake of oxygen during any given period.

Total Carbon-Dioxide Output.

If the total amount of carbon dioxide remaining in the chamber at the end of the period is the same as that at the beginning, obviously the total output during this period is the weight of carbon dioxide absorbed in the carbon-dioxide absorbing system. It is very rare, how-

ever, that these residual amounts do not vary between the beginning and the end of the period, and consequently it is necessary to make due allowance for such fluctuations. If, for example, at 7 a. m. the residual amount of carbon dioxide is 22.93 grams, and at 9 a. m., at the end of the first two-hour experimental period, the residual amount of carbon dioxide is 35.46 grams, then during this period the subject has eliminated not only the amount of carbon dioxide collected in the absorbing system, but has added to the store in the air in the chamber 12.53 grams, and consequently the total output for this period would be w, the weight absorbed in the absorbing system, plus 12.53. Similarly, if the amount of carbon dioxide residual in the chamber at 11 p. m. is 31.26 grams and at 1 a. m. 24.92 grams, it is apparent that the carbon dioxide absorbed in the absorbing system represents not only that given off by the subject during this period, but also the difference between the residual amount at 11 p. m. and that at 1 a. m., namely, 6.34 grams, and consequently the total output of the subject during this period is w, the weight absorbed in the absorbing system, minus 6.34, the amount removed in the residual air. This calculation is carried out for convenience in a table in which the residual amounts, as well as those weighed in the absorbers, are recorded and the proper corrections applied. (See p. 183.)

Total Output of Water Vapor.

The fluctuations in the residual amounts of water vapor affect the total weight of water absorbed in the water-absorber in a manner precisely similar to that in which the residual amounts of carbon dioxide affect the weights of carbon dioxide. If during an experimental period there has been an increase in the amount of water vapor in the air, then the total output of water vapor during this period must be the weight of water collected in the absorbing system plus the increase in the residual amount, and conversely, if there has been a diminution in the residual amount, this diminution must be subtracted from the weight of water in the absorbers to give the true output for the period. In all discussions thus far with regard to water, the assumption has been made that the water exists in the form of water vapor. Since, however, certain parts of the interior of the respiration chamber are frequently at a temperature below the dew-point of the air inside the chamber, there may be a very material condensation of water on these colder parts. When the heat-absorbing system, through which the cold water to bring away the heat passes, is actually below the dew-point, it becomes covered with moisture, and in certain classes of experi-

ments, namely, where excessive muscular exercise is performed, the condensation of moisture may be so great as to cause the condensed moisture to drop off and collect in troughs which are specially provided for this purpose. The water thus collected may in some experiments amount to several liters, and this amount must be duly considered when calculating the total output of water from the body. This condensed water is commonly termed the "drip" water, and its collection is described in detail on page 23 in connection with the water-absorbing apparatus. In the final calculations, therefore, for the total water output, we take into consideration not only the fluctuations in the residual amounts of water vapor in the air of the chamber, but also the amount of condensed water on the absorbing system. The amount of water thus condensed is readily determined by weighing the heat-absorbing system. (See p. 161.) In all alcohol experiments and in rest experiments with men, care is taken to regulate the temperature of the water which brings away the heat, so that the heat-absorbing system is never cooled below the dew-point. Condensation of moisture and the necessity for collecting drip water are thereby obviated, and it is therefore seldom necessary to make this correction except in work experiments.

The tabular form for computing the total output of water is given on page 181.

Computation for Total Intake of Oxygen.

Fluctuations in the residual amounts of oxygen are usually much greater than the fluctuations in the residual amounts of water vapor, and consequently it is more often important to take these fluctuations into consideration. The variations in the residual amounts of oxygen are expressed in terms of liters. By dividing by the factor 0.7, the amount in liters is converted to the weight in grams. The corrections for the variations in the residual amount are applied to the weight of oxygen admitted from the steel cylinders. If the amount of oxygen remaining in the chamber at the end of the given period is less than at the beginning, the weight of the amount of oxygen thus used must be added to the weight admitted with the cylinders to obtain the true weight of oxygen consumed by the subject. Conversely, when there has been a storage of oxygen in the system in a given period, the amount thus stored must be deducted from that admitted from the steel cylinders. The tabular form for computations is shown on page 184.

ALCOHOL CHECK EXPERIMENTS.

While from a consideration of the construction of the apparatus it is difficult to conceive of any loss or gain of carbon dioxide, water, or oxygen to the system other than that occurring through regular channels and accounted for by the regular analyses, it still remains necessary to demonstrate the practicability and accuracy of the apparatus for determining the quantity of these substances entering into an actual experiment. If a known amount of carbon dioxide could be liberated inside the chamber and then reabsorbed by the purifying system and the difference in the composition of the residual air taken into consideration, the amounts thus recovered should agree exactly with that introduced. In earlier experimenting attempts were made to do this. Similarly, a certain amount of water was vaporized in the chamber and recovered again in the ventilating current of air. The difficulty of a proper absorbent for oxygen whereby oxygen could be absorbed on a large scale precludes, however, testing the apparatus by measuring with this or any similar process the amount of oxygen utilized.

It is possible, however, by burning a known weight of a substance inside the chamber not only to produce a known weight of carbon dioxide and water, but also to use in oxidation a known weight of oxygen. As a result of our previous experience in testing the earlier forms of this apparatus, we now burn known weights of ethyl hydroxide inside the chamber and determine the amounts of carbon dioxide and water eliminated and oxygen absorbed. Considerable preliminary experimenting[1] has shown that when ethyl hydroxide is burned in a so-called Argand burner no products of oxidation other than carbon dioxide and water vapor are present in any material amounts. Consequently it becomes necessary simply to introduce into the chamber a given weight of alcohol and burn it, absorbing the carbon dioxide and water vapor and measuring the amount of oxygen required for oxidation.

Kind of Alcohol Used.

For testing an apparatus of this kind the use of ethyl alcohol has proved extremely satisfactory. The chief objection attending its use is the fact that its absolute composition is not easily determined, since the elementary organic analysis of alcohol is attended with considerable difficulty. It is not easy to weigh accurately and transfer completely to a combustion tube any liquid, and, in addition, alcohol is especially prone to take on water, and hence the use of absolute alcohol is practically

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, p. 60.

prohibited. Nevertheless, it is possible by means of determinations of specific gravity and by reference to standard tables to determine with great accuracy the percentage of absolute ethyl hydroxide present in a mixture of alcohol and water. This procedure assumes, however, at the outset that the liquid under examination contains only these substances. With many of the modern methods of preparing alcohol the final product is frequently contaminated with alcohols of a higher carbon content. The ultimate result of the presence of these alcohols is twofold. In the first place, it alters the specific gravity of the mixture; in the second place, inasmuch as the percentage of oxygen is lower, the amount of carbon and hydrogen in each gram of substance is greater with the higher alcohols than with ethyl alcohol. That these impurities are present in minute quantities in the different grades of commercial alcohol is doubtless true, but with the grades of alcohol that we have so far experimented with—those ordinarily purchased from distillers for use in biological and chemical laboratories—we have had as yet no evidence of the existence of higher alcohols in quantities sufficient to influence our results. We therefore rely upon the determination of specific gravity for a calculation of the amounts of carbon dioxide and water that should be yielded by one gram of the alcohol.

Determination of Specific Gravity.

By means of the pyknometer, devised and described by Squibb,[1] it is possible to determine the specific gravity of a mixture of alcohol and water to the fifth or even sixth decimal place.

This pyknometer is so constructed that when immersed in water at a temperature of 15.6°, 50 grams of recently boiled, distilled water fills the bottle and the graduated stem to an arbitrary number on the scale. With the pyknometer now in use the stem is graduated from 0 to 70, and we have found that when the level of water (bottom of the meniscus) stands at 42.5, the bottle contains 50 grams of distilled water. By removing water with a small strip of bibulous paper it was found that each division on the scale corresponds to a change in the weight of water amounting to 1.8 mg.

The pyknometer is first carefully dried, a very thin film of vaseline applied to the ground glass stopper in the neck, and the apparatus accurately weighed. The bottle is then filled with alcohol which has previously been cooled in a well-stoppered bottle or flask to 10° or 12°, the graduated top inserted, and the bulb immersed in water at from 15° to 16°. A lead collar fitting over the neck of the bottle holds it

[1] Journ. Am. Chem. Soc. (1897), **19**, p. 111.

in position in the water bath. The water is constantly stirred and the temperature frequently noted, with due allowances for the calibration correction of the thermometer. When the temperature of the whole mass has reached 15.6°, the level of the alcohol in the stem is brought to the graduation at 42.5. The removal of alcohol is readily made by means of a finely drawn-out glass tube and small strips of bibulous paper, and all alcohol adhering to the upper part of the stem is carefully absorbed by these means. After the proper adjustment of the level of the liquid, the pyknometer is removed, carefully dried, and weighed. The increase in weight is the absolute weight of 50 cc. of the alcohol, and this number, divided by 50, gives the specific gravity of the solution direct. The expansion of the alcohol after removal from the water bath causes the enlargement of the stem to become partly filled with alcohol, but obviously this in no wise affects the weight.

Alcoholometric Tables.

From the specific gravity the percentage of alcohol may be obtained from standard alcoholometric tables. Dr. E. R. Squibb in a personal letter recommended as especially accurate a table published in his Ephemeris.[1] A more recent alcoholometric table prepared by Morley[2] is also excellent.

Factors for Actual Amounts of Carbon Dioxide, Water, and Oxygen.

The combustion of pure ethyl hydroxide may be expressed by the following equation:

$$C_2H_6O + 3O_2 = 2CO_2 + 3H_2O.$$

From the molecular weights[3] of ethyl hydroxide, carbon dioxide, and water and the atomic weight of oxygen it can be readily calculated that one gram of ethyl hydroxide when completely burned yields 1.911 grams of carbon dioxide and 1.174 grams of water, requiring for its combustion 2.085 grams of oxygen.

Since pure ethyl hydroxide is never used, however, but rather alcohol diluted with about 10 per cent of water, it is necessary to take into consideration the percentage of alcohol used. In general the alcohol is not far from 91 per cent ethyl hydroxide by weight, and in the alcohol check experiment given on page 102 the alcohol used consisted of 90.77 per cent of ethyl hydroxide.

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[1] Ephemeris, 1884–85, part 2, pp. 562–577.
[2] Journ. Am Chem. Soc. (1904), **26**, p. 1185.
[3] Atomic weights used are given on page 82.

One gram of a mixture of ethyl hydroxide and water containing 90.77 per cent of absolute alcohol will give 1.735 grams of carbon dioxide and 1.066 grams of water, resulting from the combustion of the alcohol molecule, in addition to the 0.092 gram of preformed water present in each gram of the mixture, and thus the total amount of water resulting from the combustion and vaporization of one gram of 90.77 per cent alcohol is $1.066 + 0.092 = 1.158$ grams.

If one gram of the 90.77 per cent alcohol yields 1.735 grams of carbon dioxide and 1.066 grams of water, the amount of oxygen involved in the reaction is readily determined by adding the weights of the carbon dioxide and water and subtracting the original weight of the alcohol used.

To simplify calculations, three logarithmic factors are computed, which, when added to the logarithm of the weight of alcohol burned, yield the logarithm of the total theoretical amounts of carbon dioxide, water, and oxygen involved in the combustion. These factors obviously vary with the percentage of alcohol used, and consequently the specific gravity of a rather large amount (5 to 6 liters) is taken and the alcohol carefully preserved in a well-stoppered bottle for use exclusively in alcohol check experiments.

Alcohol Lamp.

In earlier experiments, when oxygen was not determined, it was possible to introduce through the food aperture a small alcohol lamp and change it at the end of a period for another one without material alteration of the water and carbon-dioxide content of the air inside the chamber; but the problem became complicated when the determination of oxygen was undertaken, and this simple method was no longer sufficient. Consequently a special form of lamp was devised by means of which the alcohol could be put into the chamber without disturbing the food aperture or the volume of air inside the chamber. The lamp is pictured in figure 22.

The reservoir of the lamp is a bottle with an opening on one side near the bottom and another in the center of the bottom. The burner is of the ordinary round wick, kerosene, Argand type, and is attached to the neck of the bottle by means of a short length of large rubber tubing. The wick is purposely long enough to reach nearly to the bottom of the bottle. The reservoir is filled with alcohol through a rubber tube extending from the hole in the side of the bottle through a small orifice in the outer door of the food aperture to the supply on the outside. A glass tube of small diameter, bent like a U tube, with a long and a short arm, and with the latter inserted in the opening in the bottom of the bottle, serves to indicate the level of the alcohol in the

bottle. For gross adjustments, it is possible to see the level of the alcohol through the glass of the bottle; but as the alcohol ascends in the constricted portion of the bottle, and especially in the rubber tube below the metal burner, it is impossible to note the exact level through the neck of the bottle itself, and consequently the side-gage tube is necessary. A bit of paper is attached to this small tube to indicate the proper height to which the bottle should be filled. The gage tube is drawn out to a fine jet at the top to minimize evaporation of alcohol.

At the beginning of an experiment the lamp is filled and lighted, the chimney put in place, the flame watched for several minutes to see that it is burning to the proper height, and then the chamber sealed and

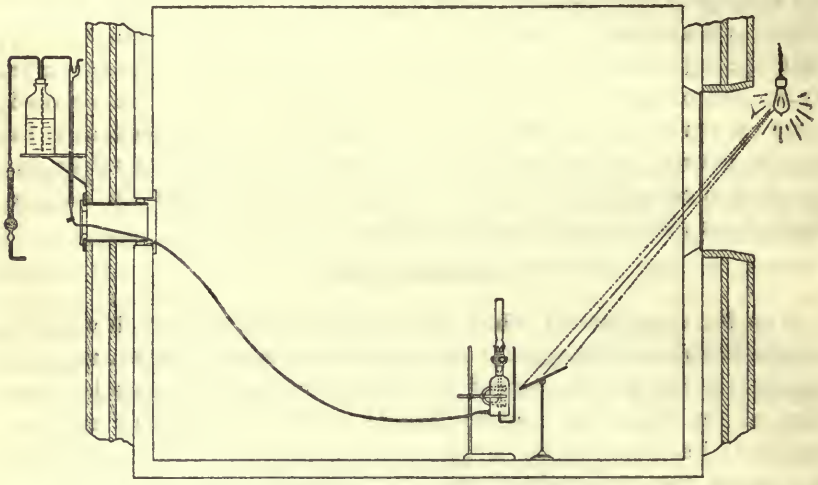

FIG. 22.—The Alcohol Lamp and Connections. The alcohol lamp is placed inside the respiration chamber and fed with alcohol through a rubber tube from the burette on the outside. An electric light in front illuminates the gage on the side of the alcohol lamp, thus enabling it to be filled to the same level each time.

the preliminary adjustments of temperature made. The lamp burns quietly and approximately at a constant rate. Just before the experiment begins, alcohol is admitted through the small rubber tube into the glass bottle until the level in the gage tube reaches the mark on the side. At this instant the experiment proper begins. At the end of the experimental period, which may be two or more hours in length, the alcohol is again filled to this level, and the exact amount of alcohol required to bring the meniscus on the gage tube back to its former position, plus the amounts added to the lamp from time to time, represents the exact amount of alcohol burned during a period.

For determining this amount, we use the following method: A supply of alcohol much larger than would be normally required during

an experiment is placed in a glass bottle fitted with a two-hole rubber stopper. Bent glass tubes passing through the holes in the stopper provide the means for forcing out the alcohol by blowing air into the bottle, as in an ordinary laboratory wash-bottle. The tube through which the air enters the bottle is connected with a chloride of calcium tube to remove moisture from the air blown into the bottle. The exit tube from the alcohol bottle is bent downward and drawn out to a point and so placed that it delivers the alcohol into a burette attached to the outside of the rear wall of the chamber. The burette is connected at the bottom by means of rubber tubing, and a glass tube through a cork in the outer door of the food aperture, with the long rubber tube leading to the alcohol lamp. A screw pinchcock controls the flow of alcohol out of the burette.

At the beginning of an experiment the observer, by looking through the glass door of the food aperture, notes the level of alcohol in the reservoir of the lamp, and at the exact moment when it reaches the mark on the gage tube he closes the pinchcock at the bottom of the burette. The alcohol supply bottle, with rubber stopper and glass tubes, is then weighed, and the height of alcohol in the burette accurately noted. At the end of the experiment the same operation is repeated, the lamp reservoir being again filled to the mark on the gage and the level of the alcohol in the burette again recorded. The alcohol supply bottle is then weighed, and the difference in the weights at the beginning and end, corrected for difference in the amounts of alcohol in the burette, gives the quantity of alcohol burned. The weighing of the bottle may be made with sufficient exactness on the balance for weighing food, or that for weighing the water and carbon-dioxide absorbers.

During the course of the experiment, as the level of alcohol in the alcohol lamp becomes low, sufficient alcohol may be admitted from time to time to keep the level well above the lower end of the wick. This successive addition of alcohol needs no special measurement, since it is the total amount (loss in weight of the bottle) admitted during a period that is actually required. Furthermore, there may be differences more or less great in the level of alcohol in the burette. It is possible with care to adjust this amount to very nearly the same at the end of each period by blowing over more or less alcohol from the bottle, and this is regularly done, though differences in level of the burette are invariably recorded and the residual amount of alcohol in the burette allowed for in the calculations.

On the particular burette used in connection with this lamp, the graduations happened to correspond very closely indeed to the weight of

the volume of alcohol delivered. This is due to the fact that this burette is one of the Geissler type, in which a ground glass rod serves as a stopcock. Obviously, therefore, when this glass rod is removed the actual amount of liquid delivered between the marks on the burette is larger than when the rod is in place. This difference happens to compensate almost exactly for the lower specific gravity of the alcohol used, and consequently the number of cubic centimeters read on this burette corresponds to the same number of grams of alcohol.

Thus the calculation of the amount of alcohol admitted to the lamp is based upon the loss in weight of the alcohol bottle and tubes and the variations of alcohol level in the burette. The lamp here described burns alcohol at the rate of about 20 grams per hour.

The electric light placed just outside the window is so situated that the rays of light fall upon a mirror which is inclined in such a position as to illuminate brilliantly the gage tube, thus materially aiding in the proper adjustment of the alcohol level at the end of the period.

Frequency and Duration of Experiments.

In the earlier years of experimenting it was deemed advisable to conduct an alcohol check test immediately before each experiment with man. With increasing skill in manipulation the necessity for these frequent tests has in a large measure disappeared, and at present three or four tests in a year are all that are required to control the apparatus.

The experiments last from 8 to 36 or more hours. Recently experiments of about 24 hours have been most common. The experiment here reported was subdivided into three periods of 3 hours 54 minutes, 5 hours 44½ minutes, and 11 hours 52 minutes, respectively, the whole experiment lasting 21 hours 30½ minutes. The total amount of alcohol burned was 406.8 grams, apportioned among the periods as follows: First period, 73.4 grams; second, 108.1 grams, and third, 225.3 grams.

Calculation of the Alcohol Check Experiments.

From the weight of the alcohol burned and the known factors corresponding to the theoretical amounts of carbon dioxide, water, and oxygen per gram of alcohol, the theoretical quantities that should be found by means of the respiration apparatus may be readily computed. Inasmuch as the quantities of carbon dioxide, water, and oxygen, as found by gain in weight of the absorbing system and loss in weight of the oxygen cylinder must be corrected for the variations in the residual amounts of these gases present in the system at the end of each period, it is customary in tabulating the results of these determinations to include in the tables the data for the residual amounts.

Determination of Carbon Dioxide.

The computations for the amounts of carbon dioxide are given in Table 1.

Table 1.—*Record of Carbon Dioxide in Ventilating Air Current.*

Alcohol check experiment, April 6–7, 1905.

Date.	Period.	Carbon dioxide.					(*f*) Ratio of amount found to amount required. *d* ÷ *e*.
		(*a*) Amount in chamber at end of period.	(*b*) Gain (+) or loss (—) over preceding period.	(*c*) Amount absorbed from air current.	(*d*) Total found by combustion. *c* + *d*.	(*e*) Required by theory.	
		Grams.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Per cent.*
April 6.....	Preliminary...	29.70					
Do.. ...	First.....	41.35	+11.65	115.05	126.70	127.32	99.5
Do.. ..	Second.....	32.62	— 8.73	196.12	187.39	187.51	99.9
April 7.....	Third..... ..	30.91	— 1.71	393.81	392.10	390 81	100.3
	Total....	..... .	.....	.....	706.19	705.64	100.1

In the first column the date on which the experiment was made is given, and in the second column the period, each experiment being subdivided into periods varying from 2 to 12 hours in duration. The amount of carbon dioxide in the chamber at the beginning of the experiment is recorded in column *a*. The subsequent amounts of carbon dioxide found at the end of the periods are recorded beneath this, and corresponding corrections for fluctuations in the residual amounts are recorded in the next column. If, then, these corrections are added or subtracted, as the case may be, to the weights of carbon dioxide absorbed in the absorbing system and recorded in column *c*, the corrected amount of carbon dioxide produced by the combustion of the alcohol is found. This is recorded in column *d*. From the computations of the theoretical quantities that should be yielded from this amount of alcohol, the data in column *e* are obtained, and the ratio between the amount found and the amount required by theory is expressed in per cent in the last column.

Obviously, when rather small amounts of alcohol are burned and consequently small amounts of carbon dioxide are evolved per period, slight errors in the determination of the residual amounts may result in a considerable percentage error for the short periods. The errors are compensating, however, for if the residual amount of carbon dioxide found in the chamber at the end of a given period is lower than it should be, the error will affect the total amount produced in the preceding period in one direction and that produced during the subsequent period

in another; consequently it is to be expected that the average of two or three periods would be much more accurate than any single period. On the other hand, if periods of 10 or 12 hours in length are considered, the possible error in determination of residual amounts becomes quite insignificant. It would seem from the experiment here reported that the determination of carbon dioxide by this apparatus, even in short periods, is extremely satisfactory.

Determination of Water.

The computations for the determination of water in the alcohol check experiments are made in a manner quite similar to those for carbon dioxide, the details for this particular experiment being given in Table 2.

The column headings are self-explanatory, and it is seen that the percentage error in the determination of water is, relatively speaking, small. When it is considered that one of the most difficult determinations in elementary organic analysis or with large respiration apparatus has been the accurate determination of water, it is seen that the accuracy here obtained is much greater than would be ordinarily expected. Indeed, the accuracy of the water determination would justify the use of the "closed circuit" were the determination of oxygen (its chief object) not practicable.

Table 2.—*Record of Water in Ventilating Air Current.*

Alcohol check experiment, April 6–7, 1905.

Date.	Period.	(*a*) Total amount of vapor in chamber at end of period.	(*b*) Gain (+) or loss (—) over preceding period.	(*c*) Amount absorbed from air current.	(*d*) Total found by combustion. $c + b$.	(*e*) Required by theory.	(*f*) Ratio of amount found to amount required. $d \div e$.
		Grams.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Per cent.*
April 6.....	Preliminary...	22.72					
Do.....	First.....	20.45	—2.27	88.78	86.51	84.98	101.8
Do.....	Second.....	21.10	+0.65	123.68	124.33	125.15	99.3
April 7.....	Third.....	20.17	—0.93	264.08	263.15	260.83	100.9
	Total .	.....	.....	.....	473.99	470.96	100.6

The Computations for Oxygen.

Inasmuch as carbon dioxide and water have been determined by other methods with apparatus as large as this with great accuracy,[1] especial interest in this particular form of apparatus lies in its power for deter-

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 136, pp. 37, 38.

mining accurately the amount of oxygen consumed, either by men or by an alcohol lamp. In Table 3 beyond are recorded, first the date of the experiment, then in succession the number of the period, the amount of oxygen residual in the chamber expressed in liters, and the differences in the amounts of oxygen residual in the chamber at the beginning and end of the different periods, expressed first in liters and then in grams. The weight of oxygen admitted from the steel cylinder is next recorded, followed by the corrected amount of oxygen used in the combustion, the theoretical amount of oxygen required to burn the weighed amount of alcohol, and, finally, the ratio of the amount found to the amount required, expressed in per cent.

The same considerations which affect the accuracy of computations of this nature for short periods, *i. e.*, the possible effect of errors in residual analyses, which were discussed when considering the computation of carbon dioxide, also influence, perhaps in a more marked degree, the computation of the amount of oxygen; but here, as in the previous case, the errors are more or less compensating, and, generally speaking, the longer the period the less the effect of the residual analyses. It would seem that in this experiment the determinations for the oxygen were, even in the short periods, extremely satisfactory.

TABLE 3.—*Record of Oxygen in Ventilating Air Current.*

Alcohol check experiment, April 6–7, 1905.

Date.	Period.	(*a*) Total amount in chamber at end of period.	Gain (+) or loss (—) during period. (*b*) Volume.	(*c*) Weight. $b \div 0.7$.	(*d*) Amount admitted to chamber from cylinder.	(*e*) Corrected amount used in combustion. $d - c$.	(*f*) Required by theory.	(*g*) Ratio of amount found to amount required. $e \div f$.
		Liters.	*Liters.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Per cent.*
April 6	Preliminary	911.26						
Do.	First	927.02	+ 15.76	+ 22.51	161.86	139.35	138.90	100.3
Do.	Second	951.95	+ 24.93	+ 35.61	242.70	207.09	204.56	101.2
April 7	Third	956.24	+ 4.29	+ 6.13	437.22	431.09	426.33	101.1
	Total					777.53	769.79	101.0

In the discussion of the tests of accuracy of the complete apparatus, *i. e.*, the respiration calorimeter taken as a whole, the heat-measuring ability of the apparatus must also be shown, and in Table 4, on page 176, we have a complete statement of the accuracy of the "respiration calorimeter" in measuring not only the chemical factors—carbon dioxide, water vapor, and oxygen—but also the heat. The table referred to gives a summary of all the results of this particular experiment.

THE CALORIMETER SYSTEM AND MEASUREMENT OF HEAT.

This section deals with that portion of the respiration calorimeter which is involved in the calorimetric measurements. It has been explained (p. 4) that the arrangements for measuring respiratory products and those for measuring heat are intimately combined in the same apparatus. In this description, however, the calorimeter will be considered for the most part as if it were independent of the respiration apparatus, though in a few instances it will be convenient to refer, for more detail, to what has already been described.

GENERAL PRINCIPLE OF THE CALORIMETER.

As a device for measuring heat, the apparatus here described may be designated a constant-temperature, continuous-flow water calorimeter. It is so devised and manipulated that gain or loss of heat through the walls of the chamber is prevented, and the heat generated within the chamber can not escape in any other way than that provided for carrying it away and measuring it. A small part of the total quantity leaves the chamber as latent heat of water vapor in the air current of the respiration apparatus, but the larger part is sensible heat absorbed by a current of cold water passing through a coil of pipe within the chamber. By regulating the temperature and rate of flow of this current of water, the rate at which the heat is absorbed may be controlled in accordance with that at which it is generated within the chamber, and thus the temperature of the chamber may be kept constant.

The quantity of heat carried out of the chamber as latent heat of water vapor is determined from the quantity of water vapor removed from the air current and the latent heat of vaporization of water. The quantity of heat absorbed and removed by the water current is determined from the quantity of water passing through the coil, its increase in temperature, and the specific heat of water at different temperatures. Theoretically the sum of these two quantities of heat thus determined should equal the total generated within the chamber, but in actual experiments with man various corrections, such as heat gained or lost by articles sent into or brought out of the chambers, etc., must also be taken into account.

The things to be especially considered in this discussion, then, are the arrangements for preventing gain or loss of heat through the walls of the chamber and the arrangements for bringing heat away from the chamber and measuring it. In the description of these many subordinate related topics must also be discussed.

THE CALORIMETER CHAMBER.

The dimensions of the chamber and its construction of metal have been given in the discussion of the respiration apparatus (p. 12). The walls, ceiling, and floor of the chamber are of sheet copper, polished on the inner surface. Copper offers many advantages as a metal surface for the interior of the calorimeter chamber, because it will take a high polish, thus aiding in the distribution of heat by reflection, and it conducts heat rapidly, thereby tending to equalize local differences in temperature. As a further aid in the reflection and distribution of heat and equalization of temperature, the four upright corners of the chamber are rounded. These features are of particular importance in the matter of determining changes in temperature of the walls, which is fundamental to the prevention of the gain or loss of heat through the walls, as explained beyond.

Outside the copper walls of the chamber and concentric with them, but separated by an air-space of 7.6 cm., corresponding to the width of the wooden framework by which the copper walls are supported, is another metal covering, the purpose of which will be described later. For this covering the cheaper metal, zinc, is very satisfactory. Sheets of zinc (Brown & Sharpe gage 25), each 3 by 7 feet and weighing 14 pounds, were used in this construction. Since this covering need not be airtight, the joints were soldered only at convenient places, and the zinc is nailed to the wooden framework between the two layers of metal. There are, however, no apertures large enough to disturb the "dead air" in the space between the zinc and the copper.

WOODEN WALLS SURROUNDING THE CHAMBER.

To protect the calorimeter chamber against fluctuations in the temperature of the calorimeter laboratory, and especially to provide opportunity for controlling the temperature of the metal walls in the manner described beyond, there are two concentric coverings of wood completely surrounding it, with an air-space of 7 cm. between the zinc wall and the inner wooden partition and a corresponding space between this and the outer wooden covering. This construction is equivalent to a double-walled wooden house, into which the calorimeter chamber is inserted. The details of the construction follow, reference being made to the horizontal cross-section in figure 8 and the end and side vertical cross-sections in figures 23 and 24.

At each corner of the house, between the two wooden walls, an upright (*b*, *b*, and *c*, *c*, in fig. 8) extends from floor to ceiling of the laboratory, thus providing rigid supports. As seen in figure 8, the two

uprights at one end (*b*, *b*) are grooved to fit the inner walls; those at the other end (*c*, *c*) are rectangular in cross-section. All four uprights are well painted to prevent absorption of moisture and consequent warping, such precaution being especially necessary because of the location of the laboratory in the basement of a stone building.

Extending between these uprights in both directions, at the top and bottom of the structure, are joists; those extending across the shorter dimension are shown in cross-section in figure 24 (*a*, *a* and *b*, *b*), and those running lengthwise in figure 23 (*a*, *a* and *b*, *b*). These eight joists and the four uprights form a rigid support for the wooden walls. Like the two uprights *b*, *b*, shown in figure 8, the two joists *a*, *a*, shown in figure 24, are grooved to receive the inner wooden partition.

The floor of the outer wooden structure rests upon two pieces of cedar 15 by 15 cm., shown in cross-section (*c*, *c*, in fig. 24), which are laid directly upon the laboratory floor. These hold the ends of the floor of the outer casing firmly against the lower edges of the joists *a* and *b*. In addition to these there are nine large blocks (*d*, *d*, *d*, in figs. 23 and 24) placed under the cleats of the floor at the points where the weight of the calorimeter is supported; that is, under the castors on which it stands. Between the floor of the outer and that of the inner wooden structure are smaller blocks (*e*, *e*, fig. 23, and *e*, *e*, *e*, fig. 24), upon which rest the cleats of the inner wooden floor, these cleats being directly under the castors.

All other parts of the walls, floors, and ceilings of both inner structures are securely fastened to the joists and uprights above described, but in such manner that when necessary they may be easily removed so as to render all parts of the outside of the calorimeter accessible. To facilitate the removal, each wall, ceiling, or floor is constructed as a panel, from matched hard pine, screwed together with a number of cleats and battens, as illustrated in figures 23 and 24. The outer panels are provided with metal handles sunk into the wood for convenience in removing them. In spite of the large size of the panels (the smallest being 1.62 by 2.24 meters), none of them shows evidence of warping after having been used over three years. Matched boards were used to avoid cracks, which would afford opportunity for the diffusion of air.

Of the eight panels forming the sides and ends of the two wooden structures, six are readily removable. The other two, namely, those at the end in which the window is built, may also be removed if necessary, but to take out the outer panel in this end involves considerable trouble in disconnecting apparatus adjacent to it on the outside. The occasions for removing this panel, however, are very rare. Even in

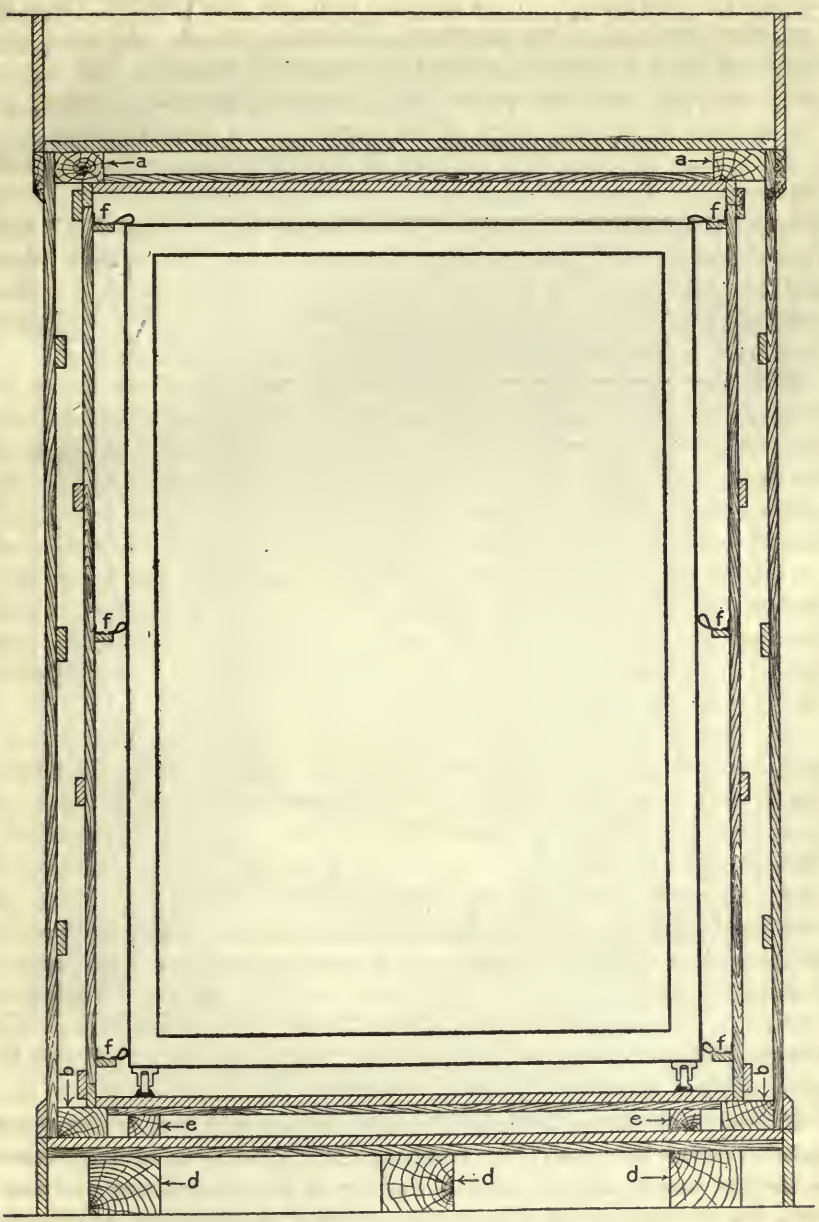

FIG. 23.—Vertical Cross-Section of Calorimeter Chamber through the end. The chamber consists of four concentric shells, two inner ones of metal and two outer ones of wood. The air-spaces and the wooden separators dividing the inner air-space (*f*, *f*, *f*, *f*, *f*, *f*), as well as the castors on which the metal chamber rests, are also shown.

case of an accident to some of the connections between the two panels at this end, it is more convenient to remove the two panels from the rear end, withdraw the metal chamber, and then take out the inner panel from the front end. Under all ordinary circumstances the two rear panels are the only ones removed. A view with these two panels taken out and resting against the side of the house is shown in figure 25.

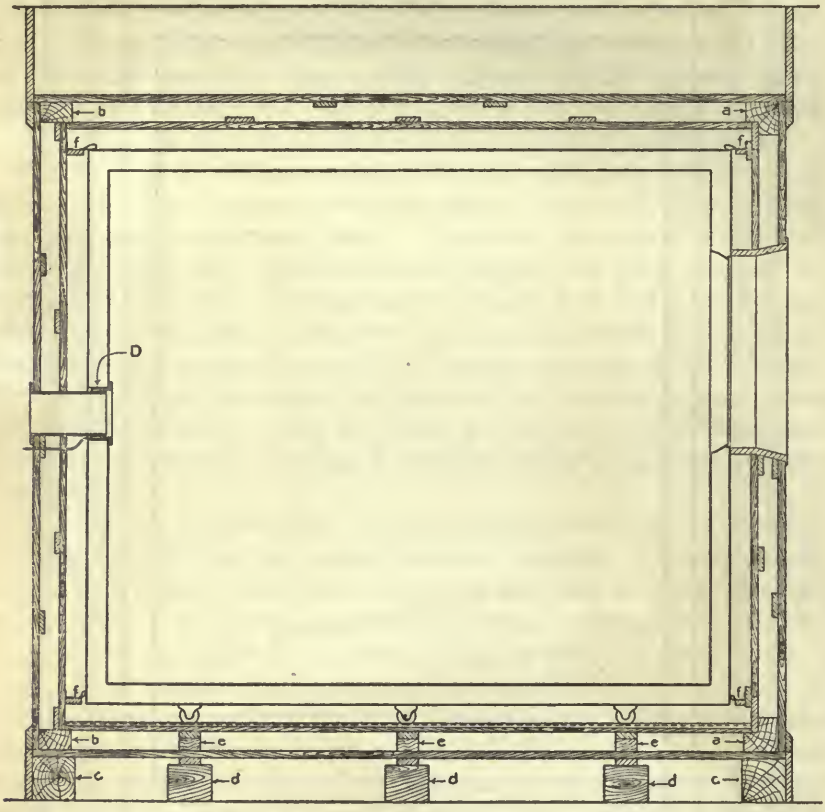

FIG. 24.—Vertical (side) Cross-Section of Calorimeter Chamber. This view shows openings for window and food aperture, position of castors, wooden separators (*f*, *f*, *f*, *f*), and panels.

The space between the floor of the laboratory and that of the outer wooden casing is inclosed by a baseboard or mopboard on all four sides. A similar board extends around the top of the calorimeter and confines the air in the space between the ceiling of the outer wooden casing and that of the laboratory. All of these boards, both top and bottom, may be easily removed.

To face page 110.

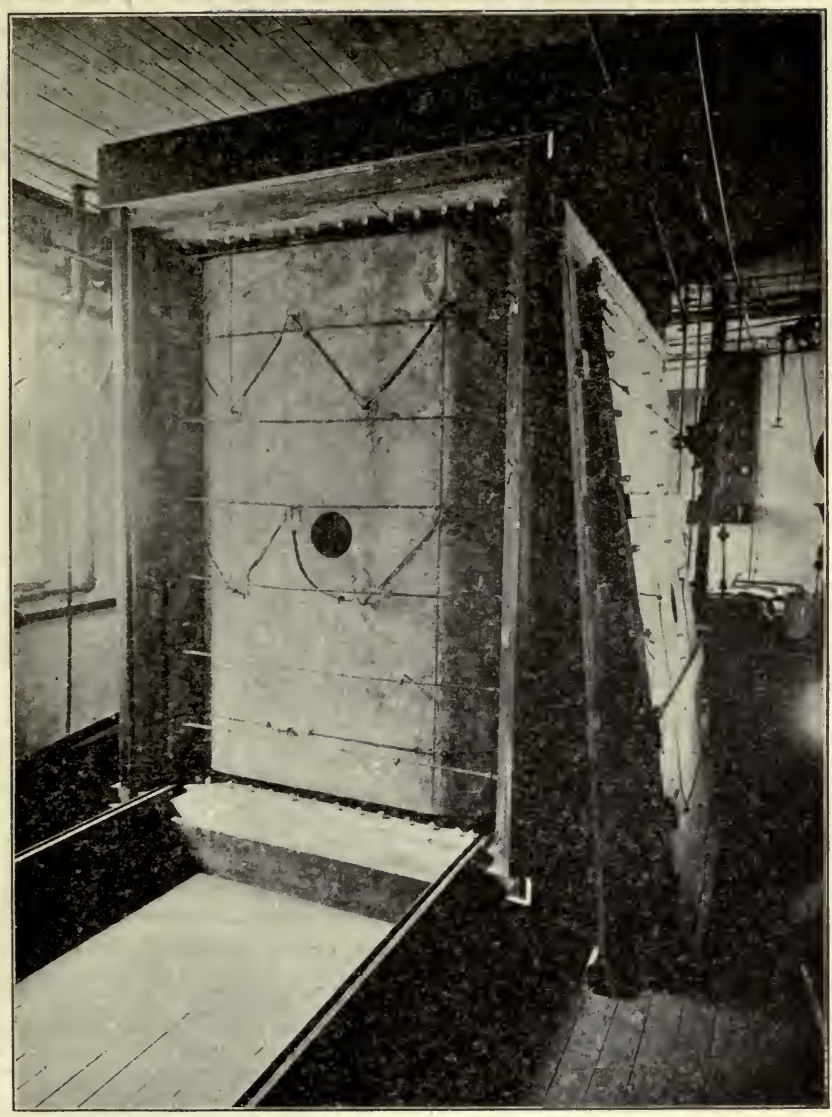

FIG. 25.—Rear View of Calorimeter Chamber showing the two panels removed and the iron tracks on which Chamber is rolled. The water-cooling pipes stretch horizontally across end of calorimeter. White porcelain knobs are usedfor suspending the heating wires. The food aperture is seen in center of Chamber.

AIR-SPACES AND HEAT INSULATION.

From the above description and the illustrations in figures 8, 23, and 24, it is seen that the calorimeter chamber and its wooden house consist of a series of concentric shells, the inner one of copper being enveloped by a zinc shell and two wooden shells, with the different shells separated by air-spaces. The important feature of this construction is the insulation against heat. Between the outer and inner wooden structures is the "outer" air-space, and between the inner wooden casing and the zinc wall is the "inner" air-space. Between the two metal walls is still a third air-space. The confined dead air in these spaces is an excellent heat insulator. To render the air in these spaces as nearly "dead" as possible, the panels are made very tight by the use of matched boards, as above described, and at the edges are fitted very closely to prevent escape or entrance of air. Further insulation against heat is provided by coating both surfaces of the inner wooden casing and the inner surface of the outer casing with asbestos paper. This was applied to the surface of the panels by means of the ordinary paste used by paperhangers, and it has shown no tendency to become loose; the fibrous nature of the asbestos furnishes a very good surface for adhesion.

It will be seen from the figures showing cross-sections that the uprights and joists of the framework divide the outer air-space into six separate sections—top, bottom, and four sides. The inner air-space surrounding the zinc wall is continuous so far as the construction of the wooden casing is concerned. It has been found desirable, however, in connection with the arrangements for controlling the temperature of this space, described later, to divide it into sections. This is accomplished by means of wooden strips, nearly as wide as the space between the metal and wooden walls, running parallel to the floor and the ceiling, one edge of the strip being attached to the inside of the inner wooden wall and the other edge being provided with a felt flap that rests against the zinc wall. The strips are attached to the wooden walls by means of hinges, so that they may be turned up out of the way when the calorimeter chamber is to be rolled out of the wooden house. The strips are shown (*f*, *f*, *f*, *f*) in figures 23 and 24, and may also be seen in figures 30 and 31. The space above the top of the chamber is divided into one section by the strips at the upper edges, and that below the floor of the chamber is likewise separated into another section by strips at the lower edges. The space surrounding the four sides of the chamber is divided into two sections by strips half way between the top and the bottom.

FACILITIES FOR REMOVING METAL CHAMBER.

In case of accident to any part of the outside of the calorimeter chamber it is necessary to have easy access to that part. The particular form of construction above described was adopted to secure ready accessibility to all parts of the apparatus, as already explained.

The calorimeter chamber, exclusive of any fittings, weighs 605 pounds. To facilitate withdrawing the chamber from the wooden casing, six large castors, three on each side, are fastened to the bottom. These castors move in iron tracks laid on the floor of the inner wooden structure, the tracks being of the grooved iron commonly used in bridge construction. The raised edges serve as guides to the wheels. Beyond the inner wooden floor each track is continued along a stiff joist, the end of which is cut so as to fit over the wooden casing of the calorimeter and thus allow the ends of the track to come together and form a continuous passage for the wheels of the calorimeter. The joists are laid on the floor of the laboratory and when not in use are removed. When supporting the calorimeter they are held rigidly upright by a cross-piece at the outside ends. Figure 25 shows the tracks extending from the wooden casing, and figure 29 shows the calorimeter rolled out upon them.

METHODS OF PREVENTING GAIN OR LOSS OF HEAT TO CHAMBER.

It has been stated that the heat generated within the chamber can not escape from it except by the means provided for carrying it away and measuring it. In order that this shall be the case and also that the amount thus measured shall include only that produced within the chamber and shall not be augmented by heat from external sources, there must be no gain or loss of heat through the metal walls, the openings in the walls, or the air current. The arrangements for preventing gain or loss of heat by these channels are here described.

Prevention of Gain or Loss through the Metal Walls.

If the zinc wall were colder than the copper there would be an outward flow of heat, *i. e.*, a loss, and if it were warmer there would be an inward flow or gain. To prevent the passage of heat in either direction, or, more strictly, to provide that the small quantity that may pass one way shall be exactly counterbalanced by an equal quantity in the other direction, the temperature of the zinc is regulated in accordance with that of the copper. This is accomplished by heating or cooling the air-space surrounding the zinc walls as necessary, according to whether the zinc is colder or warmer than the copper.

First of all, then, it is necessary to detect differences between the temperature of the copper and that of the zinc wall.

THE THERMO-ELECTRIC ELEMENTS.

Differences in the temperatures of the zinc and the copper walls are indicated by a current of electricity generated by thermal junctions[1] of iron and German-silver wire inserted between the metal walls and connected with a reflecting galvanometer. There are in all 304 pairs of such junctions distributed throughout the metal walls in groups, each group containing four pairs of junctions and comprising what, for convenience, is termed an element. The thermo-electric element used in this calorimeter is illustrated in figure 26.

Construction of the element.—Each element consists of four pairs of junctions of iron and German-silver wires, inserted in grooves in a wooden cylinder. The iron wire consists of "soft, bright Bessemer steel wire, Washburn & Moen gage No. 19." The other is so-called nickel German-silver wire, 18 per cent, Brown & Sharpe gage No. 18. Four short pieces of the iron wire were joined with silver solder, by means of a blow-pipe, to three pieces of German-silver wire of the same length and two pieces somewhat longer, and then bent in the manner shown in figure 26, in which the iron wire is represented by the solid black line. They were then crowded into slots in a short wooden rod made of thoroughly seasoned, straight-grained, hard maple. As is seen in figure 27, one of the long German-silver wires is doubled on itself and brought out parallel to the other. By this arrangement there are four soldered unions of iron and German-silver at each end of the wooden rod. The ends of the German-silver wire are fastened to copper wires leading to the galvanometer. The completed element, as above described, is finally boiled for some time in paraffin to expel moisture and insure perfect electrical insulation.

Method of installing elements.—The method of installing the elements in the metal walls is illustrated in figure 28.

The base of a copper thimble, 15 mm. in diameter and 16 mm. deep, having straight sides, is soldered to the outer surface of the copper calorimeter shell, *i. e.*, in the space between the zinc and the copper. Directly opposite this thimble in the zinc wall, a copper ring, 15 mm. internal diameter and 26 mm. long, is soldered in such a position that it extends 13 mm. outside of the zinc wall. The thermo-electric element is then slipped through the ring soldered in the zinc wall, and the inner end of the element inserted into the thimble soldered to the

[1] The use of thermal junctions for this purpose was originally suggested by Dr. E. B. Rosa. The use of this principle in calorimetric work has been attended with such excellent success that it is retained here, although the form of element has been modified. The present form was devised by Mr. O. S. Blakeslee, formerly mechanician of Wesleyan University.

copper wall. The length of the wooden cylinder and of the wires is such that when one end is thus inserted in the thimble the junctions at the other end are exactly in the plane of the zinc wall. The element is held in place by a cork firmly inserted in the outer aperture of the ring in the zinc wall. The ends of the two long German-silver wires that lead to the junctions are passed through holes in the cork, which are far enough apart to insure insulation between the two German-silver wires, and likewise far enough from the edge of the cork to insure insulation between these wires and the copper ring soldered into the zinc wall. The ends of the thermal junctions are far enough below

Fig. 26.

Fig. 27.

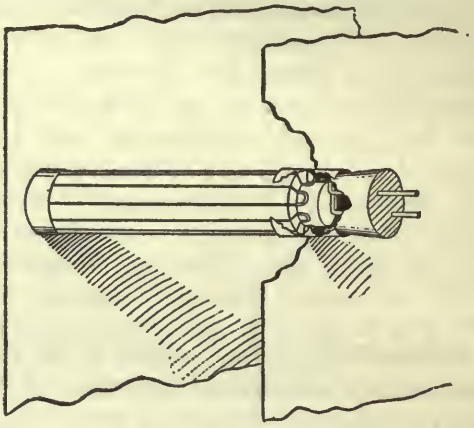

Fig. 28.

FIG. 26.—Thermo-Electric Element. Iron wires (represented by black line) and German-silver wires are soldered with silver solder, making a series of four junctions at each end.

FIG. 27.—Thermo-Electric Element Mounted on Wooden Rod. The iron and German-silver wires are pressed well into slits in the sides. The two projecting wires are for connections.

FIG. 28.—Method of Installing the Thermo-Electric Elements in the Metal Walls. A short tube soldered in the zinc wall holds the element in place.

the outer surface of the wooden cylinder to prevent any possible electrical contact with either the copper thimble on the copper wall or the ring on the zinc wall, while the small air-gap does not seem to retard unduly the passage of heat from the copper or zinc wall to the junctions. In this position a junction is able to take up rapidly at each end the temperature of the corresponding metal wall.

The detection of differences in temperature between the two metal walls by means of the thermal junctions thus inserted depends upon the fact that if the ends of the two kinds of wire forming the junction are unequally heated a current of electricity is developed, the intensity of

which is dependent upon the difference in temperature. The intensity of the current can be accurately noted with a delicate galvanometer, and consequently the difference in temperature closely measured. Obviously, in the case of noting the difference in temperature between the copper and the zinc walls, it is necessary not only that the thermal junctions be in the best possible thermal contact with the corresponding metal walls, but also that there must be absolutely no electrical contact to impair the accuracy of the measurements. The grooves in the wooden rod are sunk sufficiently deep to bring the ends of the junctions considerably below the surface of the wooden cylinder. As will be seen on studying the method of installing the junctions, this position of the ends of the junctions is necessary to secure electrical insulation from the copper and zinc walls of the calorimeter.

Distribution of elements.—As it is desired to keep the temperature of the zinc wall exactly the same as that of the copper wall, the elements should be distributed over the whole six sides of the chamber in such a manner that each one may assume the average temperature of a certain portion of the total area of metal; that is, the elements should be distributed all over the area of the calorimeter in points very closely proportional to the area. As a matter of fact, the junctions are located about 48 cm. apart, and each exercises the temperature control of an area of metal about 48 by 48 cm. The distribution of the various elements in the rear end of the chamber is seen in figure 25, which shows the respiration chamber inside the wooden house, the rear panels of which have been removed. In this figure the location of ten elements is distinctly shown. The wires attached to the calorimeter in a "zigzag fashion" are connected to elements at each point where the direction of the wire is changed. Only two elements appear in the lowest zone, and here the connecting wires do not take a zigzag course.

In figure 29 a view of the distribution of the elements on one side of the calorimeter is shown. There are here, as on the end of the calorimeter, two zigzag rows of fourteen elements and a lower row of three elements in a straight line. The number and distribution of the elements on the wall of the metal chamber opposite to that shown in figure 29 is precisely the same. Owing to difficulties in photographing the apparatus, no figure is given showing the distribution of the eleven elements on the top or the eleven on the bottom of the calorimeter. The nine elements on the front end of the chamber are shown in figure 30. There is also one additional element in a position that does not appear in any of the photographs. This makes in all seventy-six elements, each containing four pairs of thermal junctions.

Electrical connections of the elements.—As may be seen from the illustrations in figures 25, 29, and 30, all the elements are connected in series. When the ends of the whole system are connected with the galvanometer the deflection obtained is not that due to the current from a single element, but it is the resultant of all the positive and negative electro-motive forces of all the elements. It is very essential, however, to be able to determine temperature conditions for different sections of the total area of the chamber. It is conceivable, for example, that even while the zinc and copper walls at the ends and sides of the calorimeter remain adiabatic, at the top the zinc wall may be warmer than the copper, and at the bottom the copper wall may be warmer than the zinc. If there were the same difference in temperature in both cases the algebraic sum of the electro-motive forces would be zero, indicating that the temperatures of the zinc and copper walls were the same over the whole area, and consequently no passage of heat in either direction, whereas heat would actually be passing out at the bottom and entering at the top.

In order to prevent such temperature differences in local sections of the total area, the whole system of elements is subdivided into groups corresponding with different regions, so that it is possible to detect not only average temperature differences for the total area, but also local differences. The whole surface area is divided into four parts, the top being one and the bottom another. The upper double row of elements connected by wires in a zigzag line comprises the third division, and the lower zigzag row and the row in a straight line around the bottom together form the fourth division. For convenience these divisions are designated as top, bottom, upper zone, and lower zone, respectively. By means of connecting wires leading from the points at which the various sections are joined together, each individual section can be connected at will with the galvanometer and the temperature differences indicated by the electro-motive force ascertained.

It will be seen by comparing the above explanation with figure 29 that the division of the vertical walls of the calorimeter in the two zones is not an equal one, the upper zone being much less in area than the bottom. Since, however, the upper zone is subject to much wider fluctuations in temperature because of variations in the temperature and exposed surface of the heat-absorbing system, it is advisable to have temperature differences located in this small zone as precisely as possible.

While the thermal junctions in each group are used to detect temperature differences between the copper and zinc walls, no absolute measurements of such differences are made. In general, the differences

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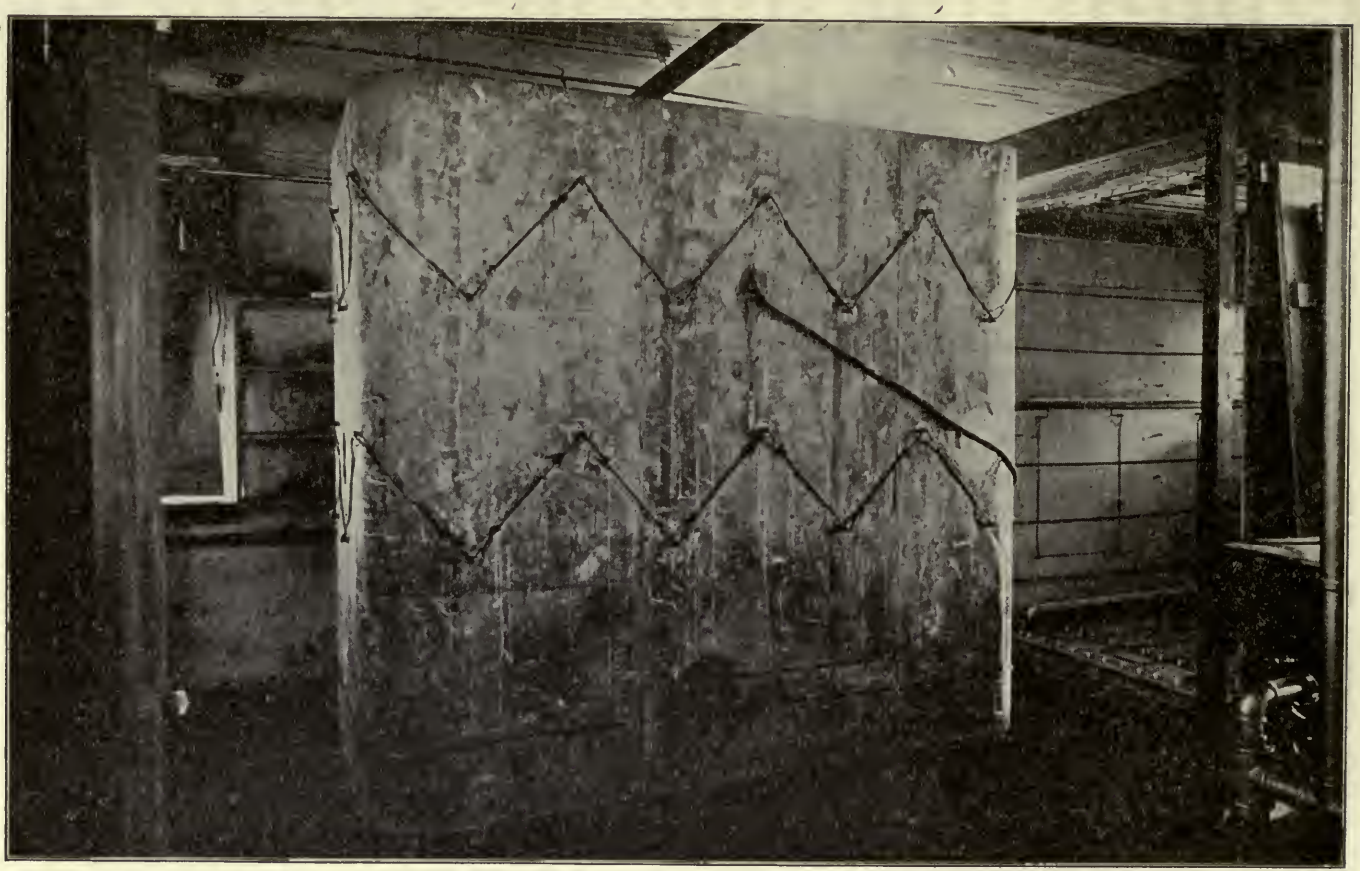

FIG. 29.—Side View of Metal Chamber rolled out on the tracks. The wooden casing with piping and wiring in interior is shown at right. The distribution of thermal junctions and the electric cable is shown on metal chamber.

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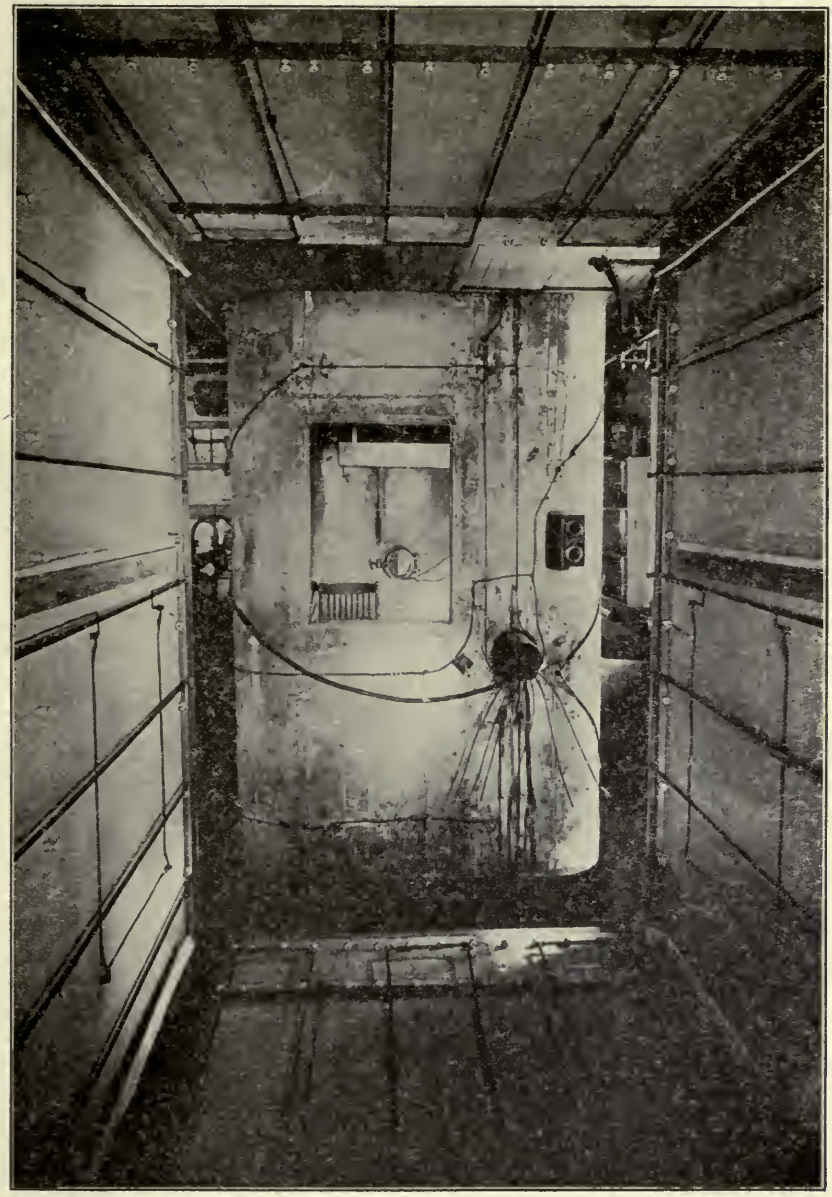

FIG. 30.—Front View of the Metal Chamber removed from the wooden casing. Through the window opening are seen a shield for the heat-absorber, the food aperture door, and the chair. The piping and wiring on the inner wooden panels as well as the movable partitions subdividing the inner air-space are also shown.

are very small, and by constantly heating or cooling the air-space next the zinc, as indicated by the positive and negative deflections on the galvanometer, the temperature of the zinc itself is increased or diminished, as the case may be, so that the temperature of the two metal walls shall always be very nearly alike.

The arrangements for heating and cooling the air-space next the zinc wall are next to be considered.

HEATING AND COOLING THE AIR-SPACE.

The air-space surrounding the zinc wall and between this and the inner wooden casing has been described (p. 111), and it has been shown that this space is divided by narrow strips into four sections, corresponding with the top and bottom of the chamber and the upper and lower halves of the walls. (See fig. 23.) Comparing this with the explanation in the paragraphs just above, it will be seen that these divisions of the air-spaces correspond with the areas covered by the different groups of elements into which the whole system of thermo-electric elements is subdivided. The devices here described for heating and cooling the air-spaces are arranged so that the different sections of the space may be heated or cooled independently. In other words, provision is made for determining temperature differences in different sections of the surface area of the calorimeter, and also for heating or cooling the corresponding areas in the zinc wall as may be indicated. Thus, it is possible to heat one space and cool the adjoining space at the same time.

Heating circuits.—For heating the air-spaces a current of electricity is passed through a circuit of German-silver wire, each separate space having its individual heating circuit. The wire is threaded through porcelain rings at the ends of each wooden panel and wound once around porcelain knobs at three different points in the length of the panel. By this arrangement the wire is firmly held in place, and even during the slight sagging due to expansion when heated, is prevented from coming in contact with the metal wall of the chamber. The white porcelain knobs or insulators on which the heating wires are strung are readily seen in figures 25, 29, 30, and especially in figure 31.

The wire itself is so fine that it is hardly discernible in some of the figures, being quite plainly seen, however, in figure 30. In the upper and lower side spaces the current flows around all four sides at the same time. The wires are attached to the wooden walls, however, in such manner that they may be disconnected at the corners when the panels are to be removed. The heating circuits for the top and bottom sections are attached in one unbroken wire stretched continuously back and forth across each of the respective panels.

Each heating circuit is connected with a variable resistance and a rheostat on the observer's table. It is possible to cut out any or all of the resistance and cause varying amounts of electricity to pass through the circuit of wire in the air-space, thus controlling its heating effect. The electrical method of heating a large air-space is ideal, inasmuch as the heat is evenly distributed all through the air-space and liberated simultaneously at all points. Furthermore, the amount of heat which can thus be liberated is instantly controlled with the greatest accuracy by varying the external resistances.

The variable resistance here used consists of a series of seven coils of German-silver wire wound on a corrugated sheet-iron pipe (galvanized conductor pipe) which has been covered with asbestos paper. There are in all nine heating circuits used for temperature control about the calorimeter, four for the inner air-space, four for the outer air-space, and one to heat the ventilating current of air as it enters the chamber, each of which is connected with the rheostat and has its variable resistance. The nine variable resistances are laid side by side under the calorimeter in the space between the laboratory floor and the outer bottom panel. As the floor of the laboratory is always cold, the extra heat developed in these resistance coils in a measure counteracts the cold floor and aids in warming the outer bottom dead-air space.

Cooling circuits.—Means for cooling the air-spaces are as essential as those for heating them. Unfortunately, there is no such ideal method for cooling as for heating an air-space. The best method available is that depending upon the passage of cold water through a small pipe which is suspended in the air-space parallel to the wires of the electrical heating circuit. (See figs. 25, 30, and 31.) Water from the city main, which has a temperature varying from 6° in winter to 16° or 17° in summer, is caused to flow through small pipes (one-eighth inch) in the air-space. The cold water absorbs the heat and thus cools the air rapidly, and as a result the zinc wall is cooled.

Heretofore iron pipe has been used for the cooling circuits, but as it rusts easily and so is liable to clog, brass pipe is being substituted.

The cooling system in the top space and that in the bottom space are individual units, in which the water enters at one end, circulates around the numerous bends in the pipe, and goes out at a point close to where it enters. With the cooling circuits for the upper and lower zones, on the other hand, it is necessary to make arrangements for disconnecting the piping when the calorimeter is to be withdrawn. The position of the pipes across the rear end of the calorimeter is shown in figure 25. These pipes are attached to elbows connecting with the pipes on the side panels by means of a brass union at each end. By dis-

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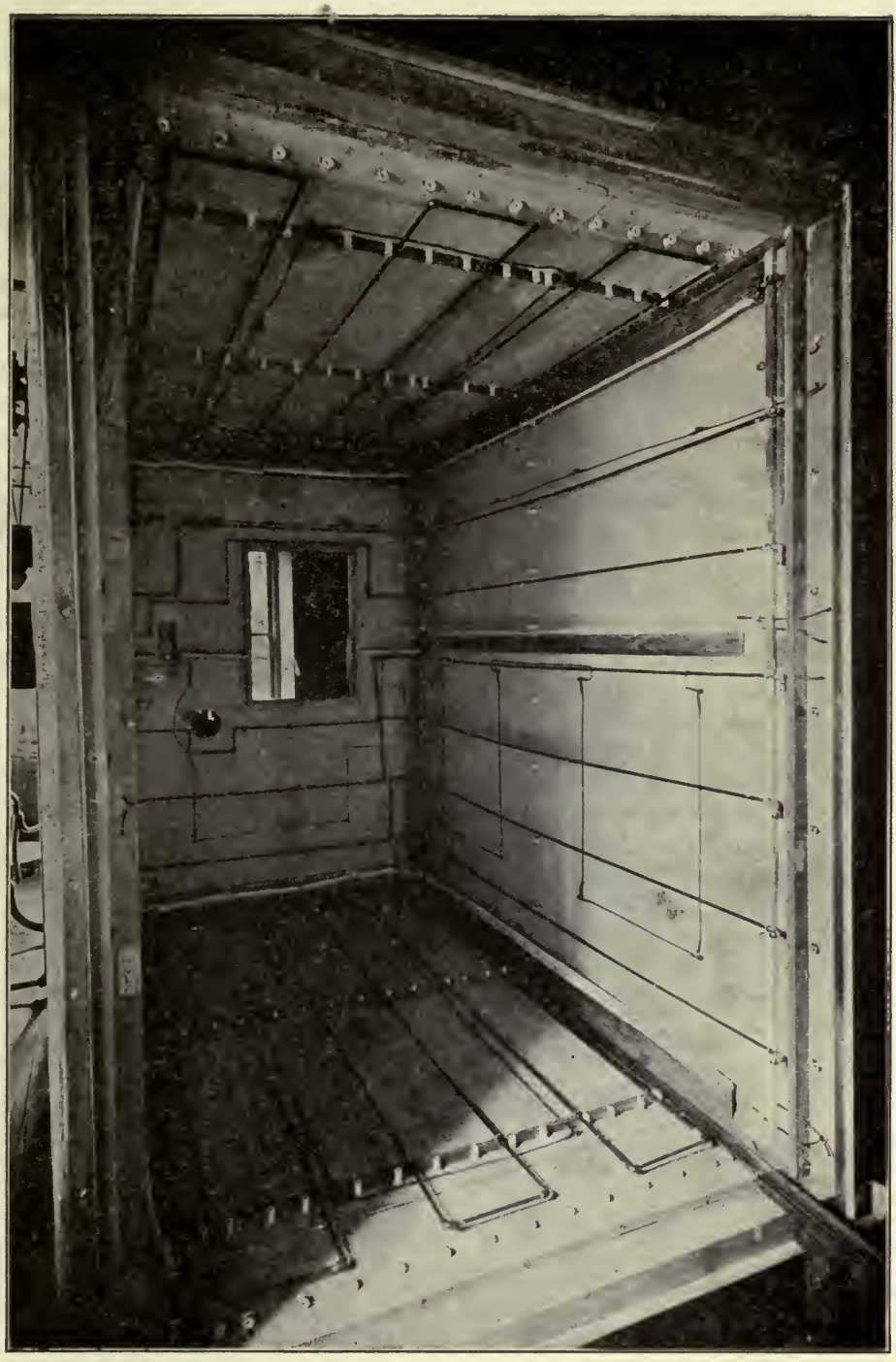

FIG. 31.—Details of Interior of Wooden Casing, showing cooling pipes, electrical heating wires, partitions for subdividing inner air-space and openings in the case to correspond to the windows, air-pipes, and water-pipes. The tracks on which the metal chamber stands are seen on the floor.

connecting the unions, each pipe can be sprung a little and thus readily removed.

The heat-absorbing capacity of the mass of water in the pipe is very great, much more so than that of the metal of the pipe itself, since the specific heat of water is about ten times that of the pipe. Consequently, in order to secure a quick and easily controlled heat absorption, it is necessary to provide for the rapid draining out of the water in the cooling system. As the water leaves the valve connected with the water main it traverses the section of the pipe with which the valve is connected. When the valve is shut off a check-valve attached to an upright section of pipe (see fig. 37) opens, allowing air to enter. As each section is purposely piped in such a manner as to allow a free outflow of the water, the water in the pipes quickly drains out, and thus the cooling effect is much more rapidly arrested.

TEMPERATURE REGULATIONS IN THE OUTER AIR-SPACE.

The temperature regulation of the air-space next the zinc wall is affected by the fluctuations in temperature inside the metal chamber, and also, in spite of the insulating of the wooden walls papered with asbestos, by the temperature of the calorimeter laboratory. The outer air-space, *i. e.*, that between the inner and outer wooden casings, dampens the effect of sudden changes in temperature of the calorimeter laboratory, but to aid in regulation provision is made to heat and cool the outer air-spaces at will. The heating and cooling circuits in these spaces are of exactly the same nature as those described above for the inner spaces, except that, since the delicate control of the temperature in the outer air-space is much less important, no provision is made for draining the water out of the water-pipes installed in this air-space.

The necessity for heating or cooling the outer spaces is likewise determined by deflections on a galvanometer connected with a series of thermo-electric elements. These are inserted in the inner wooden walls, one end of the junctions being in the inner and the other end in the outer space. There are fifty-four such elements (containing each four pairs of thermal junctions) distributed throughout the six inner panels at equal distances from each other, so as to assume more nearly the average temperature of the air-space. The black irregular line (not to be confused with the series of parallel black iron pipes) on the right-hand inner wall in figure 31 shows the method of connecting these elements. Along the upper portion of the panel, running parallel to the iron pipes, is one straight row of four elements. A somewhat different view is given in figure 30, and the distribution on the inner rear panel may be seen in figure 25, in which the panel is removed and standing at the right.

As with those on the metal chamber itself, the thermo-electric elements in this system are also subdivided into four sections—the top, upper zone, lower zone, and bottom.

On the chamber itself the different members of each group of elements are permanently connected in series, but with the system here considered it is necessary to break connections in the upper and lower zones when removing the end panels and withdrawing the chamber. The connections between the elements in the top panel and in the bottom panel are in no wise disturbed by withdrawing the metal chamber; only the wires joining the elements of the upper and lower zones on the side panels with the elements of the upper and lower zones on the end panel must be disconnected. These connections are made by nuts or binding posts.

Gain or Loss of Heat through Openings in the Chamber.

The various openings through the metal walls of the chamber have been described in detail (p. 13). The nature of some of these, or at least of the objects for which they are provided, precludes the passage of any appreciable quantity of heat in either direction. In the case of two of them, however, namely, the window in the front and the food aperture in the rear, there is a possibility of gain or loss of heat, depending upon differences between the temperature of the air within the chamber and that of the calorimeter laboratory. In fact, that there may be under certain circumstances appreciable interchange of heat through these two openings has been proved by a number of experiments in which the temperature of the calorimeter laboratory was markedly different from that of the chamber. To prevent such interchange of heat it has been found necessary, therefore, to keep the temperature of the laboratory as nearly as possible the same as that within the chamber.

To this end a mercury thermometer is hung inside the calorimeter chamber with its bulb opposite the center of the window, and a similar thermometer, with exactly the same corrections, is hung outside the window with its bulb at the same level as that of the thermometer inside. It has been found by experiment that when the thermometer on the outside registers exactly the temperature of that on the inside the interchange of heat through the glass is negligible.

One of the duties of the observer at the table is to record the temperature of these thermometers frequently and make such alteration in the heating or cooling of the laboratory as to control the temperature within the necessary limits. Unfortunately the arrangement of the heating system in the building in which the calorimeter is located is such

as to necessitate the placing of the steam-pipes near the ceiling of the calorimeter laboratory, and consequently the upper layer of air is very much warmer than that near the bottom. In fact, a temperature difference of from 6° to 10° is not at all uncommon. By means of two rotating ceiling fans, however, it is possible to distribute the warm air and thus equalize the temperature in the laboratory to a considerable degree, the blades of the fan being so adjusted as to force the warm air downward. Cooling the air is effected by opening windows at different parts of the laboratory. By these means it has been found possible to regulate the temperature opposite the window of the calorimeter with considerable accuracy.

Another mercury thermometer is hung on the outside of the rear of the calorimeter, near the food aperture. This likewise serves as a guide whereby the temperature of the air in which it is hung may be kept not far from 20°, *i. e.*, that of the calorimeter chamber. Any great interchange of heat through the food aperture is thus prevented. Furthermore, the tube of the food aperture is surrounded for part of its length by the air in the inner air-space and through another part of its length by the air in the outer air-space, and the temperature of these portions of the tube is of course that of the air in the spaces, which is controlled, as explained above, in accordance with that of the chamber. Interchange of heat between the metal of the tube and the orifice in the metal walls through which it passes is prevented by the rubber tube filled with compressed air (D, in fig. 8) by which they are separated.

The window opening in front of the calorimeter, and through it the food aperture in the rear end, may be plainly seen in figure 30. Adjacent to the window in the front end are three other openings, at the places where the dark objects are seen projecting from the metal wall. These are shown in detail in the perspective view in figure 33.

The smallest of these openings, near the lower corner of the window, is for the passage of an iron rod, which is the axis of the device for raising and lowering the shields to the heat-absorbers, described beyond. The rod is fitted very closely into a sleeve in the copper wall through which it passes. The metal of the rod is of course a good conductor of heat, but, as it passes through the two outer air-spaces, its temperature is controlled by that of the air surrounding it, and thus little opportunity is afforded for the passage of heat through it.

The larger circular opening to the right of the rod (fig. 32) is very tightly closed by a wooden plug through which pass the two pipes for conducting the water used to bring away heat from the interior of the chamber, as explained later. The wood itself is a very poor heat-conductor, and furthermore it is surrounded by the two air-spaces in which

the temperature is controlled; hence heat is not conducted from the chamber by the plug. To prevent the conduction of heat through the metal pipes, each pipe is broken about half way through the plug and the ends are connected by rubber tubing (N, fig. 32).

The other opening, which is rectangular in shape, is very tightly filled by a wooden box packed with plaster of Paris, through which pass the pipes for the ingoing and the outcoming air. Gain or loss of heat through the box is prevented by the poor conductivity of the box and packing and by the regulation of the temperature of the air surrounding the box. To prevent loss by conduction through the metal pipes, each pipe is broken within the box and the ends connected with rubber tubing. (See H, fig. 32.)

The nature of the opening in the side for the electric cable tube and that in the top for the weighing apparatus is such that no opportunity for loss of heat is afforded.

Gain or Loss of Heat Through the Air Current.

As explained elsewhere, part of the heat generated within the chamber is carried out as latent heat of water vapor in the outgoing air. So far as the air itself is concerned, however, gain or loss of heat to the chamber due to cooling or heating of the air is prevented by regulating the temperature of the air entering the chamber so that it is exactly the same as that leaving it.

The difference between the temperature of the incoming and that of the outgoing air is detected by means of iron and German-silver thermal junctions, of much simpler construction than those described above. These are made of double cotton-covered insulated wire, and are bound tightly together in the center like a sheaf of wheat, the bared ends of the junctions being spread out and separated, thus relying on air insulation. These junctions are installed in such a manner that one end is in the incoming and the other in the outgoing air. The apparatus in which they are inserted, designated the vestibule, is shown at T_j in figure 33. It consists of a 7.5 cm. copper pipe, with a copper partition. The ends of the thermal junctions are on opposite sides of this partition. The air entering the chamber passes along the under side, and that leaving is in contact with the upper side of the partition. The ends of the junctions are connected with a galvanometer, the deflections of which indicate differences in temperature of the air on either side of the partition.

The incoming air is heated or cooled as necessary, in order that the deflection may be zero. The arrangements for heating or cooling the air are shown in figure 32.

The ingoing air is caused to pass over a 32-candlepower 220-volt lamp, which is placed in an enlargement of the air-pipe made of a galvanized-iron T and a short section of pipe, with a cap. The position of the lamp is shown in figure 32. The connections between this lamp and the electrical circuits are shown in figure 37, in which it is seen that the lamp-cord is connected with two binding posts on the wall of the calorimeter. These binding posts are connected in turn by two wires leading to the rheostat on the observer's table. As with the heating circuits for the air-spaces about the calorimeter, here also the amount of heat developed in the electric lamp, and consequently the degree of warming the air current, can be regulated with great exactness by means of the variable resistance (see p. 118) connected with the rheostat.

When, as is occasionally the case, the temperature of the air in the calorimeter laboratory is greater than that of the interior of the chamber, it is necessary to cool the air current. This is accomplished by causing a current of cold water to flow through a lead pipe which is closely coiled about the ingoing air-pipe. The lead pipe is connected at one end with the water supply and at the other end with the drain. By opening a small wheel valve at the extreme left of the lower row of valves at the observer's table (see fig. 37) water can be caused to pass through this pipe and effect the cooling of the air. To prevent sudden changes caused by variations in the room temperature, the lead pipe is covered with cotton felt and canvas, as is seen in figures 3 and 37.

MEASUREMENT OF HEAT.

It has been stated that most of the heat generated within the chamber is carried away by a current of cold water. The quantity thus brought out is determined from the amount of water, its rise in temperature, and the specific heat of water at different temperatures. The devices for absorbing the heat and the method of determining the quantity generated are here described. For illustration of this description reference is continually made to the view of the interior of the chamber shown in figure 33.

The Heat-absorbing System.

The device for absorbing heat is shown at H, H, H, in figure 33. Copper pipe, of about 10 mm. outside diameter, bent to conform to the shape of the chamber, is suspended from the ceiling at about 13 cm. from each wall. A large number of sheet copper disks, about 5 cm. in diameter, are soldered along the pipe at intervals of about 1 cm., their purpose being to increase the area of surface exposed to

the heat. Two coils of such pipe, one above the other, comprise the heat-absorber. The water for taking away the heat enters the calorimeter chamber through a brass tube in the wooden plug in the front end of the chamber, flows through the rubber tube W_1 into the lower

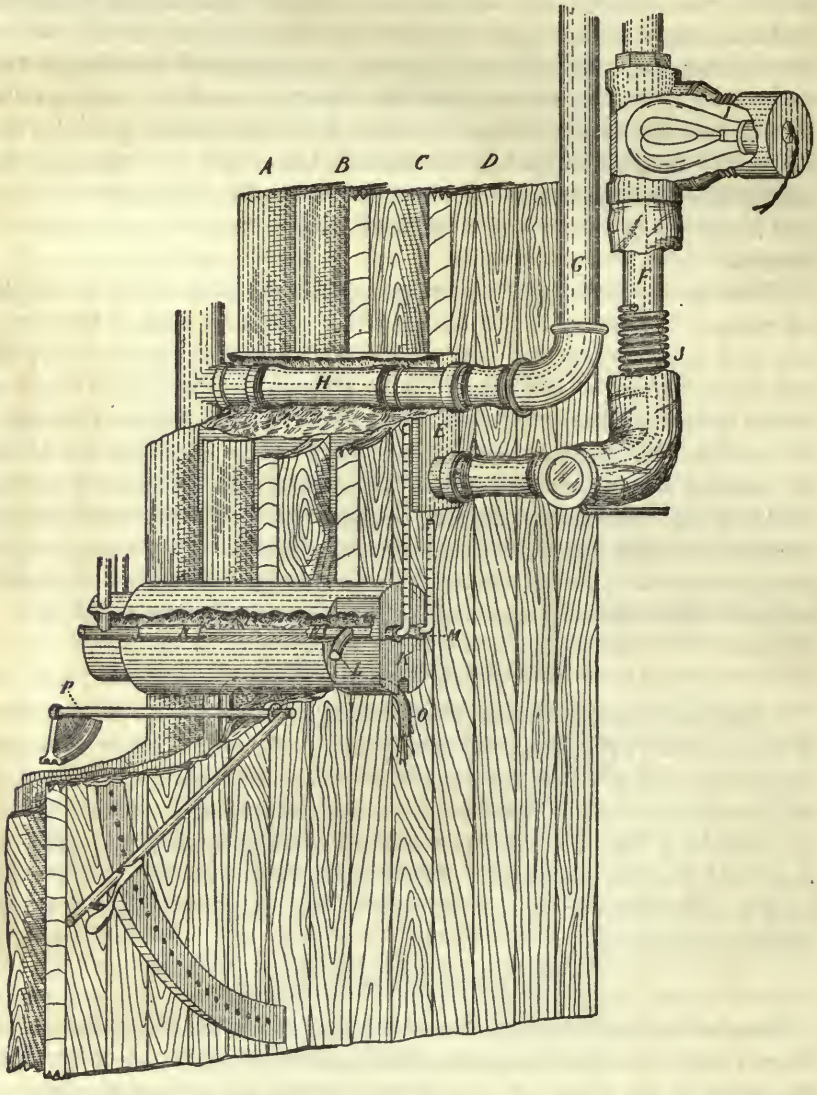

FIG. 32.—Sectional View of Walls of the Chamber, showing method of installing air-pipes, water-pipes, and rod for raising and lowering shields. The copper wall A, zinc wall B, and two wooden walls C and D are penetrated by the box E for the air-pipes F and G and by the wooden plug K. The electrical lamp I shows method of heating, and the water coil J that of cooling, the ingoing air.

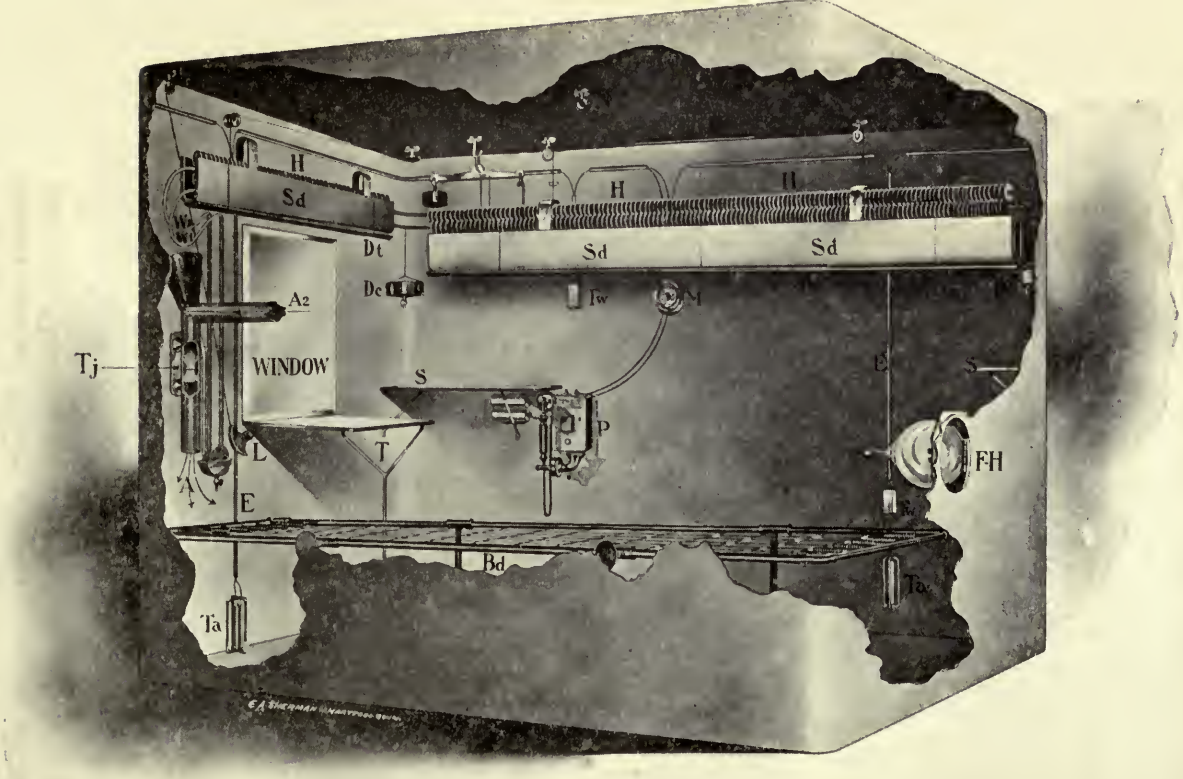

FIG. 33.—Interior of Respiration Calorimeter Chamber, showing arrangement of heat-absorbing system (*H*, *H*, *H*), the shields (*Sd*, *Sd*, *Sd*), the ventilating air-pipes (*A*, A_2), and the furniture—the bed (*Bd*), table (*T*) and telephone (*P*).

To face page 124.

A — Ingoing air current.
A_2 — Outcoming air current.
Tj — Thermal junction connecting with ingoing and outcoming air currents.
W_1 — Pipe carrying cold water into heat-absorbing system.
W_2 — Pipe bringing water out of heat-absorbing system.
H, *H*, *H* — Heat absorbers (water-pipes with disks).
Sd, *Sd*, *Sd* — Shields of aluminum for covering heat-absorbers.
Dt, *Dt* — Troughs for collecting "drip" water.
Dc, *Dc* — Cups for holding "drip" water.
L — Lever for raising and lowering shields and troughs.
I, *I* — Wires connecting lever with shields.
Tw, *Tw* — Electrical thermometers for wall temperature.
Ta, *Ta* — Electrical thermometers for air temperatures.
E, *E* — Wire connections for electrical thermometer circuits.
N — Holder for weighing systems.
M — Plug switch for electrical connections.
P — Telephone.
FH — Food aperture.
SS — Shelves.

pipe of the heat-absorber, passes once around the chamber, then enters the upper pipe and makes another circuit of the chamber, and finally passes out of the chamber by way of the wooden plug through another brass pipe connected by the rubber tube W_2. With this arrangement the water absorbs heat very rapidly, although the actual mass of water inside the calorimeter at any one time is kept at a minimum, *i. e.*, the contents of the pipe of the absorber, about 400 grams.

REGULATION OF RATE OF ABSORPTION OF HEAT.

In order that the temperature of the chamber may be kept constant, it is necessary to provide that the rate at which heat is absorbed may be varied in accordance with that at which it is produced. This is accomplished in different ways. The coarser regulations are easily made either by increasing the flow of water through the system or by lowering the temperature of the ingoing water. The finer regulations that are essential for maintaining a constant balance between heat production and heat absorption are made by increasing or diminishing the amount of heat-absorbing surface exposed, by lowering or raising shields (*Sd*, in fig. 33) provided for the purpose. When the shields are raised the air in them is cooled, and, serving as heat insulation, retards the absorption. When the shields are lowered the absorbing surface is exposed directly to the heat.

The shields are constructed of sheet aluminum. The shorter ones, which protect the absorbers on the ends of the chamber, are raised or lowered when necessary by the subject inside the chamber. Those on the sides are operated by the observer outside. A flexible cord attached to each of these side shields travels over pulleys and connects with an iron quadrant on the rod which extends through the wall of the apparatus and transmits the motion of the hand lever, shown in figure 32. It is thus possible, by raising or lowering this lever, to raise or lower the long shields inside the chamber, and the distance through which these shields are raised or lowered determines the area of the absorbing system, either exposed or covered up. A graduated arc over which the hand lever travels permits of very slight motions in the movement of the lever, and consequently of the most delicate adjustment of the position of the shields.

In ordinary experiments the two end shields are always up, and all the finer regulation is done by means of the two long shields. During the night, and when the subject is sound asleep, it is necessary to raise these shields to the highest point, cut down the rate of flow of water to a minimum, and raise the temperature of the incoming water until it is nearly at the top of the scale on the incoming water thermometer. During work experiments all the shields are lowered as far as they

will go, the incoming water is cooled to as near zero as possible, and the rate of flow through the absorbing system is at the maximum. Indeed, in one series of experiments with a professional athlete a third pipe with disks was suspended above the absorber system, thus increasing the heat-absorbing area by 50 per cent.

It is thus seen that the heat-absorbing capacity of this form of absorber can be varied within very wide limits. It is possible to vary the rate of heat absorption with this apparatus so as to bring away as low as 40 calories per hour and as high as 600 calories per hour. Both of these measurements being irrespective of the amount of heat required to vaporize the water vapor issuing in the air current, they indicate the *heat-absorbing* capacity of this form of absorber rather than the *heat-measuring* capacity of the calorimeter.

Besides serving to increase and diminish the effective surface of the absorbing system, these troughs and the gutters attached to them serve also the important purpose of collecting the large quantity of water which condenses on the surface of the absorbers and the shields, as explained on page 23.

SUPPLY OF WATER FOR MEASURING HEAT.

A regular pressure of water in the absorber pipe is quite essential. Owing to the marked fluctuations in the city water pressure, the water flowing through the heat-absorber system is taken from a tank in the second story of the building 10 meters above the point at which it enters the calorimeter. A constant-level attachment on the tank gives a steady pressure and flow of water.

WATER COOLERS.

The temperature of the water entering the calorimeter is regulated according to the amount of heat to be brought away, and may vary from 1° to 12°. In order to secure such variation, provision is made for directing a portion of the water through two coils of iron pipe in tanks that can be filled with crushed ice. These tanks are placed in a small unheated room adjoining the calorimeter laboratory. Two valves near the calorimeter provide a means for mixing the cooled water and the water direct from the supply tank in whatever proportions are desired. A system of pipes and valves makes it possible to use either one or both cooling tanks at will.

WATER METER.

To determine the quantity of heat brought out of the chamber it is necessary to measure accurately the quantity of water that flows through the absorber. Formerly the measurement of water was made

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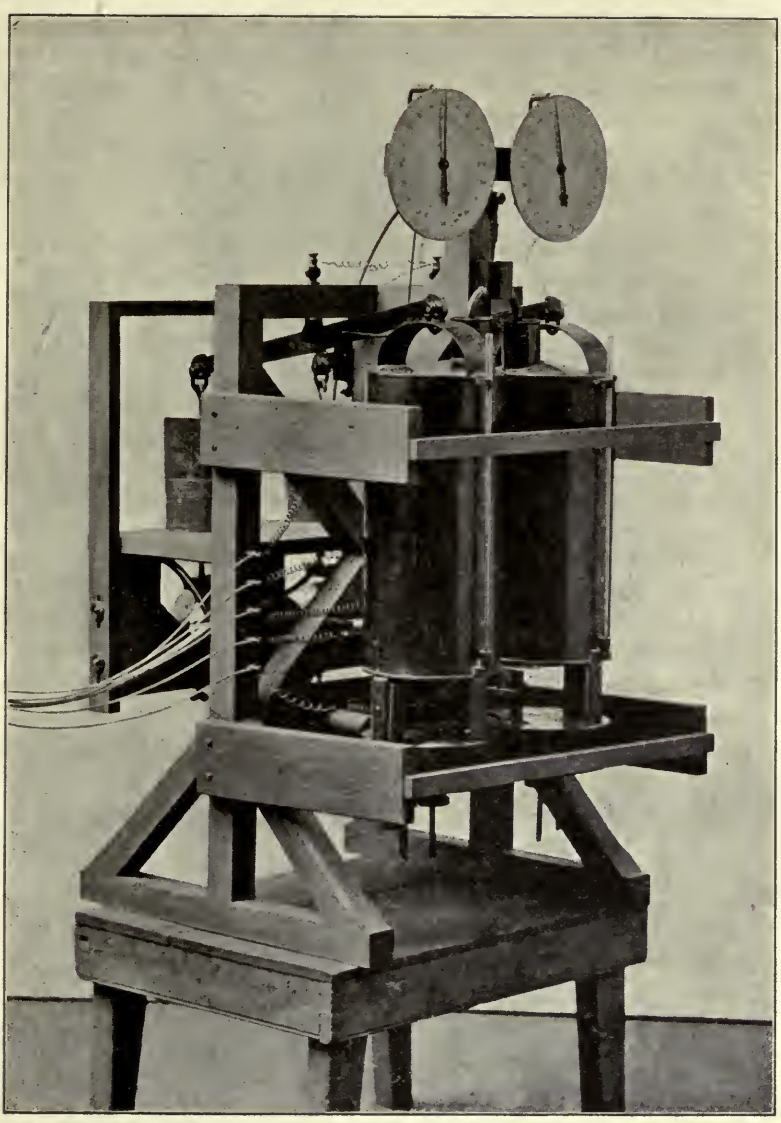

FIG. 34.—The Water Meter. The large cans in which the water collects are here shown, together with method of attachment to balance-arm and lead counterpoises just behind them. Above the cans may be seen the dials on which the weight is indicated, and below them the device for shifting from one can to the other. The various electrical connections are also shown.

by volume, by alternately filling and emptying two copper cans graduated in liters. This method involved a not inconsiderable error, *i. e.*, neglect of the variation in density of water at different temperatures. For a more accurate determination of the quantity of heat, therefore, it is essential to measure the quantity of water by weight. For this purpose the water-meter or balance shown in figure 34 was devised.

A copper can holding about 10,000 grams of water is suspended on one arm of an equal beam, and a lead counterpoise, equal in weight to the weight of the can and about 9,800 grams of water, is suspended from the other end. In addition, the remaining weight of water is taken by a spring balance, which indicates about 400 grams for a complete revolution of the pointer. When the can is nearly filled with water and the weight of the counterpoise has been overcome, the beam begins to settle. As it settles, a flexible cord attached to one arm of the beam throws the weight upon the spring balance, and the pointer on the dial indicates the exact amount of weight taken care of by the spring. The dial is graduated into 100 divisions, and the differences between divisions can be read easily by halves.

To make the meter as nearly automatic as possible and not to interrupt the flow of water through the calorimeter, two cans are provided, as is shown in figures 34 and 35.

The cans and balances are mounted side by side on a stout wooden frame. In the front view, figure 35, the two cans with their respective balances are shown. In the side view one can, the equal beam, and the lead counterpoise are shown. The equal beams were specially made by the E. & T. Fairbanks Company, of Saint Johnsbury, Vermont. It was found by preliminary tests that with a load of nearly 20 kg. on each arm, differences of one gram could be detected. The spring balances were made by the John Chatillon Company, of New York. These are also quite sensitive.

In experiments with man the amount of water passing through the heat-absorber varies greatly at different times in the same experiment, and especially with experiments of different nature. When the subject is asleep in the middle of the night, 10 kg. of water passing through the absorber system above described will suffice to bring away the heat as fast as it is generated for over an hour, and at times the rate of flow may even be cut down to 10 kg. in 2 or 2½ hours. This is the slowest rate. During periods when the subject is hard at work, on the other hand, the rate is much faster, a flow of 10 kg. in 7 minutes being sometimes necessary. In devising the water-meter, therefore, the problem was to provide for the accurate weighing of as much as 80 kg. of water in an hour. Furthermore, in order that the observer may be relieved

as much as possible from the necessity of manipulating and readjusting the apparatus every few minutes, it should be as nearly automatic as practicable. The means of providing for alternate filling and emptying of the cans automatically is illustrated in figure 35.

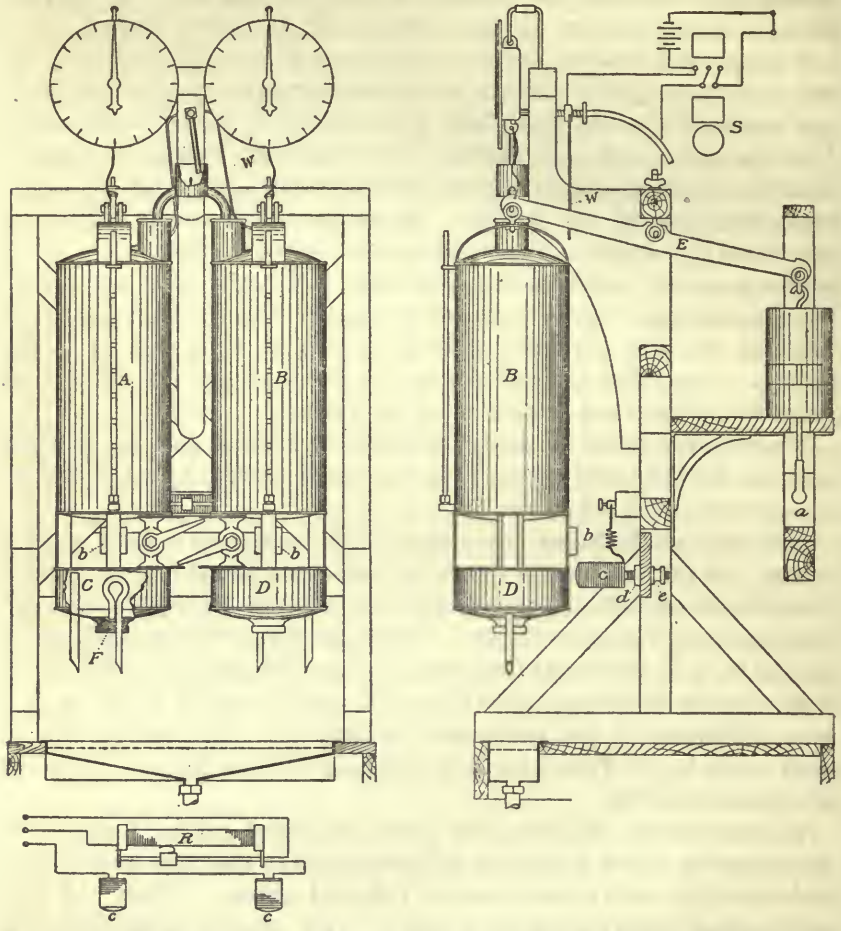

FIG. 35.—The Water-Meter. Diagrammatic sections showing front and side views. The two upper cans A and B deliver the water into the lower cans C and D by the movement of valves between these two cans. The bulk of the weight is taken up by the lead counterpoise at right of beam E.

Just below the spring dials a small cup-shaped attachment (water-receiving chamber), with curved tubes from the bottom on each side and a partition in the middle, is attached to the framework. The current of water to be measured enters through a piece of brass pipe,

the lower end of which is in this cup-shaped vessel. By swinging this pipe through a small arc the current of water is deflected to either side of the partition in the receiving cup and directed through the bent tubes into either can. This pipe is moved to one side or the other by means of wire projections, W, extending below the arms of the balance-beams. When one can is full of water and sinks, the falling end of the beam pushes against the wire and moves the outlet pipe so that the water current is deflected to the opposite side of the receiving cup, from which it flows into the empty can.

As the full can sinks, a valve in the outlet pipe is opened and the water drains into a smaller can, D, below. While this is filling there is no loss in weight, but as soon as it is full the water begins to flow away through a siphon, and also through an overflow pipe. As is seen from the construction in the drawing, the small can is provided with two openings, one of which, the overflow C, is made by soldering a piece of pipe into the bottom of the small can in such a manner that the upper end of the pipe nearly touches the top of the can. A small siphon attached to a nut, F, screwed into the bottom of the can is the second opening. As soon as the small can is filled the siphon is started. As the diameter of the siphon tube is very much less than that of the opening through the valve, the lower chamber fills up to the level of the overflow C, and water soon begins to flow out of this opening. As soon as all the water has passed out of the upper can, the overflow through the large tube ceases and the lower can is completely emptied by means of the siphon. The end of the short arm of the siphon nearly touches the bottom of the small depression in the cap F, into which all the water from the can drains. It is thus seen that the lower chamber is constructed on the principle of the Tantalus cup. It has been found by repeated experiment that the quantity of water adhering to the walls of both the upper and the lower cans is remarkably constant.

The valves in the outlets to the large cans are opened or closed automatically, as the balance-arm assumes a level position. The valve on each can has a long lever, the end of which is between the upper and lower compartments of the other can, and is moved upward or downward with the motion of the can. This construction is seen in figure 35. Thus, as one of the cans sinks, the effect is to open the valve at the bottom of the moving can and to close the valve at the bottom of the stationary can.

In figure 35 the water is shown as entering the right-hand can. The valve between the upper and lower can is represented as being closed. If, now, this can settles, the water will be deflected to the other side of the receiving chamber, the handle of the valve, which

almost touches the projection on the upper side of the lower compartment on the other can, will be moved upward, and at the same time a projection attached to the bottom of the can will accomplish the closing of the valve on the other can.

In order that the force required to open and close the valves may not interrupt the descent of the can and interfere with the proper weighing of the water, an arrangement for increasing the momentum of the full can is provided. This device is illustrated in figure 36.

The rod on which the counterpoise is suspended from the beam is tipped on the lower end with a small bulb which opens the jaws of a spring clutch, *a*. By means of a small nut with a right and left hand thread the tension of the spring may be varied at will, and is so adjusted that a pull of about 200 grams is necessary to release the bulb.

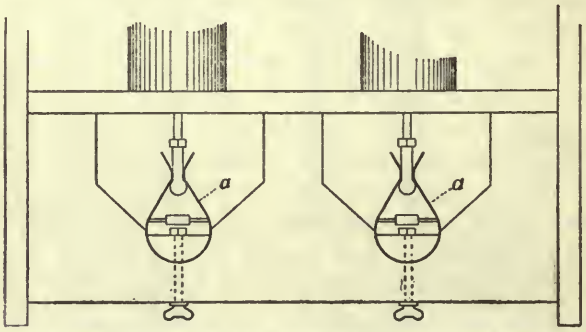

FIG. 36.—Clutch to regulate tension on Water-Meter. Two curved steel springs hold a bulb on the end of a steel rod at bottom of lead counterpoise of the water-meter.

When the tension of the clutch has been overcome the bulb is released rather suddenly, and as it passes through the jaws of the clutch, these snap together, and their converging ends, rubbing on the bulb, give a distinct impetus to the upward movement of the counterpoise, thereby imparting momentum to the whole system. By this means sufficient force is obtained to operate the valves; indeed, the end of the beam that bears the cans is invariably forced to a position below the level, and the pointer on the spring balance travels much farther than the true weight would warrant. The spring in the balance, however, soon imparts a movement in the opposite direction. This reverse movement of the spring aids materially in the use of the balance, for by its means the balance-beam is drawn a little distance away from the wire projection used to deflect the water current, and the ends of the levers on the valves are slightly removed from the projections on the cans, and thus the whole system is freely suspended. Inasmuch as about 20 seconds elapse in the passage of the water from the upper chamber to the lower

chamber before the water actually runs out of the system, ample time is given to record the exact position of the pointer on the dial. After this position is recorded, the apparatus requires no more attention until the next can is filled. As soon as about 400 grams of water have run out of the system, the equipoise settles back to the position shown in the diagram, the bulb projection on the bottom of the counterpoise resuming its position between the jaws of the spring.

As a result of the impetus given the system by the spring clutch, and that in the opposite direction by the balance-spring, the momentum of the large mass of metal and water has a tendency to cause the system to oscillate for several seconds before finally assuming a position of equilibrium. Preliminary experiments showed that this motion persisted a considerable time—longer, indeed, than the 20 seconds required for the water to flow into the lower can and begin to run out of the system. Consequently some method was necessary to check this oscillation and have the system attain equilibrium as rapidly as possible. To accomplish this end, an iron armature (*b* in fig. 35) was fastened to one of the connections between the upper and lower cans. An electro-magnet was fastened to the upright wooden frame supporting the whole system in such a position that when the can was released and was vibrating back and forth the iron armature would rub over the end of the electro-magnet. By having a feeble current passing around the magnet, the movement of the can could be very readily checked.

It was found, however, practically impossible to regulate the strength of the current so as to retard the vibration and yet not hold the armature against the end of the magnet, and thereby prevent the system from swinging freely and being weighed accurately. A circuit-breaker was devised and attached to the shaft supplying power to the calorimeter room. (See fig. 1.) By this simple device the current is made and broken every few seconds—indeed, at approximately such times as would represent the end of the vibration. The effect, therefore, is to have the armature attracted by the magnet and held firmly for an instant; the current is then broken and the system begins another oscillation, at the end of which the current again holds the system for an instant, the effect being to diminish the momentum each time the armature is in contact with the magnet. Finally, by the observer's raising a switch and thus completely breaking the current around the magnet, the can swings freely and may be weighed accurately. By means of the two nuts on the central rod of the magnet the distance of the ends of the magnet from the armature when the system is in equilibrium can be altered at will.

The end of the soft iron core of the magnet is surrounded by a brass cap, which gives a rounded surface at the end of the coil, so that when the armature settles into position it will easily slide along the end of the magnet and not catch at any point. The current used to magnetize these fields is taken from the observer's table (see p. 136), and has in series with it two 16-candlepower 110-volt lamps, one of them being the galvanometer lamp. The strength of current through the two magnets is varied by means of the resistance coil R shown in figure 35.

The equipoise beam in its descent touches the wire W, used to deflect the water current, thereby closing an electric circuit and causing an electric signal-bell to ring continuously until the operator lifts a switch on the observer's table. In operating the meter, then, the only care required on the part of the observer is to see that the readings of the pointer on the dial are accurately recorded each time the bell rings.

Calibration of the meter.—The meter was calibrated by weighing the total amount of water delivered from each can, noting carefully the position of the pointers. For this purpose a large enameled-ware pot with a hard-rubber cover was accurately weighed on the large balance (p. 56). A specially constructed funnel was placed under the overflow and siphon of one of the cans and the neck of the funnel inserted in a hole in the cover of the previously weighed pot. When the can was released the water was delivered into the weighed pot instead of into the drain. After all the water had drained out of the can and funnel, the pot, plus the water, was weighed. These weights were usually made to the tenth of a gram. A curve was plotted which showed the weights of water delivered by the meter with the pointer at different positions, and consequently it is now only necessary for the observer to record the position of the pointer.

Accuracy of the meter.—The extreme accuracy of this water-meter has been surprising, for while the amounts as indicated by the readings on the dial may be from 1 to 2 grams either side of the true amount delivered, these differences tend to counterbalance each other, and it is safe to state that in a series of observations 10 cans full, or 100 kg. of water, will be weighed to within a very few grams.

To facilitate in ascertaining the weights of water remaining in the can at the end of a short period in which less than 10 kg. of water were flowing, a water-gage graduated in liters is attached to the front of each can. It is thus possible for the observer at the end of a period to note the quantity of water in the can to within a tenth of a liter. A more exact estimate of this amount can be made by noting the time between the emptying of the last can and the end of the period.

Check measurements of the accuracy of the meter.—From time to time the accuracy of the meter is checked by direct weighing. By means of the pot and funnel mentioned above, this check is very readily and rapidly carried out. Usually, one weighing of the water delivered from each can is all that is required. With the weighing, the reading of the pointer is taken and the weight actually observed, then directly compared with the weight as indicated by the curve. The meter has been in use for two years and has given excellent satisfaction.

Thermometers for Measuring Temperature of Water.

The temperature of the water for absorbing heat is measured as it enters and as it leaves the chamber. The thermometers used for these measurements are seen in the small closet on the front wall of the calorimeter, at the left of the observer's table, in figure 37. The method of installing them in the water-pipes may be seen in figure 32.

These thermometers are of special form. They are L-shaped, with one arm 52 cm. long and the other 36 cm. long. The arm with the mercury bulb is inserted in the water-pipe, extending through the wooden plug (N, N, in fig. 32), the length of the arm being such that the bulb comes directly under the upright pipe that conducts the water to or from the heat-absorber. By this provision the temperature that affects the mercury in the bulb is that of the water just as it enters or just as it leaves the chamber.

The graduations on the other arm of the thermometer begin just above the bend and extend to near the end of the arm. The thermometer used to determine the temperature of the ingoing water is graduated from zero to 12° in fiftieths of a degree. The 12 degrees of the graduation cover a section of the stem 420 mm. long, thus allowing 0.70 mm. for each one-fiftieth degree, or 0.35 mm. for each one-hundredth degree. Readings can be taken accurately without the use of a lens to one-hundredth of a degree. The thermometer for the temperature of the outgoing water is graduated from 8° to 21°. As the temperature of the calorimeter chamber, especially in the summer time, frequently goes above 21°, an enlargement of the capillary is made at the top of the thermometer to permit of the expansion of the mercury without danger of breaking the instrument.

The thermometers have been very carefully calibrated twice each year, and although the zero points changed slightly at first, they have apparently now become fixed. The readings of the two thermometers were compared with those on a metastatic thermometer of the Beckmann type, manufactured by Fuess and calibrated by the Physikalisch-technische Reichsanstalt, of Charlottenburg, Germany.

It was found with both thermometers that the maximum corrections occurred near the beginning of the graduation, and that along toward the top of the scale the correction became smaller. This would be expected from the increase in length of the column of mercury pressing on the thermometer bulb. The thermometer readings are corrected accordingly, and only the corrected readings used in determining the differences in temperatures.

CORRECTION FOR PRESSURE OF WATER ON THE MERCURY BULB.

As pointed out by Armsby,[1] the pressure of the water current on the bulb of the thermometer may introduce an appreciable error in measurement. Since differences in temperature are what is desired, this error would of course be negligible were the pressure the same on both thermometers. This, however, is not the case. The pressure on the thermometer bulb in the water entering the chamber is greater than that on the bulb of the second thermometer, as the latter is much nearer the water exit. It was found by actual trial that when the water was passing through the system at the rate of 10 kg. in 7 minutes, which is the maximum rate in experiments, suddenly shutting off the current caused a fall of 0.07° in the column of mercury in the thermometer in the ingoing water, and of 0.015° in that of the thermometer in the outgoing water. For this rate of flow, therefore, the mercury in the ingoing water thermometer reads 0.07° too high, and that of the outgoing water thermometer 0.015° too high. Unless these corrections are applied, the difference in temperature is obviously 0.055° too low; consequently this amount is added to the difference as observed. The necessary corrections for all rates of flow occurring in actual experiments have been determined and are always applied to the readings, though in many of the experiments the rate of flow is so slow that the effect of pressure on the bulb is inappreciable.

MEASUREMENT OF TEMPERATURE OF THE CALORIMETER.

It has been stated that the rate at which heat is absorbed and carried out of the chamber is regulated in accordance with that at which it is generated within it, so that the temperature of the chamber may be kept constant. To this end it is necessary to be able to determine fluctuations in the temperature of the chamber.

While mercury thermometers have been used to indicate the temperature of the water current in the heat-absorbing system, their use in measuring the temperature of the air in the calorimeter, or of the metal walls of the chamber, has not been successful, and we rely on the measurement of changes in resistance of coils of pure copper wire which are distributed at several points on the walls of the chamber.

[1] U. S. Dept. of Agr., Bureau of Animal Industry Bull. 51, p. 34.

The resistance of pure copper wire to the passage of an electric current increases proportionally with the temperature. By means of a Wheatstone bridge and a delicate galvanometer it is possible to measure with great accuracy the changes in resistance of a coil due to temperature fluctuations. Where, as in this case, temperature differences rather than absolute temperatures are involved, the problem becomes a comparatively simple one.

Inasmuch as the average temperature of the whole mass of air inside the chamber is desired, it is necessary to distribute the coils in such manner that the variations in resistance will represent as closely as possible the actual temperature fluctuations of the air. For this purpose the amount of wire the resistance of which is to be measured is wound on five separate coils connected in series and suspended from hooks at different points on the walls of the chamber. Whatever local temperature fluctuations there may be in the different parts of the chamber, each coil will rapidly acquire the temperature of the air immediately surrounding it, and consequently the average variations of the five coils taken as a whole will closely approximate the average temperature fluctuations of the air inside the chamber.

The coils consist of No. 32 pure copper wire, double-silk covered. They are wound on wooden frames and are well protected by metal guards. The total resistance of the coils is not far from 20 ohms. Variations in resistance which indicate temperature changes of 0.01° are easily detected by the Wheatstone bridge and galvanometer used in connection with these coils.

These coils (T_a, fig. 33), suspended as they are about 2.5 cm. from the copper wall, acquire the temperature of the air rather than that of the copper wall itself. In determining accurately the temperature changes of the whole mass of material, it is frequently desirable to know the temperature changes, not only of the air, but of the copper wall. For this purpose four copper coils (T_w, fig. 33), having an aggregate resistance of about 20 ohms, are wound on wooden frames and slipped into copper pockets made by soldering a copper box to the copper wall. These coils, therefore, are likely to assume the temperature of the copper wall rather than that of the air. The temperature changes can be detected by means of the switch, galvanometer, and bridge as closely as suggested above for differences in temperature of the air.

Variations in resistance of the copper coils are detected by means of a Wheatstone bridge and a galvanometer. For many years we have used a D'Arsonval galvanometer constructed by O. S. Blakeslee in the mechanical laboratory of Wesleyan University. This instrument is very sensitive and dead beat, allowing 10 readings each minute. The

phosphor-bronze suspension wire of the instrument is still intact after eight years' use.

The galvanometer is placed in a black-cloth hood, shown in figure 37, and a straight filament, 16-candlepower lamp (a so-called bung-hole lamp) used as a source of illumination, the image of the filament being reflected on a millimeter scale immediately before the observer.

The variations in resistance of the copper coils can be measured in two distinct ways. In the one case it is possible to adjust a very delicate variable resistance so that by comparing the resistances of the copper coils with a Wheatstone bridge the slight variations in resistance due to temperature fluctuations can be expressed in fractions of an ohm. The second method depends upon the fact that the deflections on the galvanometer are very nearly proportional to the amount of current passing through it, and consequently slight variations in the current caused by slight alterations in resistance will produce corresponding alterations in the deflection of the galvanometer. The amount of current passing through the galvanometer is a function of two variables—electro motive force and resistance. If the electro-motive force is maintained constant, any alterations in resistance of the copper thermometer coils, through which the current must flow when passing through the galvanometer, will result in variations in the amplitude of the galvanometer deflection.

The first method of temperature measurements, *i. e.*, the use of the slide-wire Wheatstone bridge, was followed entirely in the earlier form of respiration calorimeter,[1] but the long-continued use of the slide-wire bridge is open to serious objections. Temperature measurements in experiments with the respiration calorimeter are made at intervals of not more than 4 minutes, and frequently the experiments continue from 10 to 13 days. The constant wear and tear of the sliding contact on a bridge of this type is a factor that must be taken into account in the most accurate work, and accordingly we have devised an apparatus for indicating temperature changes on the second of the two plans outlined above. This apparatus is described in detail on pages 139–150.

Observer's Table.

The various devices concerned in the regulation of the temperature of the calorimeter and the measurement of heat are controlled from the observer's table at the front of the apparatus. Figure 37 gives a general view of the table and the adjacent apparatus.

The wires from the systems of thermal junctions in the metal walls and the surrounding air-spaces, and those from the resistance thermometers

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, pp. 25–27.

To face page 136.

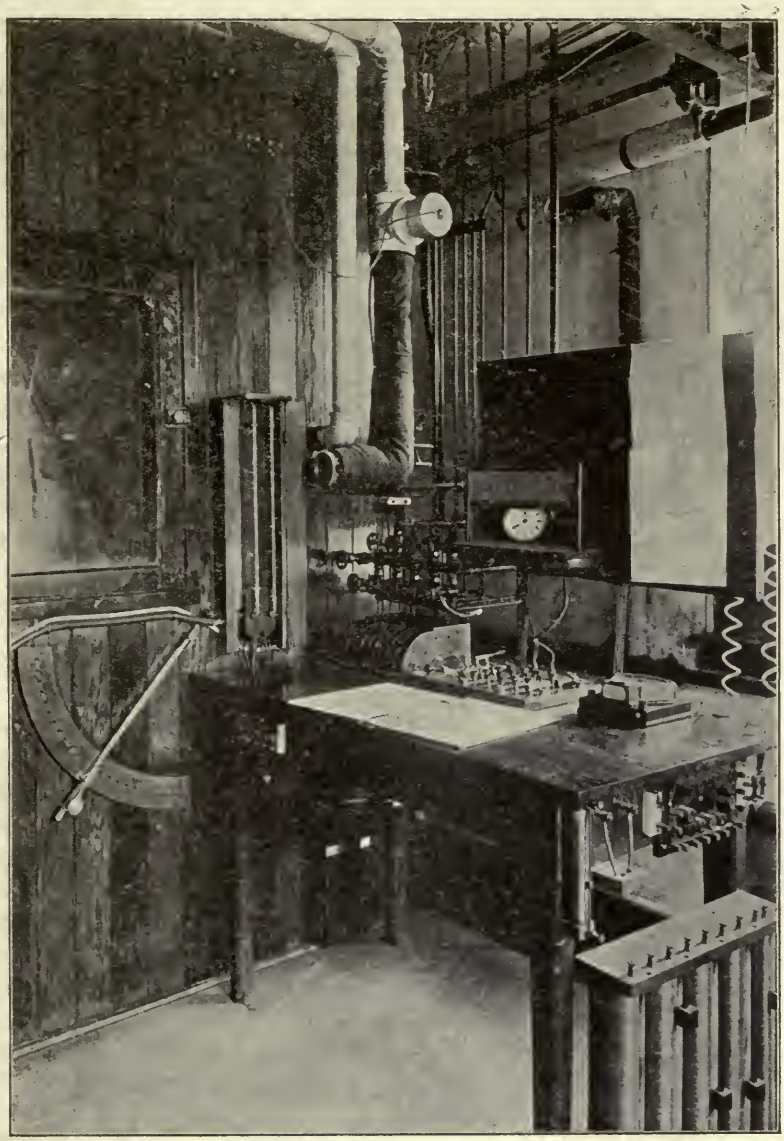

FIG. 37.—Observer's Table. At left, the window, lever for raising shields, and water thermometers; on table at left is the rheostat, above it the valves for controlling cooling water, and in the center of table the mercury switch. Incidental electrical connections and instruments are shown on right of table. The galvanometer scale is immediately above table.

within the chamber, pass out through a groove in the under side of the circular wooden plug projecting from the wooden walls at the left of the table and terminate in the mercury switch at the rear of the center of the table. This switch is described in detail beyond.

The electrical connections for the heating systems in the different sections of the air-spaces are made through the rheostat at the rear of the left end of the observer's table. Inasmuch as there are eight sections of the air-spaces, and one resistance lamp is used to vary the temperature of the incoming air, the rheostat has nine sections, each of which is connected, by means of a cable passing through the floor of the platform (seen under the table in fig. 37), with its resistance coil lying between the respiration chamber and the floor, as explained on page 118.

The flow of water through the pipes for cooling the different sections of the air-spaces, and through the pipe for cooling the ingoing air, is regulated by the ten valves immediately above the rheostat. The upper four valves control the four sections of the inner air-space, the four immediately beneath them those of the outer air-space, and the fifth valve on the lower line, the circuit for cooling the ingoing air. The valve at the extreme left is used to maintain a constant flow of water into the supply tank in another part of the building. (See p. 126.) At the right of the table are several resistance coils, and upon the table a portable voltmeter, used in electrical check experiments. (See p. 169.)

The millimeter scale on which the deflections of the galvanometer are read is immediately in front of a small clock on the black-cloth hood in which the galvanometer is placed. The two upright thermometers inserted in the wooden plug at the left of the observer's table indicate the temperatures of the ingoing and outcoming water for the heat-absorbing system. A little below and at one side is seen the lever for raising or lowering the shields to the heat-absorbers inside the chamber. This moves over a graduated arc into which a peg on the handle fits, thus allowing for fine adjustments. Of the three small switches under the edge of the table, at the left, one completes the telephone circuit to the chamber and the others are for connections with the bicycle ergometer (see p. 164) and with electrical devices used within the chamber in electrical check experiments.

The water-meter, which is not shown in figure 37, stands on the floor immediately at the right of the observer, as it appears in figure 3. Thus it is seen that from the position of his chair the observer can note through the glass door the movements of the subject inside the chamber, read the mercurial thermometers in the water-cooling circuit, heat or cool various sections of the chamber, raise or lower the shields, note temperature differences on the galvanometer, and note the quantity of water passing through the water-meter.

ELECTRICAL CONNECTIONS ON THE TABLE.

The scheme of the various electrical connections on the observer's table is given in figure 38.

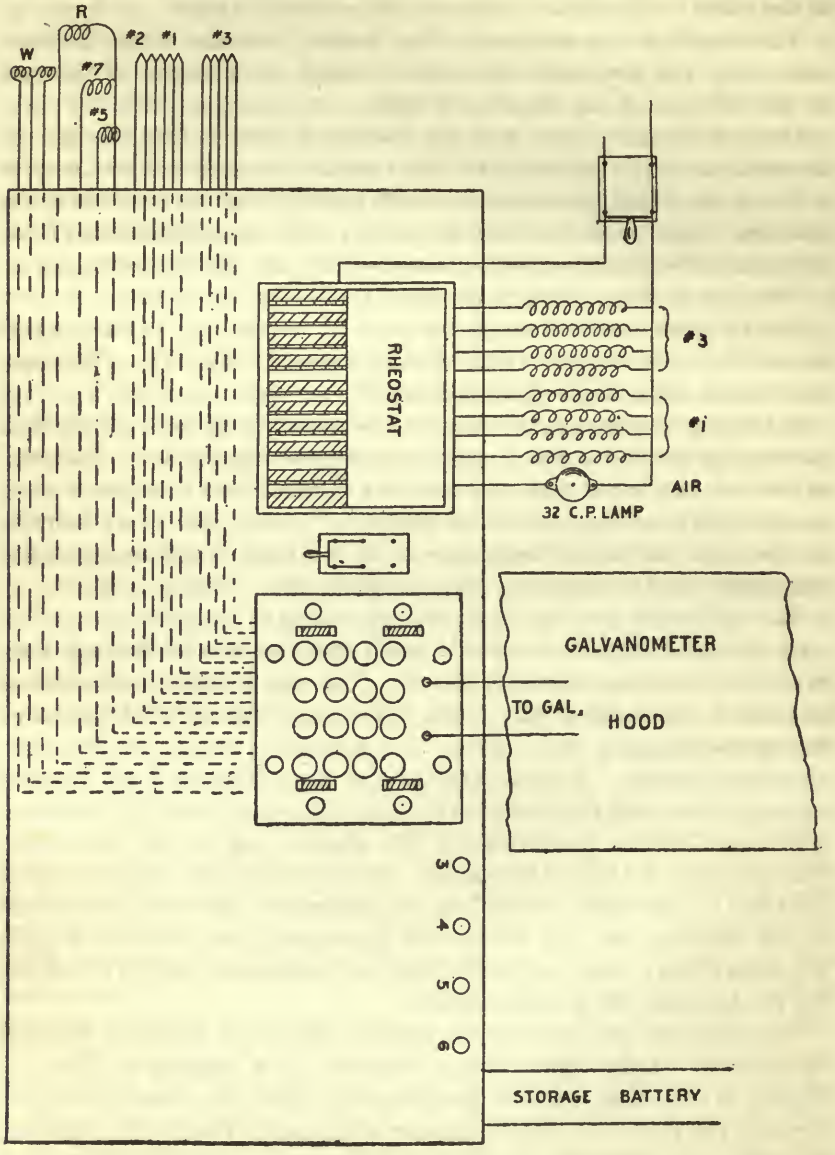

FIG. 38.—Electrical Connections on the Observer's Table. All electrical connections are, for convenience, brought to the observer's table. The rheostat controlling the heating circuits, the mercury switch, the thermal junctions and thermometer circuits, and, at right, connections for storage battery for use in electrical check experiments and for magnetizing the fields of the bicycle ergometer are shown.

The thermal junctions are indicated in the upper left-hand corner by the numbers 1, 2, and 3. In No. 1 there are four subdivisions corresponding to the four sections—top, upper zone, lower zone, and bottom—of the metal walls of the chamber. No. 2, which is here indicated as in series with No. 1, represents the thermal junctions in the air current. No. 3 represents the four subdivisions of the system of thermal junctions in the inner and outer air-spaces.

The resistance thermometers for indicating temperature changes in the air of the chamber and the copper wall are represented by the coils 5, 7, and R. These are here shown to be connected so as to have one common return. The coil W represents a resistance thermometer for measuring differences in temperature of ingoing and outgoing water for heat absorption. (See p. 149.)

All the above connections terminate in the mercury switch at the rear of the center of the table. Extending backward from this are two wires leading to the galvanometer.

In the upper right-hand corner of the table is the rheostat controlling the heating circuits. No. 1 represents the four circuits in the different sections of the inner air-space and No. 3 the circuits for the corresponding sections of the outer air-space. The 32-candlepower lamp is that used in heating the ingoing air. The switch in the upper right-hand corner of the diagram connects the rheostat with the city electric main.

On the lower right-hand corner are wires leading to a storage battery. The binding posts numbered 3, 4, 5, and 6 are for connections for electric check tests and for magnetization of the fields of the bicycle ergometer.

MERCURY SWITCH AND BRIDGE.

In order to keep the two metal walls of the chamber adiabatic, each thermal junction system—*i. e.*, those corresponding to the top, upper zone, lower zone, and bottom—is connected so that the differences in electro-motive forces of the junctions in thermal contact with the zinc and the copper walls can be measured on the galvanometer and thus furnish an indication as to whether the zinc wall should be warmed or cooled. Similarly, the four outer thermal junction systems in the inner wooden wall are so connected that they may be put in series with the galvanometer. Not only are the individual sections of these two thermal junction systems thus connected, but the wiring is such that the algebraic sum of the electro-motive forces of the junctions in all four sections may be noted for each system; consequently there are five connections necessary for each system, *i. e.*, the four parts and the

whole. The thermal junction system in the air current is likewise capable of being placed in series with the galvanometer. There are, then, eleven different thermal junction connections to be made with the galvanometer.

Any system of switches for such a number of connections must obviously be somewhat complex, and, furthermore, the wear and tear on them would be such as to render their use extremely unsatisfactory. The sliding contacts would frequently become covered with dirt or grit,

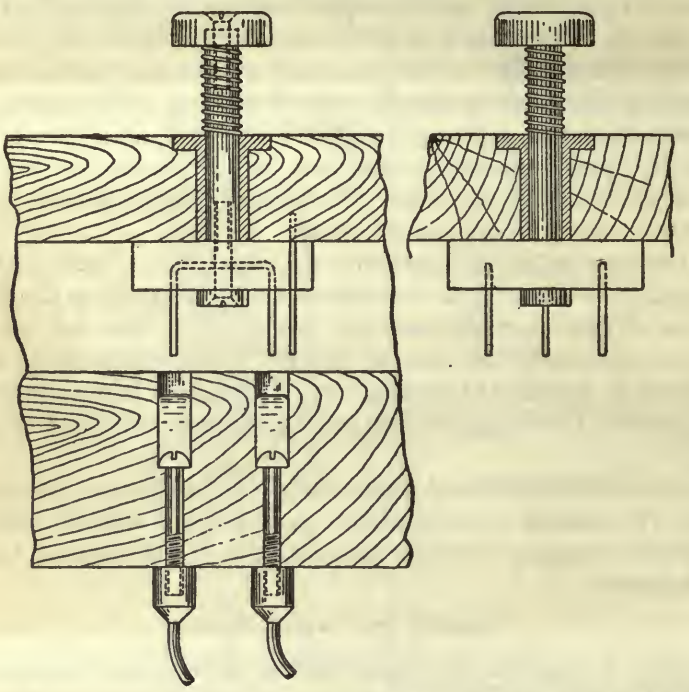

FIG. 39.—Unit Key of Mercury Switch. By depressing the key the two ends of a copper link are caused to dip into mercury in holes in a wooden block. The mercury insures connection of the screw and nut with the proper electrical devices.

and the working parts would soon give way. An ingenious method of using mercury contacts for the thermal junction systems, thereby avoiding poor contacts and excessive wear and tear, was devised by our mechanician, Mr. S. C. Dinsmore. Later, this mercury contact device was incorporated in an instrument which combined a mercury switch and a bridge system.

The connection between each thermal junction circuit and the galvanometer is made by dipping two copper links into four mercury cups, two of which are connected with the wires leading from the thermal

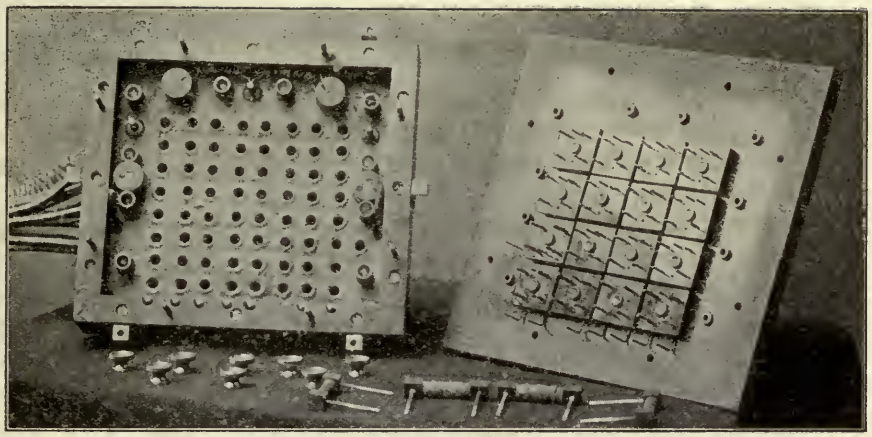

FIG. 40.—Mercury Switch, top removed. At left, the switch with its mercury cups and comparison coils; at right, the top with the keys and copper links. In the foreground are shown the comparison coils and nuts for holding top in place.

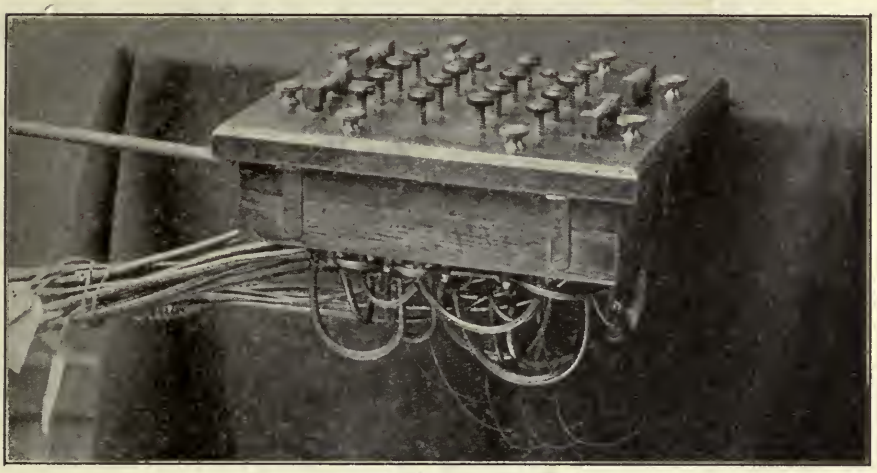

FIG. 41.—General View of Mercury Switch.

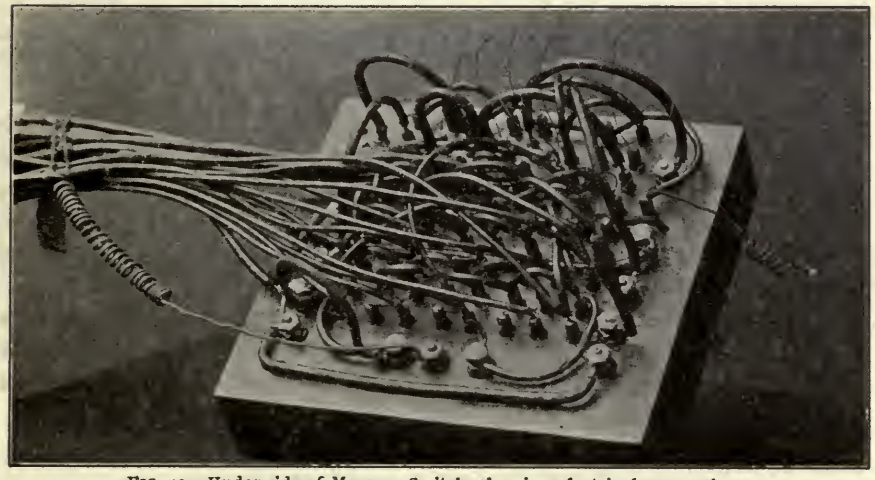

FIG. 42.—Under side of Mercury Switch, showing electrical connections.

junction system and two with wires extending to the galvanometer. The special feature of this switch is the device for closing the circuit. The two copper links, each of which is in fact composed of several strands of No. 16 copper wire, are fastened to a square of hard rubber on the end of a steel rod. A cross-section of a unit connection on this switch is shown in figure 39.

A hole drilled in a block of oak serves as the mercury cup. At the bottom of each cup there is an iron or steel screw which extends through the oaken block to a brass nut on the under side. The wires leading to the galvanometer and thermal junction circuit, respectively, are soldered to the brass nuts. The holes in the oaken block used for mercury cups are shown at the left in figure 40. The wood was boiled for several hours in paraffin and a thick coating of paraffin covers all of it. The crater-like appearance of each hole is due to the deposit of paraffin about the rim.

The cover of the switch, which is not so thick as the base, is made of mahogany. The steel rod to which the square of hard rubber with the copper links is attached passes through a metal bushing set in the cover, and the two copper links are held suspended over the mercury cups by a spring coiled around the steel shaft. On the upper end of the steel shaft a hard-rubber button is attached. A steel guide wire driven into the cover and passing through a hole in the square of hard rubber insures the copper links entering the mercury cups in the proper position when the key is pressed. The manipulation is not unlike that of depressing the key of a typewriter, save that the key is held down for several seconds. The details of the under side of the cover are shown in the right-hand portion of figure 40.

The whole switch, with the cover in place, is shown in figure 41. In figure 37 the switch may be seen in position on the observer's table. Some idea of the intricacy of the wiring is obtained from the view given in figure 42, which shows the under side of the switch.

The details of the electrical connections between the switch and the different parts of the calorimeter with which it is concerned are illustrated in figure 43.

Here it is seen that a number of connections other than those having to do with the thermal junction system are included in this switch. To distinguish the different thermal junction systems, we have designated those belonging to the system between the two metal walls of the chamber as No. 1 ; those in the air current as No. 2, and those in the inner wooden walls as No. 3. The different sections of circuits Nos. 1 and 3 are further subdivided into top (T), upper zone (U), lower zone (L), and bottom (B). Consequently the circle on figure 43, in which the

designation T No. 3 is placed, represents the outline of the key, which, when pressed, will connect the two wires leading from the upper section of the thermal junction system in the inner wooden wall with the two wires leading to the galvanometer.

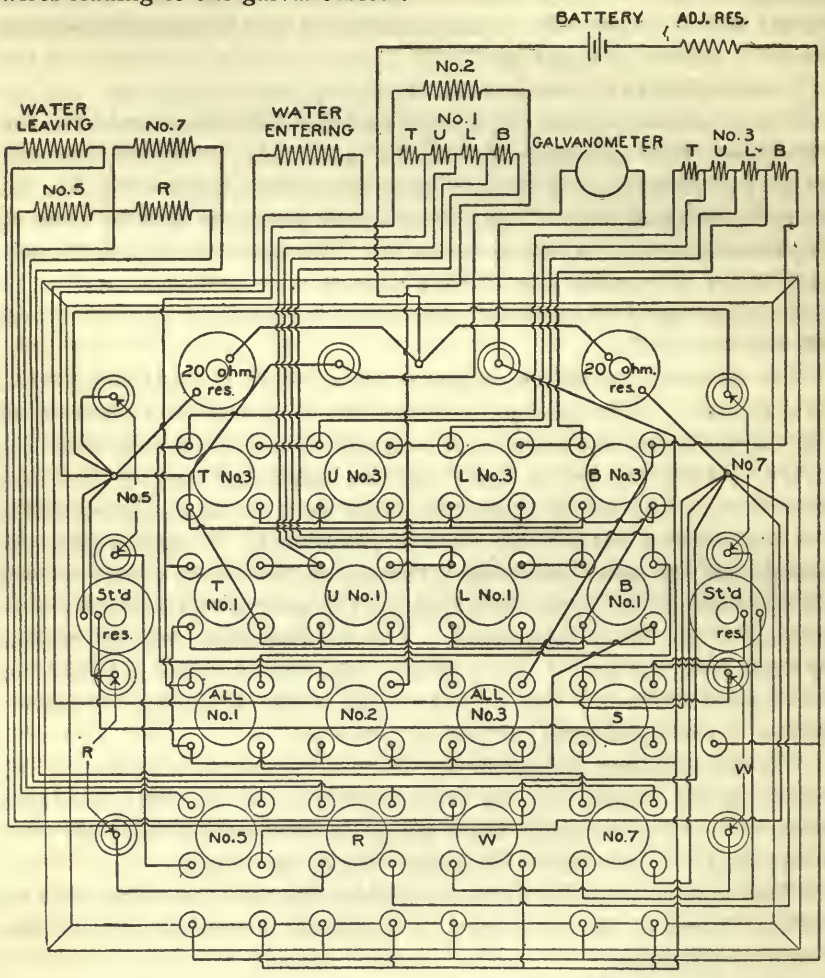

FIG. 43.—Diagram of Electrical Connections of Mercury Switch. The upper portion of diagram represents the thermometers and junctions and the galvanometer with which the bridge is connected.

The four sections of this thermal junction system are connected with the four upper keys of the switch. The four sections of the inner thermal junction system, *i. e.*, No. 1, are connected with the four keys immediately beneath those for system No. 3. In order that the algebraic sum of the electro-motive forces for the four parts of system

No. 1 may be read at once, the outer connecting wires which take in all the junctions in system No. 1 are carried to the mercury cups beneath the key designated A L, L, No. 1. As is seen on page 116, this deflection corresponds to the *average* temperature difference between the zinc and copper wall. In the same way the algebraic sum of the deflections of the four parts of No. 3 system can be read directly by depressing the key designated as A L, L, No. 3.

The key designated as No. 2 controls the connecting wires from the ventilating air-circuit, and by depressing this key the temperature differences between the ingoing and outcoming air are noted directly, not as absolute temperature measurements, but rather as an indication of the necessity for warming or cooling the entering air to adjust its temperature to that of the air leaving the calorimeter chamber.

It is thus seen that eight keys control the temperature indications of the sections of the thermal junction circuits, and that three keys indicate temperature conditions respectively in the whole of system No. 1, the whole of system No. 3, and the air current. For the indication of these temperature conditions, therefore, eleven keys are employed.

The connections shown by the wires in figure 42 can be followed more exactly by the plan of wiring given in figure 43. This diagram can be compared advantageously with the view of the switch given at the left in figure 40, as the diagrammatic features of the plan of wiring are made to correspond very closely with the exact location of the different parts of the switch proper. For example, the two coils wound on hard-rubber spools and fastened to the switch by screws through the center of the spool, which are shown in figure 40 at the top, correspond to the two coils marked 20-ohm res. on the diagram. The two iron cups which are filled with mercury when the switch is in use, and in which the galvanometer terminals are immersed, are between these two coils, while the iron post from which wires pass to each of the 20-ohm coils is between the galvanometer connections, exactly in the middle of the upper portion of the switch. The two wires leading from the galvanometer can readily be traced on figure 43 to these two iron cups. It can be seen further that one of the wires from the battery connects directly with the iron post between the galvanometer cups, which corresponds to point B′ in figure 44 beyond.

On each side of the circle designating the galvanometer is placed a diagram of a thermal junction system, that corresponding to the inner metal-wall system, *i. e.*, No. 1, on the left, and that corresponding to the outer system, *i. e.*, No. 3, on the right. Furthermore, the connections of the separate sections, T, U, L, B, are shown for each system. Immediately above system No. 1 is the representation of system No. 2,

or that in the ventilating air current. It will be noticed that systems No. 1 and No. 2 unite at the left of T in system No. 1, and thus one wire serves for the return from both systems.

The connections between the several thermal junction systems and the galvanometer are relatively simple; it is with the bridge system for temperature measurements that the electrical connections are the most complicated. For these measurements a type of Wheatstone bridge, illustrated by the diagram in figure 44, is used.

In the simple form of Wheatstone bridge shown in figure 44 there are in fact four parts—two 20-ohm resistance coils, a standard resistance, and the coil of copper wire whose temperature fluctuations (variations in resistance) are to be measured. The battery is connected at the two points B′ and B″. The galvanometer connections are made at G′ and G″.

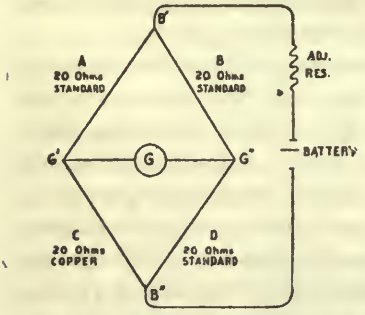

FIG. 44.—Diagram of simple form of Wheatstone Bridge. A current from a battery passes through an adjustable resistance and connects with the bridge at points B′ and B″. When all arms of the bridge are proportional, no current flows through the galvanometer G. If C is greater or less in resistance than D, the current passes through G.

The two 20-ohm resistance coils A and B are made of a form of wire that has no temperature coefficient, *i. e.*, there are no changes in electrical conductivity due to changes in temperature. These two coils are calibrated with the greatest accuracy, so that the resistance of the coils and connections between B′ and G′ is exactly equal to those between B′ and G″; thus A and B correspond to the proportional arms of a Wheatstone bridge. These two coils are shown in the diagram, figure 43, being marked 20-ohm res. Their position on figure 40 is likewise clearly seen. The iron post between these two coils corresponds to the point B′ of figure 44. The points B″ and G′ and G″ are not so readily discerned on the drawing in figure 43, owing to the complex nature of the electrical connections.

The other two arms of the Wheatstone bridge (fig. 44) are composed of a standard coil, D, made of wire similar to that used in coils A and B and having approximately 20 ohms resistance. This coil is used for comparison with the unknown resistance of the copper thermometer coil and connections, which correspond to coil C in figure 44. As this coil (for example, the copper thermometer used for measuring the temperature fluctuations of the air in the calorimeter chamber) changes in resistance, and obviously may rarely be exactly equal in resistance to coil D, there is a disturbance of the equilibrium of resist-

ances in the two arms of the bridge, C and D, and consequently a small current of electricity passes through the galvanometer. The current may pass from G′ to G″ if the coil C has a greater resistance than D, or it may pass from G″ to G′ if the coil C has less resistance than coil D. It is important to bear in mind that the resistances of the coils, plus the resistance of connecting wires, must be taken into consideration rather than the resistance of the coils alone. Unless the resistance of the coil C and all its connections with the points G′ and B″ (fig. 44) is exactly equal to the resistance of the coil D and its connections with the points G″ and B″, a current of electricity will pass through the galvanometer.

In the ordinary form of Wheatstone bridge, provision is made for altering the resistance of coil D until the equilibrium is again established, the degree of alteration in coil D being an index of the resistance change (temperature change) in coil C. The so-called "slide-wire" form of Wheatstone bridge alters the position of the point B″, thus varying the total resistances between B″ and G′, and B″ and G″, until the equilibrium is established and no current flows through the galvanometer. With either of these two methods of resistance adjustment, elaborate and delicate apparatus is required and the continuous use of such instruments is accompanied by a constantly increasing inaccuracy in their use, due to the wearing of parts. In the mercury contact switch and bridge described here, the use of a Wheatstone bridge and resistance box, or a slide-wire bridge, is obviated.

If in the system shown in figure 44 the resistance of coil C varies and is not identical with coil D, a current will pass through the galvanometer and produce a deflection. This deflection will, in general, be nearly proportional to the amount of current flowing through the galvanometer, and, as the current is equal to the electro-motive force divided by the resistance, it follows that with a constant electro-motive force the current varies inversely as the resistance. Assuming that the resistance, coil C (fig. 44), at a given temperature is such as to cause a current of electricity to pass through the galvanometer and produce a deflection of 100 mm. on the scale, if the resistance of the coil C is now decreased a larger current will pass through the galvanometer and the deflection will become larger. Conversely, if the resistance of C increases, a smaller current of electricity will flow through the galvanometer and the deflections will grow smaller. If, now, the resistance of C is increased further, there will be a point at which the resistance of C is equal to D and no current will pass through the galvanometer, and if the resistance is still more increased, the current will tend to flow through the galvanometer in the opposite direction, and constantly increasing deflections, though in the opposite direction from

those at the beginning, will be obtained. Obviously, the direction of the current through the galvanometer and the direction of the deflection for increasing or diminishing resistances in C depend upon the direction of the current from the battery and also upon the connections through the galvanometer terminals, for by interchanging the wires leading from the galvanometer to G′ and G″ the current through the galvanometer may be made to pass in the opposite direction.

Of the four resistances in the bridge system, but one is affected by temperature changes, *i. e.*, that composed of the copper coils ; hence any differences in the deflection of the galvanometer may be ascribed directly to variations in resistance of the copper coil, provided the electro-motive force of the battery remains constant. To insure a constant electro-motive force, we have relied upon the establishment of an arbitrarily adjusted bridge system, in which the coils C and D are slightly out of proportion, *i. e.*, coil C has a somewhat lower resistance than coil D. Both coils (C and D) in this system are made of wire with zero temperature coefficient. These coils are mounted on the mercury contact switch (fig. 40), one on each side of the rows of mercury cups in the oak base and about midway of the sides. The coils are similar in form to the two 20-ohm coils mentioned before, and while one has a resistance of exactly 20 ohms, the other is a small fraction of an ohm lower in resistance. Inasmuch as these coils belong to a bridge system that is used to standardize the electro-motive force from the battery, they are called standard coils, or standard resistances, and on figure 43 they are marked St'd res.

With the bridge system thus arranged, the closing of the battery and galvanometer circuits should result in a deflection of the galvanometer, owing to the inequality of arms C and D of the bridge. The deflection of the galvanometer is then approximately proportionate to the electro-motive force, and by adjusting the number of cells of the battery and varying the resistance in the battery circuit it is possible to produce a deflection of any definite magnitude. Since all coils are of wire with zero temperature coefficient, no changes in temperature will affect the bridge system, and the amount of current necessary to produce a deflection of 100 mm., for example, will be constant, provided there are no variations in the galvanometer constant. This latter factor can be tested readily, and in fact varies but slightly, so that we have by this bridge system an excellent method of compensating for variations in the electro-motive force of the battery. As a source of current, we use ordinary dry cells, with a small variable resistance in series with them. With this arrangement and with the connections as now made, the amount of current required to produce a deflection of 120 mm. is used as the standard for all our work. Inasmuch as the temperature of the cal-

orimeter room is always of such uniformity as to cause only slight variations in the electro-motive force of the batteries, small alterations in the variable resistance serve to keep the standard current well in hand. Variations from hour to hour rarely amount to more than 2 or 3 mm. on a deflection of 120 mm. This method of obtaining a constant current is, for the purpose of this research, sufficiently accurate and on the whole distinctly preferable to the use of a standard cell.

The adaptation of the mercury contact to this form of bridge is shown in figure 43. By depressing the key marked S the copper links enter the mercury in the cups in such a manner that the bridge and battery circuits are made before the galvanometer circuit. In this key it is necessary to have five mercury cups instead of four, as in the keys connecting the thermal junction systems. The fifth mercury cup is made outside of the square inclosing the regular cups, and is seen at the right, immediately in line with the standard resistance coil in figure 40. The fact that these bridge systems were added to the mercury contact switch after it was first built explains the irregularity of the position of the extra mercury cups, not only in this standard circuit, but also in the four bridge circuits controlled by the four keys on the bottom row.

The flow of the current through the different connections, when the key is depressed, may be followed very readily if it is borne in mind that all the copper links connect cups with those that are immediately above. On the whole switch there is but one exception to this rule, and that is the connection for the battery circuit for the standard system. Here the copper link connects the extra mercury cup with the nearest cup.

In figure 40 the top of the switch at the right is removed and shown in such a position that were it brought over like the cover of a book the copper keys would fall over the proper mercury cups. Hence it can be seen that the two upper rows are for the cups connecting with the two thermal junction systems, while the first key on the next to the lower row corresponds to the standard bridge system. Indeed, the copper link extending on one side is clearly seen. This link dips into the extra mercury cup. The four lower keys, each with one or more extension links, belong to the four other bridge systems.

Of these four systems, one controls the measurement of temperature changes in the copper thermometer suspended in the air in the calorimeter chamber. This is designated as system No. 5, and is controlled by the lower left-hand key (fig. 43). The standard coil of zero temperature coefficient wire used for comparison with the copper thermometer No. 5, *i. e.*, the coil corresponding to D in the bridge system (fig. 44), is wound on a small hard-rubber spool, and is provided with

two heavy copper terminals, which can be dipped in the iron mercury-cups. Four of these coils, corresponding to the four bridge systems, are shown immediately in front of the switch in figure 40. They are shown in position in figure 41. The terminals of the coil for system No. 5 are slipped through two hard-rubber bushings in the cover, and extend beneath the cover far enough to have their lower ends well immersed in mercury in two iron cups similar to those used for the galvanometer terminals. Those for system No. 5 are at the left and near the top of the switch, as shown in figure 40. A line terminating in arrow-heads and broken by the designation No. 5 shows in figure 43 the position of these cups and the connections with their lower ends. The iron mercury-cups, as well as the iron posts for the battery and bridge connection previously mentioned (see p. 143), are provided on the under side with hexagonal nuts, which are used to insure the best electrical contact for the various parts of the bridge system. These nuts and the wiring from several of the iron cups and posts are shown in figure 42. As can be seen by a comparison with the direction of the bundle of wires extending outward from one side, the switch has been tipped forward through 180° from the position in figure 40 to give the view in figure 42; consequently the three nuts at the bottom of figure 42 correspond in figure 40 to the two galvanometer terminal mercury cups and the iron post connecting with the battery.

Although the hexagonal nuts aid in making a good contact, the connections for all the bridge systems, especially the connections which, if defective, would disturb the equilibrium of either arm of the bridge, are further insured by having soldered joints. All connections between the iron mercury-cups and the calorimeter chamber are made of very heavy (No. 10) copper wire to eliminate the effect of temperature fluctuations other than those in the thermometer coils.

The key controlling the temperature measurements of the copper thermometers which indicate the temperature of the copper wall, No. 7, is in the bottom row (fig. 43), at the extreme right. The comparison coil dips in two iron cups filled with mercury. These cups are at the right of the switch, in a position corresponding to that occupied by the comparison coil No. 5. The line terminating in arrow-heads is broken by the designation No. 7.

The key marked R controls the temperature measurement of a copper coil used for obtaining the rectal temperature of the subject of the experiment. This thermometer is described in detail elsewhere. (See p. 156.) The comparison coil for R is immediately at the left of the keys A L, L No. 1 and No. 5.

The key marked W is not as yet in practical use. Experiments are in progress to utilize this method of temperature measurement to obtain the differences in temperature of the ingoing and outcoming water currents, temperature differences now measured by mercurial thermometers. (See p. 133.) The coil W is immediately at the right of the keys marked S and No. 7.

With the large area of wire exposed in the copper thermometer coils No. 5 and No. 7, and the consequent rapid radiation, we have found that the slight amount of current, 0.03 ampere, produces no appreciable local heating effect in the coils; hence the reading of the galvanometer may be taken with the circuit closed and after the deflection has become constant. The method of reading the deflection obtained when the R coil is used is that of observing the amplitude of the first swing. As the coil for the R thermometer is compactly wound, and therefore does not radiate heat readily, the passage of the current through it heats the coil, giving rise to erroneous readings. The amplitude of the first swing has been found to be sufficiently accurate for these readings, and the rectal thermometers are calibrated to be read under these conditions.

At the upper left-hand side of figure 43 the various coils and their connections with the switch are shown. It is thus seen that coils No. 5, No. 7, and R all have a common return wire from the calorimeter chamber.

The connections for the coils for the bridge system inside the calorimeter—*i. e.*, copper thermometer for the air (No. 5), thermometer for the copper walls (No. 7), and the rectal thermometer—are conducted from the mercury switch through a cable having a number of strands of heavy flexible wires to a plug switch fastened to the copper wall of the calorimeter. This cable is seen in figures 29 and 30, while the location of the plug switch is seen at M, figure 33. The connections for the bridge systems corresponding to No. 5, No. 7, and R are made by inserting tapered plugs into the different sections of this switch. Other sections (there are ten in all) can be used for other electric circuits, such as the telephone, wires for electrical check experiments, and connections for the bicycle ergometer (see p. 164), but they are connected with much smaller (No. 18) wires with a set of switches under the edge of the observer's table. (See fig. 37.)

In the connections between the thermal junction system and the galvanometer, relatively large changes in resistance in the contacts are without effect on the deflection of the galvanometer; but it is readily seen that with the bridge systems the matter is very different. Here the mercury contacts become a part of the connection between G′ and

B″, and G″ and B″, of figure 44; hence the necessity for the reliability of these connections. With clean mercury and good copper links, the connections are all that could be desired.

This switch has been in constant use three years and has given excellent satisfaction. Inasmuch as all temperature measurements are relative, not absolute, and the variations in temperature are slight, it can readily be seen that this form of bridge is especially well suited for experimental work of this nature. The sensitiveness is all that could be desired, since with the present adjustment 60 deflections (millimeters) correspond to 1° C.; hence readings of 0.01° are readily obtained, an accuracy sufficient at present for experiments with the respiration calorimeter. That some form of potentiometer could be used for this work with good results is, of course, not to be doubted, but the compact form of this switch and bridge leaves little to be desired for the purposes for which it was devised.

DETERMINATION OF THE QUANTITY OF HEAT ELIMINATED.

It has been shown that heat is regularly carried out of the calorimeter chamber in two ways—partly as latent heat of water vapor in the air current, but chiefly as sensible heat taken up by a current of water circulating in the heat-absorbers. Theoretically, the sum of the two quantities of heat thus removed should equal the total amount eliminated within the chamber, but in actual practice various corrections must be made to determine the actual quantity of heat. The method of computing the quantity of heat removed in these two ways and the necessary corrections to be applied remain to be described.

Latent Heat of Water Vapor.

The quantity of heat removed from the chamber in water vapor is found by multiplying the quantity of water collected in the water-absorbers by the factor for latent heat of vaporization of water. In these experiments the factor used is 0.592 calorie per gram, which was deduced from Regnault's formula, as discussed in detail elsewhere.[1]

It is greatly to be desired that this factor be verified by investigations in which water is vaporized under the conditions that obtain during an experiment with man; but although considerable preliminary investigation of this nature has been made, we have no results that warrant our taking other than the commonly accepted figures of Regnault for this calculation. Presumably the error involved, if any, is not very large. Certainly it is not larger than the probable physiological error in experiments of this type.

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, p. 57.

The number of grams of water removed by the absorbers multiplied by the above factor gives the number of calories of heat escaping from the chamber in water vapor. To obtain the total quantity of heat involved in the vaporization of water, however, it is necessary to make allowance for the latent heat of water vapor still remaining in the chamber, the correction being added or subtracted according to whether the amount of residual vapor at the end is larger or smaller than that present at the beginning of the experimental period.

Sensible Heat Removed in the Water Current.

UNIT OF HEAT.

The ordinary definition of the large calorie is the quantity of heat required to raise the temperature of 1 kg. of water 1° C. This, however, is only approximately correct, because the specific heat of water varies with the temperature.[1] It is therefore necessary to define the unit of heat somewhat more exactly.

In experiments the temperature of the calorimeter chamber is maintained very constant at 20° ; hence the specific heat of water at 20° is taken as the standard ; and the calorie here used is the quantity of heat necessary to raise a kilogram of water from 19.5° to 20.5°.

CALCULATION OF THE QUANTITY OF HEAT MEASURED.

The weight of the water determined by the water-meter, multiplied by the difference between the temperature of the water as it enters and that as it leaves the chamber, gives the quantity of heat as measured at the mean between the temperatures of the ingoing and outgoing water. According to the explanation given above, however, this must be corrected for the difference between the specific heat of the water at this mean temperature and that at 20°. The latter value is designated as heat measured in terms of C_{20} ; the former value is designated as heat measured in terms of C_t, in which t is any temperature other than that of 20°.

In finding the true value of C_t, it is necessary to know the mean specific heat of water for the range of temperature employed in any given period. The temperature of the ingoing water is sometimes as low as 1° ; that of the outgoing water is rarely above 15°, and more frequently not far from 10°. If, for example, the water enters the calorimeter at 2°, a condition that is very common during the hard-work

[1] The results of a large number of experiments on the specific heat of water at different temperatures have been discussed in considerable detail in another publication (U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, p. 55). From a table there given showing the specific heat of water at different temperatures and referring to that at 20° as a unit, it is seen that the specific heat of water at 0° is 1.0090 ; at 5°, 1.0056 ; at 10°, 1.0029 ; at 15°, 1.0010. The difference between C_{20} and C_0 is one of nearly 1 per cent.

experiments, and leaves the chamber, after having passed through the absorbing pipes, at 12°, the result will be in terms of $C_{(2-12)}$ or in terms of the mean calorie from 2° to 12°. From the table above referred to it is found that the specific heat at 2° is 1.0076 and at 12°, 1.0020. The average of these two is 1.0047. This variation is approximately 0.5 per cent. Since the accuracy of the calorimetric measurements is considerably within 1 per cent, it is evident that the correction above suggested must be applied.

In making the correction, the quantity of heat measured in terms of C_t is multiplied by the specific heat of water at C_t referred to that at C_{20} as a standard.

Corrections to Measurements of Heat.

As explained above, to obtain the true final measurement of heat, allowance must be made for certain quantities of heat introduced or removed in various ways. The different corrections to be made are discussed in the following sections.

The hydrothermal equivalent of the calorimeter.

With the heat-regulating devices previously described, it is in general not at all difficult to control the temperature of the calorimeter within very narrow limits; but there are times when the calorimeter system, as a whole, may have a different temperature at the end of a period than at the beginning, and there may be accordingly either a storage or a loss of heat in the system. Obviously, in accurate experimenting, especially in short periods, it is necessary to know the actual amount of heat thus stored or lost. This involves a knowledge of the hydrothermal equivalent of the calorimeter, since the mass of material thus raised or lowered in temperature must be known and expressed in its equivalent weight of water.

With a calorimeter of this type of construction it is not an easy matter to determine the hydrothermal equivalent with great accuracy. The inner copper wall is heated by the heat radiating from the subject. The outer zinc wall is heated by the electrical current in the air-space surrounding it. If the chamber undergoes a certain rise in temperature, it is difficult to state exactly what proportion of the heat given off by the subject is utilized in raising the temperature of the copper wall and what proportion is utilized in raising the temperature of the zinc wall, for while there is obviously a distinct period during which the copper wall is warmer than the zinc wall, it is by no means absolutely certain that when the temperature is rising all the heat from the man's body escapes to the zinc wall before the electrical heating circuit begins

to warm up this wall. Conversely, if there be a fall in temperature, it is possible that the reverse may result.

Inasmuch as with experienced observers the variations in temperature are very slight, and as the press of experimental work has prevented our making further determinations of the hydrothermal equivalent, we have used in all the investigations so far the results of an experiment published[1] in 1899. In this test the calorimeter was held at a constant temperature for several hours; a small electrical current was then passed through a resistance coil in it for two hours. During this period of time especial pains were taken to keep the thermal junction circuits in the metal walls at equal temperatures, and as a result, since no heat was allowed to pass through the walls, the temperature of the calorimeter slowly rose. At the end of two hours the current was stopped and the calorimeter allowed to assume a constant temperature. From the rise in temperature and the amount of heat generated by the electric current, it was calculated that the apparatus required about 60 large calories to raise its temperature 1°; hence its hydrothermal equivalent is not far from 60.

The true significance of this factor is becoming less and less each year as the experimental skill of the manipulators increases. It is our purpose, however, to repeat these tests, and consider a fall in temperature as well as a rise in determining exactly the hydrothermal equivalent of the apparatus. Suffice it to say that for the fluctuations ordinarily occurring in experimental apparatus, it is known with sufficient accuracy.

An attempt has been made to calculate the hydrothermal equivalent from the weight of the different parts of the apparatus; but, as these weights were not taken at the time the apparatus was constructed and the quantity of wood, solder, etc., involved in the framework is not definitely known, these results are not at present available for use.

CORRECTIONS FOR TEMPERATURE OF FOOD AND DISHES.

In order to compute the total income and outgo of heat from the calorimeter system, it is necessary to know the temperature of all articles passed into or taken out of the calorimeter chamber. If the food, drink, and dishes going into the chamber are below the calorimeter temperature, there will be a certain amount of heat absorbed in warming the material to the temperature of the chamber; and, conversely, if any of the materials are warmer than the interior temperature, they will gradually radiate heat until they assume the temperature of the calorimeter. Similarly, if material is passed out of the chamber at a higher or lower temperature, there is a loss or gain of heat.

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, p. 44.

Theoretically, all material should enter or leave the calorimeter chamber at the inside temperature, but in practice it has been found impossible to do this; hence a correction is necessary.

From the weights of all materials entering the chamber and their specific heats, their hydrothermal equivalent can be readily calculated, which, multiplied by the difference in temperature, gives the amount of heat added to or lost from the chamber. These corrections are made for each experimental period, the data being determined directly from a record sheet posted near the food aperture.

ADIABATIC COOLING OF GASES.

With fluctuations in barometric pressure, the air inside the calorimeter expands or contracts, and consequently liberates or absorbs heat according to the well-known laws of adiabatic cooling. In consideration of the large volume of air in the calorimeter, the probable effect of fluctuations in barometric pressure on the amount of heat liberated during a given period has to be considered.

From data furnished by the chief of the Weather Bureau,[1] it has been computed that a maximum fall of 10 mm. in the barometer is accompanied by a cooling of 1.1°, which is equivalent to 1.624 large calories, or 0.1624 calorie per millimeter. This amount of heat is absorbed (rendered latent) as the barometer falls, and liberated as the barometer rises.

Save in very exceptional fluctuations in the barometer, this correction does not have to be taken into consideration, and thus far has not been necessary. It is possible, however, that in rest or fasting experiments, in which the amounts of heat liberated are small, this correction may amount to a percentage of the whole so large that it should be allowed for.

CORRECTION FOR HEAT ABSORBED BY BED AND BEDDING.

When the subject retires (at 11 p. m.), the heat radiated from the body is absorbed by the bed and bedclothes till the temperature of the portions nearest his body are warmed from chamber temperature (20°) to approximately that of the body (35°). As a result, the heat measured from 11 p. m. to 1 a. m. is too low. On the other hand, when the subject leaves his bed (at 7 a. m.), the bed and bedding again cool down to the temperature of the chamber, and the heat measured from 7 a. m. to 9 a. m. is too high. In determining the heat output by periods, correction should be therefore made for heat stored in this way. The data available for estimating the exact amount of this heat are by no means

[1] U. S. Weather Bureau, Report (1899), II, p. 492.

so complete as could be desired. A tentative figure, which is, however, little more than a rough estimate, is 30 calories. In practice it has been our custom to add 30 calories to the heat measured during the period from 11 p. m. to 1 a. m., and to deduct 30 calories from the heat measured during the period from 7 a. m. to 9 a. m. following. If the subject be restless or uneasy during the night, so that bedding is removed, the correction is of course affected, and such condition must be considered in applying the correction.

This correction applies only to the measurements of heat for different periods of the day. For the whole day the two corrections are compensating and are therefore negligible.

CORRECTION FOR CHANGE OF BODY TEMPERATURE AND BODY WEIGHT.

In the calculations thus far outlined it has been assumed that the temperature of the body of the subject has been constant throughout an entire period, and that there has been no gain or loss of body weight. It is obvious, however, that in an actual experiment either or both of these assumptions may be incorrect. Accurate temperature measurements show a considerable variation even under apparently uniform conditions, and the body weight undergoes a continual loss through the elimination of body carbon and hydrogen as carbon dioxide and water vapor by the lungs and skin, besides the marked gains and losses following the intake of food and the excretion of feces and urine.

The effect of such fluctuations may be that of either increasing or decreasing the amount of heat measured during the period. Thus, if the body weight has remained constant, but the body temperature has increased, there has been an absorption of heat by the body which has escaped measurement. An amount equivalent to the gain in temperature multiplied by the body weight and the specific heat of the body is therefore to be added. On the other hand, a fall in temperature would give a correction to be subtracted. Similarly, if the temperature remains constant, a gain in weight denotes a correction to be added to the heat measured, since with this gain of weight a certain amount of heat, depending upon the specific heat of the substance gained and the difference in temperature of the body and the chamber, has been required to raise the substance from the temperature of the chamber to that of the body. In case both body temperature and body weight have varied, the correction may be either positive or negative.

In practice, readings of body temperature are taken, when practicable every four minutes, and arrangements are such as to permit of weighing the subject at the end of each period if desired. The necessary corrections may then be applied.

Measurements of body temperature.—In experiments in which the heat production is determined, it has been commonly supposed that the body temperature at any given hour of the day is practically the same from day to day. Inasmuch as the body temperature undergoes a daily fluctuation, with a minimum in the morning, usually between 2 and 4 o'clock, and a maximum in the afternoon about 5, a true measure of the heat production by short periods (two or three hours) can only be determined by making corrections for changes in body temperature at the beginning and end of any given period. To ascertain these fluctuations of temperature, a special form of thermometer, based on variations in electrical resistance, was devised. The thermometer, its calibration and method of use, and a large number of observations made with it are described in detail elsewhere.[1] An illustration of the apparatus and a brief description of it are here given.

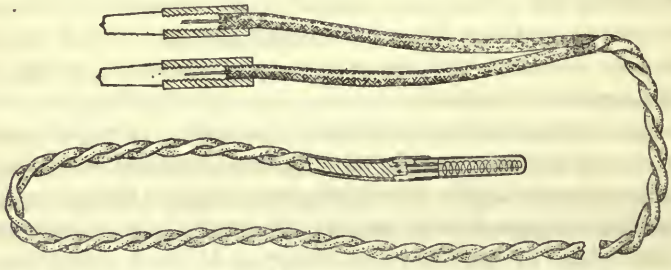

FIG. 45.—Rectal Thermometer. A coil of fine platinum or copper wire inclosed in a pure silver tube is connected by an incandescent lamp cord to two metal plugs which fit in a switch. About 20 cm. of the other end is covered with rubber.

A coil of fine double-silk covered wire (either copper or platinum), having a resistance of about 20 ohms, is inclosed in a small silver tube 30 mm. long and 5 mm. in diameter. The two ends of a flexible cable pass through a hard-rubber plug in the end of the silver tube and connect with the coil. A piece of soft-rubber tubing is slipped over the flexible cable and the ends well fastened with silk and shellac. The thermometer may then be inserted some 10 to 12 cm. in the rectum and worn with little inconvenience to the subject. The cable is connected with the plug switch and the variations in resistance of the rectal thermometer are measured by one of the bridge systems in the special form of mercury switch previously described. (See p. 148.) Fluctuations of one-hundredth of a degree Centigrade can be readily determined.
is thus possible to have observations of the body temperature of the subject within the respiration chamber recorded independently by the observer outside of the chamber. Observations are usually made every 4 minutes.

[1] Archiv. f. d. g. Physiol. (Pflüger), 1901, **88**, pp. 492–500, and 1902, **90**, pp. 33–72.

Weighing objects inside the chamber.—Aside from the variable weight of the body of the subject of the respiration calorimeter experiments, there is a continually fluctuating weight of the absorber system, the bedding, furniture, and clothing, due to variations in water content. A number of preliminary experiments, made several years ago in this laboratory, to attempt to determine the variations in weight of sheet copper exposed to different hygrometric conditions, gave negative results, and hence it has been assumed that any changes in the amount of water condensed on the surface of the metal chamber must be very slight and may be neglected; but we have found repeatedly that wood and textile fabrics absorb an appreciable amount of water which must be considered in accurate work.

There is not, however, much wood in the chamber. A wooden chair is used, in which the man is weighed, and there is some woodwork on the bicycle ergometer and telephone, but these are well shellacked and polished, and we have no reason to believe that they alter in weight, although the construction of the apparatus is such as to render actual weighings somewhat difficult.

With the clothing and bedding of the subject, we have conditions under which there may readily be wide fluctuations in weight. If, however, provision can be made for weighing such articles accurately, the fluctuations in weight can be determined and a correction applied accordingly.

The large differences in the amount of water condensed on the absorbing system have been referred to on pages 23 and 126. In order to know the exact amount of water in the chamber at any given time, it is necessary to know the variations in weight of the absorbing system.

The variations in weight of the subject are of special significance in their use as a check on the oxygen determinations, for if we have the weight of the income of food and drink, the weight of the outgo, and the variations in weight of the body of the subject, it is possible to calculate arithmetically the amount of oxygen taken out of the air by the man. In considering the fluctuations in the weight of the subject, however, it is impossible to distinguish between the water in the body of the subject and that on the surfaces of metal, or absorbed by the woodwork, clothing, etc., all of which are liable to changes in weight; and since the water on the coat of the subject can not be differentiated from the same weight of water in the body of the subject, it is therefore necessary to know not only the changes in weight of the body of the subject, but also the changes in weight of the bedding, absorber system, etc. Only by knowing these variations in weight can the

changes taking place in the water content of the body be stated accurately. It is evident further that inasmuch as it is impossible to distinguish between water in the body of the subject and the water on the bedclothes, it is useless to weigh the bedclothes any more accurately than the weight of the man's body can be obtained, and also useless to provide for the weighing of the bedclothes if the man's body can not be weighed.

In the earlier experiments we endeavored to weigh the subject by means of a platform balance; but though the balance was extremely sensitive when standing on the laboratory floor, it was found that when placed inside of the calorimeter chamber the inequalities of the floor surface were such as to make accurate weighing practically impossible, though probably the error was not greater than 100 to 200 grams under the most favorable circumstances.

Description of weighing apparatus.—In considering any method for weighing the subject inside the chamber, it was seen that, to be of any value, the weights should be accurate to at least within 5 grams, since 5 grams would correspond to the weight of about 3 liters of oxygen. Furthermore, the weighings must be carried out fairly rapidly, and whatever apparatus was used must be capable of sustaining a weight equal to that of the body of the subject. It was, moreover, deemed highly important to devise a method by which all of the weighings could, if possible, be made outside of the respiration chamber, where the weights could be properly checked by a second observer.

The space between the ceiling of the laboratory and the top of the calorimeter is small, but it was possible, by going to the floor above and cutting through the ceiling, to arrange a platform balance immediately over the center of the top of the chamber. A hole was then cut straight down through both top panels of the calorimeter and through the double wall of the metal chamber, and through this an apparatus was arranged for suspending objects within the chamber from the platform scale. The arrangement of the apparatus is shown in figure 46.

A copper shoulder, threaded on the inside, was securely soldered to the copper wall of the chamber. A long fiber tube was screwed into this wall and thus gave an opening in the wall through which could pass vertically a cord or rod on which the object to be weighed could be suspended. To make the opening continuous to the upper side of the ceiling of the calorimeter laboratory, the fiber tube was lengthened out by screwing a brass tube to its end. This gave a straight opening, 30 mm. in diameter, from the floor above down into the calorimeter chamber. It was well adjusted in a vertical position and thus permitted the suspension of a weight by a rod without having the rod touch the sides of the tube.

In weighing any suspended object, some up-and-down motion is of course necessary. If an equipoise were used, this motion would extend through several inches, but if a platform balance is used, it may be cut down to a small fraction of an inch. Moreover, a series of tests showed that if all lateral motion could be eliminated it was possible to remove the hooks fastened to the under side of the platform and designed to prevent lateral motion and thus materially increase the sensitiveness of the balance.

The balance in use is of the Fairbanks platform type, designated by the manufacturers as a silk platform scale. It is graduated to 10 grams and has a capacity of 150 kg. It was put in place exactly over the opening through the floor down into the calorimeter, carefully leveled by placing thin strips of copper under each of the corners, and was rigidly fixed in this position. A hanger was constructed of half-inch pipe, and a quarter-inch rod attached to the lower part of the hanger extended through the opening into the calorimeter. On the lower end of this rod was attached a rubber stopper for closing the opening when the weighing is completed, and a stout iron ring into which various supports for weighing the man and other objects could be hooked. The adjustment of the balance and this tube were such that the rod swung freely, and even with considerable vibration on the lower end would not touch the sides of the tube.

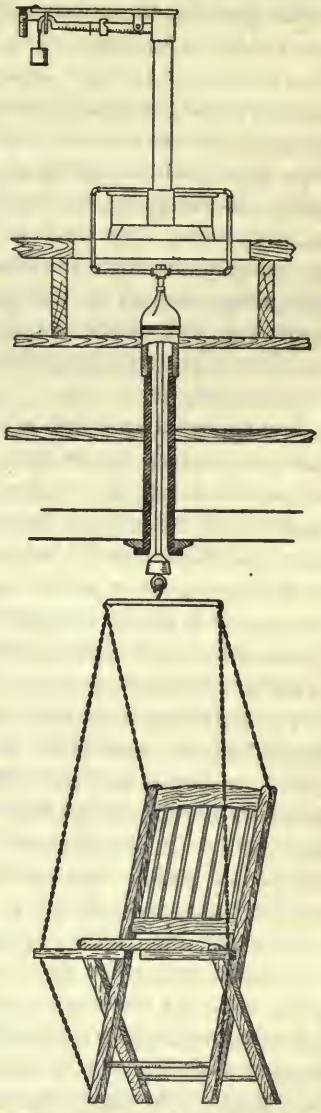

FIG. 46.—Weighing Apparatus for Objects Inside the Chamber. A chair is suspended on a rod extending from top of calorimeter chamber. A metal yoke is hung over the platform of balance, so that chair and subject can be weighed directly. A rubber diaphragm prevents escape of air.

The same conditions affecting the opening through the food aperture as regards necessity for preventing leakage of heat or air obtained in making this opening through the calorimeter chamber. The leakage of heat was prevented by using

the fiber tube, which is an excellent non-conductor of heat. To prevent the leakage of air, we at first used a thin rubber balloon with a small opening in one end so that the rod could pass through it, the balloon being tightly tied to the rod and attached to the tube. It was thus possible to provide for not only the necessary up-and-down motion, but also a slight lateral motion which would accompany the weighing and at the same time prevent any loss of air from the system. Later, thin-walled rubber tubing of large diameter was substituted. This thin rubber diaphragm prevents the escape of air; but it is necessary to rely on this closure only during the actual period in which the weighings are being made, since the flexibility of the diaphragm is such as to allow the rubber stopper on the lower end of the suspension rod to be raised about 1.5 cm., which is sufficient to crowd it well into the open end of the fiber tube, thus completely shutting off the tube from the calorimeter chamber proper.

The rubber diaphragm is so light that the slight vertical motion produces no variation in weight. The extreme sensitiveness of the platform balance under these conditions makes it possible to read not only the graduations on the scale-beam, which are made in 10-gram divisions, but also the differences in height at the end of the scale-beam itself. A small metal pointer is attached to the end of the scale-arm and a millimeter scale is placed immediately behind it in such a manner that, during the progress of weighing, the pointer moves over the millimeter scale. A certain arbitrary point is taken on this scale as the zero point. The finer weighings are made by means of a second hanger, which is very much smaller, consisting practically of a stout piece of copper wire, which is of such a weight that moving it through a section of the graduated beam corresponding to 200 grams is equivalent to an alteration in weight of 5 grams; and it was found that by its use, even with a weight of 90 kg. suspended from the platform balance, weighings to within 2 grams or even 1 gram could be accurately made.

In using this balance it is necessary only to obtain actual differences in weight, and hence no correction is made for the added weight of the pointer on the scale-arm, the removal of the hooks from the platform balance itself, the weight of the hanger and suspension rod, or of the stopper and ring at the lower end. The actual weight of the man can be obtained, however, since two series of weighings are made, one in which the man, bedding, clothing, etc., are weighed with the man sitting in the chair, and one in which only the chair plus bedding and clothes are weighed. The difference between these two weights obviously gives the weight of the man himself.

To support the man in a comfortable position while being weighed, we have provided a chair which can be suspended from the rod of the weighing apparatus. A hard-wood folding-chair, which has been in use regularly inside the chamber for a number of years, was utilized for this purpose. This is shown in figure 46.

A chain (or at present a phosphor-bronze tiller rope) is fastened to the back of the chair and to the legs in such a manner that it can be suspended. To spread the rope at the front end of the chair seat, two oak blocks through which the rope passes were hinged under the seat. A piece of gas-pipe with a hook serves to suspend the chair and act as a spreader at the top. By using this spreader arm more space is given between the chains for the arms and shoulders of the subject. The chair is hooked into the spreader arm in such a position that during the weighing the subject faces the window.

The upper end of the suspension rod for the weighing system passes through a hole in the hanger on the platform balance. Two nuts are screwed on the end of the rod, the upper one of which serves as a lock-nut. It is thus possible to raise or lower the rod by adjusting these two nuts. The rod is so adjusted that when the rubber stopper is removed from the fiber tube it swings perfectly free, and there is no danger of touching the side of the fiber tube. When the stopper is put in place, the suspension rod slips freely up through the hole in the hanger, and the friction of the rubber stopper in the fiber tube holds the rod up in place. It has been found by experience that the taper on the stopper is such that it can be inserted in the fiber tube and support the rod above it without any danger of slipping out. When not in actual use for weighing, the stopper is always crowded well into place.

On the end of the suspension rod there is simply a large iron ring, and it was found inconvenient to suspend everything from this ring without any intervening adjustment; consequently a hanger consisting of a regular gas-fitter's cross was attached. Into opposite sides of two of the openings in the cross two half-inch pipes (16 mm. internal diameter) are screwed. These pipes are 14 cm. long, are open at the end, and have a 7 mm. hole drilled on the under side 8 mm. from the open end. A stout iron hook is screwed into a hole drilled in the side of the cross, and can be inserted in the ring on the end of the suspension rod. When suspended in this way, the cross lies parallel to the top of the chamber. In the other two arms of the cross, reducers and smaller pipes 18 cm. long and 10 mm. internal diameter are screwed and are used for suspending the absorbing system.

Weighing the absorbing system.—In weighing the absorbing system as was formerly done by the use of spring balances, the accuracy was not

at all comparable with the precision obtainable in weighing with the system just described. Arrangements were accordingly devised so that the absorbers could be weighed by this system.

The bulk of the weight of the absorbing system is borne by three equipoises, one of which is shown in figure 33. These three points of support prevent any great lateral motion of the system. The system is suspended by attaching eighth-inch iron pipe (3 mm. internal diamter) to the pipes in the hanger and thence to the absorbing system. A piece of stout copper wire was wound about the upper coil of pipe in the absorbing system at the rear of the chamber so as to form a loop. The 3 mm. pipe was slipped through one end of this loop and the other end into the pipe of the hanger. Two similar loops of stout copper wire were attached to the absorbing system near the front on both sides about 42 cm. from the corner. A long T was then made of three pieces of the 3 mm. pipe, the two arms of the T were slipped through these copper loops, and the stem of the T inserted in the pipe in one arm of the cross or hanger. When the shields were lowered to such a point that their weight rested on the copper disks, the lead counterpoises were raised from their position and the whole system became suspended on the central suspension rod of the weighing system. Owing to variations in the amount of water condensed on the surface of the different portions of the absorbing system, it became necessary to balance the system in such a manner that the three lead counterpoises and equal beams should be in an approximately level position and clear of the absorbing system. This balancing was done by shifting two lead weights provided with hooks in the top, which could be hung on the 3 mm. pipe used to support the absorbing system. After a little practice the subject could slide the weights along these pipes and bring the whole system into equilibrium very rapidly. When in equilibrium an observer outside signaled the assistants stationed at the balance overhead and the weighing was made.

Owing to the multiplicity of bearings of the three equipoises, the degree of accuracy obtained when weighing the man was not to be expected. It was found, however, that when the adjustments were properly made, differences in weight of the absorbing system of 1 or 2 grams could be accurately determined. Thus we have a method for noting changes in weight of the absorbing system that is as accurate as could be desired, for it is more than probable that the amount of moisture condensed on the surface of the calorimeter, the bicycle ergometer, the telephone, connecting wires, etc., sometimes amounts to 1 or 2 grams, and hence weighings closer than this would have no significance.

Before weighing the absorbing system, it is necessary that the subject draw off all drip water that can be removed from the cans at the corners of the absorbing system. It is absolutely essential that no considerable amount of water remains in the aluminum shield. It occasionally happens that the outlet pipe from the shield becomes clogged with dirt or dust, and the drip water, instead of running directly into the cans, accumulates in the shield itself. Under these conditions, when the subject attempts to adjust the absorbing system for weighing, the water will flow back and forth from one end of the absorber to the other end and thus produce a constantly changing weight that can not be properly estimated.

After the weighing is completed, the observer outside raises the lever-arm until the flexible cable begins to raise the shields, thus removing a portion of the weight of the absorbing system. The lead counterpoises then settle into position and the subject can remove the pipes used to suspend the absorbing system. After removing the cross, the rubber stopper can be re-inserted in the fiber tube.

Routine of the weighings.—Since the experimental day begins at 7 o'clock in the morning, it is desirable to have the weight of the subject, bedding, and furniture at this hour every day ; consequently the following routine was utilized in the later experiments of 1904 : The subject was called at 7 a. m. He immediately rose, and, having slept in underclothing and socks, no change in clothing was made. He then rolled up the bedding, fastened the bed to the side of the wall, suspended the chair in which he was to be weighed from the iron hook in the end of the suspension rod, and, taking all the bedding and clothing in his lap, sat in the chair. By means of a speaking tube and an electric bell connected with the closet upstairs in which the balance is placed, a signal was given, whereupon two observers upstairs brought the balance to equilibrium and the actual weight was recorded by both. The subject was then signaled to get up from the chair, and he immediately placed all the clothing (save that which he was actually wearing) and the bedding in the chair. This weighing was made, followed by the adjustment and weighing of the absorbing system.

It is thus seen that the most rapidly fluctuating weight, *i. e.*, the weight of the man, was made first, almost immediately after 7 o'clock. The weight next most liable to fluctuate, *i. e.*, that of the bedding and of the clothing, was made a few moments later, and the absorbing system, which it is supposed would fluctuate in weight the least, especially at this hour of the day, was not weighed until the last.

The necessity for weighing the man as soon as possible after 7 o'clock is seen when it is considered that there is a loss in respiration and per-

spiration amounting to not far from 1 to 2 grams per minute, and hence it was our effort to have the weight of the man recorded at exactly the same moment after 7 o'clock. Theoretically, inasmuch as the quantities of carbon dioxide and water vapor in the air are determined precisely at 7 o'clock, the three weighings should be made at exactly this hour; but, as a matter of fact, this was distinctly impracticable, and we believe that the routine here employed gives results that are not far from correct. With a subject who had never been inside the chamber before, this routine of weighing man, then chair plus bedding, then absorbing system, took not far from 10 to 12 minutes each morning.

Checks on the accuracy.—This method of weighing was very carefully checked by weighing the subject in the chair and then placing several brass weights in his lap. It was found that, allowing for the slight loss from perspiration and respiration, the gain noted by the observers on the platform balance above corresponded exactly to the weights added. The accuracy of the weighing of the absorbing system was determined in a similar way. A small wire basket was constructed so as to hang directly from the hanger itself or in any position on the trough, and thus correspond to varying quantities of moisture. By placing weights in the basket in different positions, the accuracy and sensitiveness of the whole system could thus be easily tested. Frequently weights were placed on the lead counterpoises, and the apparent loss of weight of the system, as detected on the platform balance, always agreed very satisfactorily with the weights thus added.

It seems fair to assert, therefore, that it is possible to weigh a man, his bedding and clothing, and the absorbing system to within 5 grams, if not less, and thus the weighing of these objects is now sufficiently accurate to serve as a check on the oxygen determinations. Indeed, it is not impossible that the indirect determination of oxygen by this means may ultimately take the place of the direct method now employed.

THE ERGOMETER.

Many problems in metabolism require for proper study a knowledge of the external muscular work performed by the body. The utilization of the various nutrients as sources of muscular energy, the isodynamic replacement of the nutrients in diets for muscular work, and the efficiency of the body as a machine may be mentioned as among the problems of this nature. Considerable attention has therefore been devoted by investigators to securing an accurate measurement of external muscular work.

The first method used in connection with the experiments with the respiration calorimeter consisted of raising and lowering a weight by

To face page 164.

FIG. 47.—The Bicycle Ergometer. The rear wheel of a bicycle is replaced by a copper disk which can be rotated in the field of a magnet. The strength of the magnet can be varied by the quantity of electricity passing through the field coils. The principle is that of the electric brake.

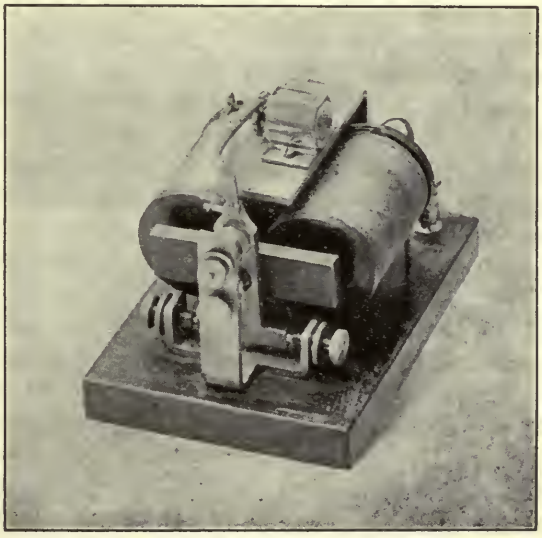

FIG. 48.—The Electric Counter. An armature which is attracted by two magnets is caused to actuate the ratchet on a revolution counter. The instrument is connected electrically with the bicycle ergometer.

means of a cord over a pulley, though the still cruder means of filing a given weight of iron filings from a piece of cast iron was used in one of the preliminary experiments. In both of these methods obviously but very crude estimates as to the actual amount of external muscular work performed could be made. As measures of relative rather than absolute amounts, they were less objectionable, but at best they were far from the accuracy that has been striven for in the development of the respiration calorimeter and its accessory apparatus.

It was observed that the greatest amount of work, with the minimum fatigue, could be performed on a bicycle, and accordingly an ergometer was constructed in which a pulley attached to the armature shaft of a small dynamo was braced against the rear tire of a bicycle wheel.[1] This instrument could be calibrated but roughly, to be sure, but did, however, serve its purpose in the transitional period during which the bicycle ergometer described beyond was in process of development.

Retaining the bicycle form so that the bulk of the work is done by the powerful leg muscles, the present ergometer consists of an arrangement for rotating a heavy copper disk, corresponding to the rear wheel of a bicycle, in the field of an electro-magnet, which thus gives the effect of an electric brake. The apparatus is shown connected ready for use in figure 47.

The principle is the well-known one of magnetic induction. A current of electricity is passed through the field coils of the magnet, and when power is applied to the pedals of the wheel and transmitted to the revolving disk, it is transformed into heat. To calibrate the apparatus, it is put inside the respiration chamber in such a way that the axle of the wheel is connected to a shaft which passes through the food aperture and is revolved by power applied outside. The rate of revolution is shown by a cyclometer. The strength of the magnet is determined by the electric current through the coils, which is measured. With a given strength of magnetization the power applied to the pedals and consequent heat generated will vary directly as the speed of revolution; the heat is therefore measured for different rates of speed. The data thus obtained show the amounts of energy transformed per revolution with the given magnetization. The mechanical friction in the ergometer per revolution is constant and included in the calibration. Accordingly, when the man is working on the ergometer, the number of revolutions as recorded by a cyclometer multiplied by the energy per revolution gives the muscular work done at the pedals. We believe the measurements are accurate within a fraction of 1 per cent. The apparatus has proved very satisfactory.

[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 136, p. 31.

The number of revolutions of the pedal of the ergometer is recorded on the observer's table by the cyclometer shown in figure 48, which is designated as the Dinsmore electric counter, since it was devised by our mechanician, Mr. Dinsmore.

This instrument consists of an electro-magnet and armature, the latter having a projection which extends to the ratchet wheel of the cyclometer. A device on the crank wheel of the ergometer closes a circuit to the magnet at each revolution, and thus actuates the armature.

Correction for the magnetization of the fields of the ergometer.—In work experiments with the ergometer a correction of the heat measured by the calorimeter is necessary because of the heat added to the chamber in magnetizing the fields of the ergometer. The amount of heat thus added varies with the strength of current.[1] For the strength generally employed, namely, 1.25 amperes, it amounts to 10.94 large calories per hour, which is accordingly deducted from the heat measured.

Blanks used for Heat Records.

A specimen page from the calorimetric records, showing the printed blank in use in the heat calculations, with observations for a portion of an actual experiment recorded therein, is given on page 167. For a clear understanding of this sheet, reference to figure 43 is also necessary.

It will be noted that at the top of the sheet are recorded the date, the number of the experiment, and the name of the observer. Then follow ten vertical columns, in which are inserted the various readings for one hour. A space at the bottom of the sheet allows for further observations if necessary.

In the first vertical column is inserted the time of each reading. It is so arranged that these may be recorded every two minutes, though as a matter of fact it has been found that in ordinary rest experiments four-minute readings are sufficient, except at periods of increased bodily activity, as at 7 a. m., when the subject is dressing and carrying out the somewhat extensive routine elsewhere outlined. At such times certain readings are recorded every two minutes as long as vigorous activity continues.

The second column is headed "Inner walls, No. 1." In this are recorded the deflections produced by pressing down the key marked A L, L, No. 1, in figure 43. The third column gives similar readings for the incoming air current, as shown by key No. 2, and the fourth the deflections for the outer walls, as indicated by the key marked A L, L, No. 3. The readings obtained from these three keys are recorded,

[1] The calculation is made according to the formula $C \times E \times t \times 0.2385 =$ calories. See page 172.

Metabolism Experiment No. 70. H. C. Martin, Observer.

Date, December 20, 1904.

Time. (a. m.)	Inner walls. No. 1. −	Inner walls. No. 1. +	Moving air. No. 2. −	Moving air. No. 2. +	Outer wall. No. 3. −	Outer wall. No. 3. +	Inside temp. No. 5.	Temp. water therm.	Corrected temp.	Difference.	Heat calculations. No. 7.	T	B	Sundries. R	S = 120.
	8½		½					14.24	14.18						
10.00		2		½	1		106½	10.39	10.38	3.80	60	20.3	20.84	31½	
02															
								14.26	14.20						
04		5		1½	½		108	10.29	10.28	3.92	61			31½	Sits up and drinks.
06											68.4 at 10:08:42				
								14.29	14.23						
08		8½		½		5	113	10.24	10.23	4.00	63	45.25 at 4.114		31½	Lies down; reads.
10												10.050 K.			
								14.32	14.26						
12		2½	½			13	116	10.16	10.15	4.11	66			31½	41.35 calories.
14															
								14.51	14.45						
16	4		1			1½	115	10.16	10.15	4.30	66½			31½	
18															
								14.58	14.52						
20	3½		1½			1½	114	10.12	10.11	4.41	66			30½	
22															
								14.60	14.54						
24	1½		1½		1½		112½	10.04	10.03	4.51	65			31	
26															
								14.58	14.52						
28	1½		1½		3½		111½	10.23	10.22	4.30	64½			31½	
30															Telephones.
								14.59	14.53						
32		½		½	6½		110½	10.20	10.19	4.34	63½			31½	Sits up and opens food aperture.
34												19.8	20.87		
								14.68	14.62						
36		6		3½		1½	117½	10.14	10.13	4.49	67			32½	
38															Lies down and reads.
								14.87	14.81						
40		2		½		13	117½	10.14	10.13	4.68	68			33½	
42															
								14.99	14.93						
44	6		3		7		113½	10.21	10.20	4.73	67½			33½	
46															
								15.01	14.95						
48	2½		2		5½		111	10.26	10.25	4.70	65			33½	
50											79.8 at 10:52:38				
								14.76	14.70						
52		1½	1		5½		110½	10.26	10.25	4.45	64½	49.02 at 4.456		33½	
54												10.102 K.			45.01 calories.
								14.57	14.51						
56		1½		2½	1½		110	10.32	10.31	4.20	63			34½	
58															
	27½	29½	12½	10½	.....	.....	.....	.....	.....	.....					

REMARKS:

if positive, on the right-hand side of their respective columns, under the sign +, and if negative, on the left-hand side, under the sign —. As has been explained, the deflections should with each key be as near zero as possible. This is especially necessary with Nos. 1 and 2. At the end of each hour the sum of the readings in each of these columns is taken, and the difference between the sums carried over to the following sheet, to be compensated for if possible during the next hour.

The fifth column is headed "Inside temp., No. 5." In this are recorded the deflections with key No. 5, which represent the temperature just inside the copper walls as measured by the electrical thermometer described on page 135. This temperature is held as nearly uniform as practicable.

The three columns following are used for recording the temperature of the incoming and outgoing water current. That headed "Temp. water therm." gives the readings of the mercurial thermometers, that in the outgoing water current being recorded above with the corresponding reading of the incoming water current immediately below. In the next column are the readings as corrected for the calibrations of the thermometers (see p. 133). The column headed "Difference" contains the differences between the corrected readings for the incoming and outgoing water current, or, in other words, the rise in temperature of the water current.

In the column headed "Heat calculations" are recorded various miscellaneous data. The left-hand margin contains the readings with key No. 7, the electrical thermometer connected with the copper walls and showing their temperature. Readings of T, the mercurial thermometer just outside the window, and of B, the mercurial thermometer inside (see p. 120), are also taken from time to time and recorded in this column. Whenever one of the cans on the water-meter is full, the reading of the dial, together with the time, expressed in hours, minutes, and seconds, is recorded; for example, 79.8 at 10 o'clock 52 minutes 38 seconds. Just below this is written the sum of all temperature differences while the can was filling. This sum divided by the number of readings gives the average rise in temperature of the water in the can. For example, the sum of 11 readings was 49.02, the average of which was 4.456. This value, multiplied by the weight of the water as determined from a plotted curve for the point corresponding to the figure registered by the dial (see p. 132), gives the heat in calories brought out from the calorimeter system for the period of time. This value is recorded in the last column (45.01 calories).

The final column, marked "Sundries," also serves for miscellaneous data. When the rectal thermometer is in use, its readings

are here recorded under the designation R. Occasional readings of S, giving normal or standard deflections of the galvanometer, are here given, and any additional observations of the assistant, particularly as to the movements of the subject, are here briefly stated.

The heat sheet therefore serves as a source of original data regarding the gain or loss of heat through the walls, the maintenance of constant temperature, the estimation of the heat brought away by the water current, the body temperature, and the more important movements of the subject.

TESTS OF THE ACCURACY OF THE HEAT-MEASURING APPARATUS.

For testing the accuracy of the calorimetric features of the apparatus two special forms of test have been devised. In one a definite amount of heat is generated inside the chamber by means of the passage of an electric current through a known resistance. Knowing the strength of current and the fall of potential, it is possible to calculate accurately the quantity of heat thus developed and compare it with that brought away by the water current. These tests are called electrical check experiments.

A second test is obtained by burning known weights of ethyl alcohol inside the calorimeter and measuring the energy thus produced. From the weight of the alcohol and the heat of combustion as determined by the bomb calorimeter it is possible to compute the amount of heat which theoretically should be developed and compare it with that brought away by the water current. These are called alcohol check tests.

ELECTRICAL CHECK TESTS.

The development of a known amount of heat by means of the electric current necessitates an accurate knowledge of four factors: First, the strength of current; second, the fall of potential; third, the time in seconds, and fourth, the factor for the conversion of electric units to that of heat. Of these four factors we have to consider only those of the strength of electric current, fall of potential, and the conversion factor. The strength of the current in these experiments was determined by passing it through a milli-ammeter, which was especially calibrated for us by the Weston Electrical Instrument Company, of Newark, New Jersey, and guaranteed by them to give readings within 0.1 per cent. In this instrument the maximum current that could be measured was 1.5 amperes. The instrument has been compared from time to time with a Kelvin balance with no noticeable variations in accuracy.

The fall in potential is measured by an accurate voltmeter, constructed by the same company, with an accuracy guaranteed to be within 0.1 per cent. The maximum voltage that can be read on this instrument is 150. The accuracy of this instrument has been frequently tested by comparison with a standard Weston voltmeter.

The electrical connections are shown diagrammatically in figure 49.

The present arrangement consists of a 100-ohm resistance coil of German-silver wire wound on a wooden frame and suspended within the chamber. This coil is capable of carrying a current of 1.5 amperes.

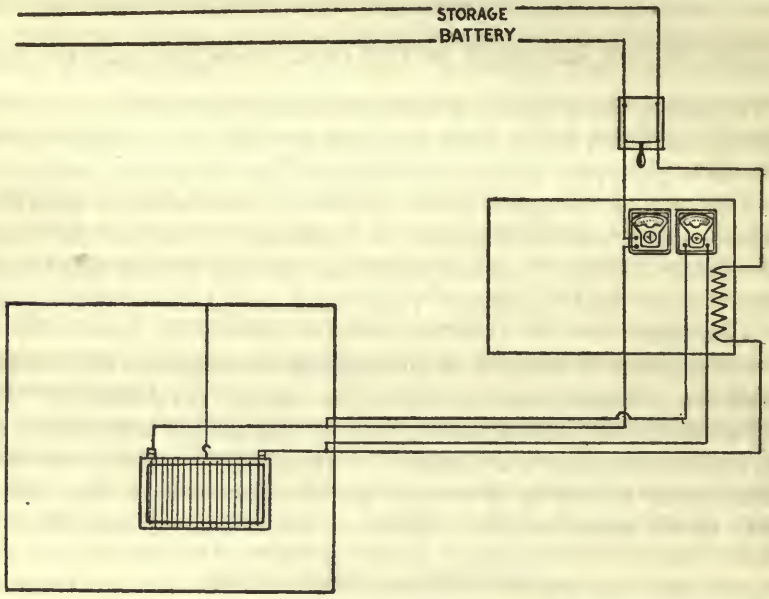

FIG. 49.—Connections for Electrical Check Experiment. An electric current from a storage battery is passed through the ammeter and then through a coil hung in calorimeter chamber. By means of a variable resistance the strength of current can be kept constant. A voltmeter gives the fall of potential.

Connections are made with the milli-ammeter on one side and with a switch connected with the storage battery on the other side. The milli-ammeter is also connected with a switch. Two wires connect the voltmeter with the coil inside the chamber, and thus the fall of potential as the current passes through the coil is accurately measured. The current from the storage battery therefore passes in series through the milli-ammeter, the coil inside the chamber, and then through a variable resistance back to the switch. By varying this resistance, the strength of current passing through the coil can be adjusted with great accuracy. Both electrical instruments can be read with a magnifying glass to 1

part in 1,000. A sufficient number of cells of storage battery are employed to give a strength of current through the coil of about 1 ampere with a voltage of about 120.

Electrical Unit Used.

In the fall of 1904, in a discussion of the accuracy of the bomb calorimeter[1] used in connection with these experiments, it was pointed out by Dr. L. J. Henderson, of Harvard University, that the heat of combustion of standard materials such as naphthalene, benzoic acid, and cane sugar were noticeably different when determined by the bomb calorimeter used at Wesleyan University and when determined by the bomb calorimeter used by Fischer and Wrede.[2] The calorimeter used by these writers was standardized by Jaeger and von Steinwehr[3] by an electrical method in which the factor 0.2394 was used to convert watt-seconds to calories.

This matter was referred to Dr. E. B. Rosa, formerly professor of physics in Wesleyan University and at present physicist of the National Bureau of Standards. The following statements are essentially those furnished us by Dr. Rosa.

The values found for the mechanical equivalent of heat by the electrical method differ appreciably from those obtained by the mechanical method. There is reason for believing, however, that the values of the international volt and ampere are about 0.1 per cent too large. This is a subject the Bureau of Standards and others are now investigating, but absolute measurements for determining independently the volt and ampere are difficult to make and the question is not yet settled. Assuming this error in the electrical units, the values of J determined electrically agree very well with Rowland's value determined mechanically, and this is the best value yet obtained by the mechanical method.

The most probable value for J (assuming the correction of 0.1 per cent in the electrical units) is

$$J = 4.181 \times 10^7 \text{ ergs. at } 20°.$$

Allowing for the variation in the specific heat of water, the heat required to raise the temperature of a gram of water 1° at 10° would require $4.181 \times 10^7 \times 1.0030 = 4.1935 \times 10^7$ ergs.

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[1] For a description of the form of bomb calorimeter here used see Jour. Am. Chem. Soc. (1903), **25**, p. 659.

[2] Sitzungsber. K. Akad. Wiss. (1904), pp. 687–715.

[3] Verhandlungen ber. deut. phys. Gesell. (1903), **5**, 2, pp. 50–59.

The energy of an electric current is $CE\ell \times 10^7$ ergs., and this expressed in calories at 10° is

$$\frac{CE\ell \times 10^7}{4.1935 \times 10^7} = CE\ell \times 0.23846 \text{ calories.}$$

But this is on the assumption that our electric units are 0.1 per cent too small. Since we are using these same small units in our work, it is evident that the numerical values of C and E are both too large by this amount, and therefore the product too large by 0.2 per cent. This gives $0.23846 - 0.00048 = 0.2380$ as the true conversion factor.

We can reach the same result by taking the mean of the results for the mechanical equivalent of heat obtained by Griffiths (4.192), Schuster and Gannon (4.189), and Callendar and Barnes (4.186) without correction for the supposed error in the electrical units. The mean of these three values is $J = 4.189 \times 10^7$ at 20°. Correcting this to 10°, we have, multiplying by 1.003 as before, $J = 4.2016 \times 10^7$ at 10°. Then

$$\frac{CE\ell \times 10^7}{4.2016 \times 10^7} = CE\ell \times 0.2380, \text{ as before.}$$

Thus no account need be taken of the supposed error in the electrical units, inasmuch as the three English investigators above quoted all used substantially the same electrical units that are now used in Middletown. This value (0.2380) is slightly different from that used earlier[1] (0.2378), because the latter is based on Griffith's value, which is somewhat larger than the mean of the three used in this calculation.

To compare this with the value given by Fischer and Wrede, it is necessary to reduce to 15° and to correct for the difference between our electrical units and those used in Germany. The first correction amounts to 0.0019, giving $0.2380 \times 1.0019 = 0.23845$. The second amounts to

$$\frac{24}{14340} = 0.0017.$$

Thus $0.23845 \times 1.0017 = 0.23885$, which is the proper value at 15° to use in Germany; that is, with German electrical units.

A value as large as 0.2394 can not, in the light of the most recent work, be justified.

As used by Jaeger and von Steinwehr it was apparently taken from the values given by Graetz.[2]

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[1] U. S. Dept. of Agr., Office of Experiment Stations Bull. 63, p. 43.
[2] Winkelmann's Handbuch der Physik, **2**, 2, p. 415.

Graetz quotes the results obtained by Joule, Rowland, and Miculescu. The more recent investigations of Griffiths, Schuster and Gannon, and Callendar and Barnes are not given. Joule's value for J is a little smaller than Rowland's and the recent values found by the electrical method. Graetz takes the mean of the three values quoted, and the lower value of Joule's result makes the mean a little lower, namely, 4.177×10^7 at 15°. The reciprocal of this is 0.2394, the value used by Jaeger and von Steinwehr and Fischer and Wrede.

According to Dr. Rosa, the best principle would be to use the number 0.2385 at 15° and then correct the number of gram-degrees measured to calories at 15° by multiplying by the ratio of the specific heat at the given temperature to that at 15°.

The importance of the electrical unit and conversion factor in connection with the experiments with the respiration calorimeter is seen when it is considered that, given accurate electrical units and factors, it is possible to verify the bomb calorimeter by the respiration calorimeter. By burning alcohol in the bomb calorimeter a certain heat of combustion is obtained, and if the alcohol is then burned in the respiration chamber, which has been calibrated and standardized by the electrical method, obviously the same heat of combustion determined by both forms of calorimeter is a verification of the bomb.[1]

It is furthermore significant that the difference between the heat of combustion of cane sugar, naphthalene, benzoic acid, and other standard materials, when determined by the bomb calorimeter used in Middletown and when determined by Fischer and Wrede, is exactly proportional to the difference between the two conversion factors used. Pending a revision of the electrical units by the National Bureau of Standards, we use here the factor 0.2385 for converting watt-seconds to calories at 15°.

Length and Duration of Experiments.

After the coil and connections are properly installed inside the chamber the switch is closed, and the water current passing through the heat-absorbers is regulated so that the heat is brought away at the same rate at which it is generated. After an hour or two, during which period the apparatus comes into equilibrium, the experiment proper is begun. The experiment lasts usually from eight to twelve hours, during which time the current is measured by the milli-ammeter and is kept

[1] For a discussion of the verification of the bomb calorimeter by the respiration calorimeter see Atwater and Snell, Jour. Am. Chem. Soc. (1903), **25**, p. 698.

constant by means of the variable resistance. Readings on both electrical instruments are taken frequently to insure complete accuracy. At the end of the period the time in seconds is noted and the average reading of the instrument taken. The formula for computing the amount of energy developed during the experiment is therefore $C \times E \times t \times 0.2385 =$ calories, in which C is the strength of the current in amperes, E the fall of potential in volts, and t the time in seconds.

Results of Electrical Check Experiments.

The last electrical check experiment made with the apparatus was on November 22, 1904. The actual period of measurement extended from 1.06 p. m. to 10.04 p. m., or 8 hours and 58 minutes. During this period there was a current of 0.950 ampere passed through the coil and a fall of potential of 99 volts. By using the formula given above, the heat generated during this period was computed to be 723.7 calories. The heat measured during this period by the respiration calorimeter was 721.73 calories, or 99.72 per cent of that generated. A test conducted a month before gave the ratio of heat measured to that generated corresponding to 99.59 per cent. It thus appears that the apparatus measures heat developed within it electrically with great accuracy.

THE COMBUSTION OF ETHYL ALCOHOL AS A CHECK ON THE HEAT MEASUREMENTS.

Although the electrical check experiments are carried out with great accuracy, they still do not permit of the testing of the apparatus under conditions approximating those in which it is used in actual experimenting, and obviously the question of the heat of vaporization of water plays no rôle in the electrical check experiment. As early as 1779, Crawford[1] endeavored to study the accuracy of the heat measurements of his calorimeter by burning known weights of charcoal, lamp oil, wax, and tallow inside the chamber. Subsequent experimenters have used hydrogen, stearin candles, ether, and other substances. As a result of a large number of experiments in which a number of different combustibles were tried, we have relied upon the combustion of ethyl alcohol of known water content for this purpose. Inasmuch, however, as the combustion of ethyl alcohol inside the chamber results not only in an evolution of heat, but also of carbon dioxide and water, and in the absorption of

[1] Experiments and Observations on Animal Heat; see also Zeits. f. Biol. (1894), **30**, p. 76.

oxygen, the combustion of alcohol is also used to check the accuracy of the respiration apparatus. Such experiments, as well as the kind of alcohol used and determination of its specific gravity, have already been considered in detail (see pp. 96–105).

For the purpose of checking the apparatus as a calorimeter, a knowledge of the heat of combustion of the alcohol used is essential.

Heat of Combustion of Alcohol.

For the determination of the heat of combustion we resort to direct combustions in the bomb calorimeter. A large number of such combustions have been made in this laboratory. Since absolute alcohol absorbs water rapidly from the air, we have prepared aqueous solutions of varying degrees of strength for use in these tests.

A known weight of alcohol is placed in small gelatin capsules, such as are used frequently for the administration of medicine. When gelatin capsules are used there is no loss by volatilization, and as the heat of combustion of the gelatin is quite constant (about 4.452 calories per gram) the absolute amount of heat introduced with the alcohol can be determined with considerable accuracy. The capsules weigh not far from 0.3 gram, thus introducing about 1.3 calories.

Inasmuch as in the combustion of alcohol a certain portion of the oxygen combines with the hydrogen of the alcohol to form water, which is condensed inside the bomb, the gas in the bomb is at a somewhat less pressure at the end than at the beginning of the combustion. The slight expansion of the residual gas, as a result of a diminished pressure, produces a cooling effect, and the heat of combustion of the alcohol must be corrected for constant pressure. It is necessary, therefore, to add to the heat of combustion of the alcohol a certain factor which is obtained in the following manner: To reduce the molecular heat of combustion of a solid or liquid, the formula of which is $C_nH_pN_rO_q$, from that at constant volume to that at constant pressure, a correction would be added of $(\frac{1}{2}p - q - r)T$ calories, where T equals the absolute temperature of the calorimeter.[1] To reduce the specific heat of combustion at constant volume to that at constant pressure, the amount to be added is, therefore, $(\frac{1}{2}p - q - r)\,T \div M$, where M equals the molecular weight of the substance. For alcohol this correction amounts to 13 calories per gram. The corrected heat of combustion of anhydrous ethyl alcohol is taken in this discussion as 7.080 calories per gram.

[1] For discussion of this point see Atwater and Snell, Jour. Am. Chem. Soc., **25**, 1903, pp. 690, 691.

Results of Alcohol Check Experiment.

As has been stated, the combustion of known amounts of ethyl alcohol inside the respiration chamber furnishes the means for verifying the accuracy not only of these portions of the apparatus which have to do with the measurement of the respiratory products, but also of the heat-measuring features. Consequently, instead of discussing the check on the heat determinations as a separate section, a summary of the alcohol check experiment in its relation to the determination of water, carbon dioxide, and oxygen as given on pages 102–105 is included in Table 4, with the data on the determination of energy.

Table 4.—*Summary of Determinations of Water, Carbon Dioxide, Oxygen, and Energy.*

Alcohol check experiment, April 6–7, 1905.

Period.	Duration.		Alcohol burned.	Water.			Carbon dioxide.		
				Found.	Required.	Ratio.	Found.	Required.	Ratio.
	Hrs.	*Mins.*	*Grams.*	*Grams.*	*Grams.*	*Per cent.*	*Grams.*	*Grams.*	*Per cent.*
First.....	3	54	73.4	86.51	84.98	101.8	126.70	127.32	99.5
Second.....	5	44½	108.1	124.33	125.15	99.3	187.39	187 51	99.9
Third.....	11	52	225.3	263.15	260.83	100.9	392.10	390.81	100.3
	21	30½	406.8	473.99	470.96	100.6	706.19	705.64	100.1

Period.	Duration.		Alcohol burned.	Oxygen.			Energy.		
				Found.	Required.	Ratio.	Found.	Required.	Ratio.
	Hrs.	*Mins.*	*Grams.*	*Grams.*	*Grams.*	*Per cent.*	*Calories.*	*Calories.*	*Per cent.*
First.....	3	54	73.4	139.35	138.90	100.3	417.86	421.40	99.2
Second.....	5	44½	108.1	207.09	204.56	101.2	619.03	620.61	99.7
Third.....	11	52	225.3	431.09	426.33	101.1	1,292.97	1,293.45	100.0
	21	30½	406.8	777.53	769.79	101.0	2,329.86	2,335.46	99.8

This experiment, a fair sample of a large number of the sort, gives a true test of the apparatus in all its phases. The determinations of energy are as satisfactory as could be expected, averaging 99.8 per cent of the required amount. The summarized results for the determination of water, carbon dioxide, and oxygen show that the apparatus is sufficiently accurate to determine these three factors as well as the energy with an accuracy approaching that of the most approved methods of chemical analysis.

EXPERIMENT WITH MAN.

Obviously with an apparatus constructed on this plan, the final test of its practicability lies in an experiment with man. Since the completion of the new apparatus, 22 experiments with 5 different subjects, covering a total of 60 days, have been conducted. These experiments lasted from 1 to 13 days, during which time the subject remained inclosed in the calorimeter chamber. Ordinarily the experiment lasts 3 or 4 days. In general, each experiment is preceded by a preliminary period outside the chamber, during which the subject is given the special diet to be tested, and his habits of life so modified as to conform with those to be followed in the chamber. When the subject is to be engaged in muscular work, he devotes considerable time in the preliminary days to riding a bicycle in the open air, the amount of work performed being as nearly as can be judged equivalent to that to be done later on the bicycle ergometer inside the chamber. The food for the whole experimental period, including the preliminary days, is carefully weighed, sampled, and daily portions placed in proper containers ready for consumption. The more easily decomposed materials, such as milk and cream, are sampled, weighed, and analyzed each day. The bread and meat when used are carefully sterilized in glass jars. The diet may be so planned as to maintain a uniform quantity of nitrogen and a constant calorific value from day to day.

Measurement of Intake and Output of Material.

In experiments with man as carried out with this apparatus and accessories, the following determinations of intake and output of material are made:

The intake consists of food, drink, and oxygen from respired air. The amounts are determined by weighing. The analyses include determinations of water, ash, nitrogen, carbon, hydrogen (organic), and at times sulphur and phosphorus. The output of material consists of products of respiration and perspiration, urine, and feces. The dry matter of feces and urine is subjected to a series of analyses similar to those for food, and the water and carbon dioxide of perspiration and respiration are determined according to the methods discussed in this report. The determinations of nitrogen in perspiration are made, when necessary, according to methods given elsewhere.[1]

[1] U. S. Dept. of Agr., Office of Experiment Stations, Bull. 136, pp. 52–53.

Measurement of Intake and Output of Energy.

The intake is derived from the potential energy, *i. e.*, heats of combustion of the food. The output consists of sensible heat given off from the body, the latent heat of the water vaporized, and the potential energy, *i. e.*, heat of combustion of the unoxidized portions of the dry matter of urine and feces. In certain cases, *e. g.*, work experiments, a not inconsiderable portion of the output is in the heat equivalent of external muscular work.

As has been stated elsewhere, the heats of oxidation are determined by burning the substances in the bomb calorimeter; the heat given off from the body is measured by the respiration calorimeter; the external work is measured by a specially devised ergometer. Allowance is made for heat introduced and removed by the ventilating air current, food, feces, and urine, and for that involved in changes of body temperature, which is also measured.

Analytical Methods.

The nitrogen is determined by the Kjeldahl method, the carbon and the hydrogen by the modified Liebig method,[1] and the heats of combustion by the bomb calorimeter.[2]

The observers work in relays and all the work is systematized. An elaborate system of checking weights and observations serves to minimize errors or faulty manipulation.

METABOLISM EXPERIMENT NO. 70.

The particular experiment here used as an illustration was not preceded by the customary preliminary period, as it was designed to study metabolism after a period of fasting. The experiment shows the metabolism on the first day after a 5-day fast.

Since it is not the purpose of this report to discuss metabolism in general, but rather to describe the apparatus and methods of calculation, the results for the experimental day are here given mainly in the form of tables.

Subject.

The subject was a young medical student, B. A. S., who had accustomed himself to periods of fasting varying from 3 to 10 days. He was in excellent health, and previous to beginning his fast had lived his usual routine of life.

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[1] Benedict: Elementary Organic Analysis.
[2] Jour. Am. Chem. Soc. (1903), **25**, p. 659.

Food.

On the experimental day here reported, the diet consisted of 1,652.90 grams milk modified by a large proportion of butter fat, and 5 grams of the desiccated milk proteid sold under the trade name Plasmon. In addition to the milk and Plasmon, 139 grams of water were used. These quantities of food furnished 53.31 grams of protein, 211.87 grams of fat, 75.41 grams of carbohydrates, and 2,569 calories of energy.

Routine of Experiment.

The experiment was carried out according to the customary routine established in this laboratory for experiments with the respiration calorimeter. Detailed accounts of this routine have been published elsewhere.[1] Minor, though important, changes in the preparation, sampling, and analysis of the milk and cream have since been introduced to facilitate in accuracy and manipulation.

The feces were separated in the usual way by means of lamp-black capsules, though in experiments either during fasting or immediately following fasting we have experienced great difficulty in securing satisfactory separations. For the want of more satisfactory technique, therefore, we are now in the custom of collecting the total feces for the food period (in this case 3 days), including that passed after the subject has left the respiration chamber, and ascribing an aliquot portion of the feces to each food-day.

The daily routine followed by the subject in the respiration chamber consisted mainly in rising from bed, dressing, eating, care of food and excreta, sitting at a table, reading or writing, and occasionally standing or taking a few short steps. In general, the subject followed pretty closely a definite program previously prepared.

Ordinarily the subject enters the respiration chamber at 11 p. m. on the day before the actual experiment begins. This enables him to become accustomed to the environment, and affords opportunity to secure constant-temperature conditions inside the chamber after a long night's sleep. In this particular case, the subject had already remained in the chamber for 5 days of fasting, so that there was no preliminary period for the food experiment, which began at 7 a. m. From this time to the close of the experiment a careful record was kept of all data for computing the total income and outgo of matter and energy. So far as the measurements of heat, carbon dioxide, water, and oxygen are concerned, the day was, as usual, divided into 12 periods of 2 hours each. It has not been found feasible to make such short separations

[1] U. S. Dept. of Agr., Office of Experiment Stations Bulls. 44, 63, 69, 109, and 136.

of the urine, and consequently the analyses are not made on periods shorter than 24 hours, save in the case of determinations of total nitrogen, which are at times made on 6-hour periods.

Statistics of Food, Feces, and Urine.

In Table 5 the percentage composition of the food materials, feces, and urine are given.

Table 5.—*Percentage Composition of Food Materials, Feces, and Urine, Metabolism Experiment No. 70.*

Lab. No.	Material.	(a) Water.	b Protein.	(c) Fat.	(d) Carbohydrates.	(e) Ash.	(f) Nitrogen.	(g) Carbon.	(h) Hydrogen.	(i) Energy per gram.
		Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Calories.*
3806	Milk	79.14	3.00	12.63	4.59	0.64	0.48	12.86	2.00	1.525
3807	do	78.46	3.[illegible]	13.56	4.35	0.63	0.48	13.50	2.10	1.598
3773	Plasmon	9.80	74.50	0.15	6.88	8.67	11.92	44.21	6.14	4.829
3809	Feces	66.39	3.71	2.78	20.15	6.97	0.59	19.75	3.13	2.447
3815	Urine	96.11	.....	.....	.....	0.44	.....	0.86	0.23	0.100

These values are determined directly in the case of water, fat, ash, nitrogen, carbon, and hydrogen. The protein is obtained from the nitrogen by multiplying by the factor 6.25. The carbohydrates are determined by difference. The heat of combustion per gram is determined by combustion in the bomb calorimeter.

In all cases except that of the feces the materials are analyzed on the fresh basis, *i. e.*, original weights are on the fresh material. The feces of necessity are analyzed after drying.

The total amounts of food, with the quantities of nutrients and energy supplied, are shown in Table 6.

Table 6.—*Weight, Composition, and Heat of Combustion of Food, Metabolism Experiment No. 70.*

Lab. No.	Food material.	(a) Total weight.	(b) Water.	Water-free substance. (c) Protein.	(d) Fat.	(e) Carbohydrates.	(f) Ash.	(g) Nitrogen.	(h) Carbon.	(i) Hydrogen.	(j) Oxygen.	(k) Energy.
		Gms.	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms*	*Gms.*	*Calories.*
3806	Milk	1,320.10	1,044.73	39.60	166.73	60.59	8.45	6.34	169.76	26.40	64.42	2,013
3807	do	332.80	261.11	9.98	45.13	14.48	2.10	1.60	44.93	6.99	16.07	532
3773	Plasmon	5.00	0.49	3.73	0.01	0.34	0.43	0.60	2.21	0.31	0.96	24
	Total	1,657.90	1,306.33	53.31	211.87	75.41	10.98	8.54	216.90	33.70	81.45	2,569

For purposes of further computation the amount of oxygen in the water-free substance of the food is here given, though obviously this is a result of indirect determination.

Similar data for the feces and urine are given in Table 7.

TABLE 7.—*Weight, Composition, and Heat of Combustion of Urine and Feces Metabolism Experiment No. 70.*

	(*a*)	(*b*)	Water-free substance.					
	Total weight.	Water.	(*c*) Ash.	(*d*) Nitrogen.	(*e*) Carbon.	(*f*) Hydrogen.	(*g*) Oxygen.	(*h*) Energy.
	Grams.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Calories.*
Urine	1,031.50	991.37	4.54	13.04	8.87	2.37	11.31	103
Feces	60.97	40.48	4.25	0.36	12.04	1.91	1.93	149

The amount of oxygen in the water-free material is also included in the table for subsequent use.

Summaries of the data for the determination of water, carbon dioxide, and oxygen are given in Tables 8 to 10.

STATISTICS OF WATER ELIMINATED.

The quantities of water exhaled by the subject during each experimental period are calculated from the determinations of the amount of water removed from the ventilating air current and the difference between the quantity remaining in the air inside the apparatus at the beginning and end of the period. These computations are summarized in Table 8.

TABLE 8.—*Record of Water in Ventilating Air Current, Metabolism Experiment, No. 70.*

Date.	Period.	(*a*) Total amount of vapor in chamber at end of period.	(*b*) Gain (+) or loss (−) over preceding period.	(*c*) Change in weight of heat-absorbing system—gain (+), loss (−).	(*d*) Change in weight of chair, bedding, etc.	(*e*) Total amount gained (+) or lost (−) during period. (*b*+*c*+*d*)	(*f*) Total amount in outgoing air.	(*g*) Total water of respiration and perspiration. (*b*+*f*)*
1904.		*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
Dec. 20	5 a. m. to 7 a. m.	36.07	.....	.....	.....	.....	.....	.....
Dec. 20–21	7 a. m. to 9 a. m.	38 74	+ 2.67	.....	.....	.....	71.87	74.54
	9 a. m. to 11 a. m.	39.91	+ 1.17	.....	.....	.....	65.22	66.39
	11 a. m. to 1 p. m.	38.91	— 1.00	.....	.....	.....	67.55	66.55
	1 p. m. to 3 p. m.	41.73	+ 2.82	.....	.....	.....	61.85	64.67
	3 p. m. to 5 p. m.	36.93	— 4.80	.....	.....	.....	68 95	64.15
	5 p. m. to 7 p. m.	37.76	+ 0.83	.....	.....	.....	69.70	70.53
	7 p. m. to 9 p. m.	37.28	— 0.48	.....	.....	.....	65.96	65.48
	9 p. m. to 11 p. m.	37.23	— 0.05	.....	.....	.....	66.26	66.21
	11 p. m. to 1 a. m.	39.97	+ 2.74	.....	.....	.....	69.30	72.04
	1 a. m. to 3 a. m.	46.06	+ 6.09	.....	.....	.....	84.41	90.50
	3 a. m. to 5 a. m.	39.71	— 6.35	.....	.....	.....	76.55	70.20
	5 a. m. to 7 a. m.	33.18	— 6.53	.....	.....	.....	70.31	63.78
	Total	.....	— 2.89	— 2.00	+ 5.26	+ 0.37	837.93	*838.30

*The total for this column is the sum of (*e*) + (*f*).

The quantity of water removed from the air current during each period is determined by weighing the water-absorbers at the beginning and end of the period. The values thus found are expressed in column (*f*). The quantity of water in the air remaining in the chamber at the end of each period is learned by analysis of a sample of the air. These determinations are given in column (*a*). The increase or decrease in the quantity of vapor residual in the air for each period, which is simply the difference between the quantity at the end of one period and that at the end of the next, is given in column (*b*), an increase being indicated by + and a decrease by —.

The quantity of water exhaled by the subject during each period, shown in column (*g*), is the algebraic sum of the quantities in columns (*b*) and (*f*). If the value is indicated by + in column (*b*) it is added, because it represents an excess that has been added by the subject during the period; it is subtracted when the sign is —, because that means that the absorbing apparatus has removed from the air so much more than was exhaled by the subject.

As a result of the variation in hygrometric conditions inside the respiration chamber, there may be a noticeable change in the amount of moisture deposited upon the bedding, clothing, etc., of the man and also upon the heat-absorbing system. In general, this latter is negligible in the case of the rest experiments, such as experiment No. 70 reported here. On the particular day here given there was a loss of weight in the heat-absorbing system amounting to 2 grams, and an increase in weight of the chair, bedding, etc., of 5.26 grams. These are recorded in columns (*c*) and (*d*), Table 8. In column (*e*) the algebraic sum of (*b*), (*c*), and (*d*) is given. Obviously, for the entire day the total water of respiration and perspiration is the algebraic sum of (*e*) and (*f*) and not of (*b*) and (*f*).

Statistics of Carbon Dioxide Eliminated.

The determinations of the quantity of carbon dioxide exhaled by the subject during each period depend, like those for water, upon the quantity removed from the ventilating air by the absorbers and that remaining in the air within the apparatus. These data for carbon dioxide are summarized in Table 9. The determinations of the total quantity of carbon dioxide removed from the air current during an experimental period, ascertained by weighing the absorbing apparatus at the beginning and end of each period, are shown in column (*c*). The quantities of carbon dioxide remaining in the air of the chamber at the end of each period, as determined by analysis of a sample of the air, are shown in column (*a*). The difference between the quantity residual in the air at the end of one period and that at the end of the next period is shown

in column (*b*), with a plus sign to indicate a gain and a minus sign a loss in the residual amount in the air during the given period. The total amount of carbon doxide given off by the subject, as shown in column (*d*), is the sum of the quantities in columns (*b*) and (*c*).

TABLE 9.—*Record of Carbon Dioxide and Carbon in Ventilating Air Current, Metabolism Experiment No. 70.*

Date.	Period.	Carbon dioxide. (*a*) Amount in chamber at end of period.	(*b*) Gain (+) or loss (−) over preceding period.	(*c*) Amount absorbed from outcoming air.	(*d*) Corrected weight exhaled by subject. (*b* + *c*)	(*e*) Volume exhaled by subject. (*d* × 0.5091)	(*f*) Carbon in carbon dioxide exhaled. (*d* × 3/11)
1904.		*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Liters.*	*Grams.*
Dec. 20	5 a. m. to 7 a. m.	39.10	.....	.....	.....	.....	.....
Dec. 20–21	7 a. m. to 9 a. m.	33.47	− 5.63	69.24	63.61	32.38	17.35
	9 a. m. to 11 a. m.	51.19	+ 17.72	42.35	60.07	30.58	16.38
	11 a. m. to 1 p. m.	37.97	− 13.22	68.71	55.49	28.25	15.13
	1 p. m. to 3 p. m.	55.59	+ 17.62	42.10	59.72	30.40	16.29
	3 p. m. to 5 p. m.	39.13	− 16.46	73.67	57.21	29.13	15.60
	5 p. m. to 7 p. m.	33.03	− 6.10	66.17	60.07	30.58	16.38
	7 p. m to 9 p. m.	37.32	+ 4.29	55.68	59.97	30.53	16.36
	9 p. m. to 11 p. m.	30.80	− 6.52	60.02	53.50	27.24	14.59
	11 p. m. to 1 a. m.	28.76	− 2.04	53.45	51.41	26.17	14.02
	1 a. m. to 3 a. m.	26.83	− 1.93	51.04	49.11	25.00	13.39
	3 a. m. to 5 a. m.	28.03	+ 1.20	40.41	41.61	21.18	11.35
	5 a. m. to 7 a. m.	21.96	− 6.07	47.16	41.09	20.92	11.21
	Total	.....	− 17.14	670.00	652.86	332.36	178.05

In computing the respiratory quotients given in Table 10, it is necessary that the quantities of carbon dioxide exhaled by the subject be expressed in volume rather than in weight. These values are shown in column (*e*) in Table 9, which are obtained from those in column (*d*) by the factor expressing the relation of volume to weight of carbon dioxide. The quantities of carbon in the carbon dioxide exhaled by the subject during each period, which are likewise used in computations of later tables, are shown in column (*f*). These values are calculated directly from those in column (*d*).

STATISTICS OF OXYGEN CONSUMED.

The quantity of oxygen consumed by the subject during each period is learned from the determinations of the quantity admitted from the cylinders to the chamber and that remaining in the air at the end of the period. These data are summarized in Table 10.

The amount of oxygen supplied during each period is determined by the loss in weight of the cylinder between the beginning and end of the period and the purity of the oxygen in the cylinder, and is recorded in column (*d*).

The quantity of oxygen in the air of the chamber at the beginning and end of each day is learned by analysis of samples of the air taken at 7 a. m., and is given in column (*a*). Similar values for the different experimental periods, given in the same column, are found by calculation, as explained on page 95.

The quantities in column (*b*) represent the increase or decrease in the oxygen content of the air during the different periods. These are expressed by volume in column (*b*) and by weight in column (*c*). The algebraic difference between the quantities in columns (*d*) and (*c*) is the amount consumed by the subject.

TABLE 10.—*Record of Oxygen in Ventilating Air Current and Respiratory Quotients by Periods, Metabolism Experiment No. 70.*

Period.	Oxygen.					(*f*) Volume of oxygen consumed ($e \times 0.7$)	(*g*) Volume of carbon dioxide exhaled.	(*h*) Respiratory quotient. ($g \div f$)
	(*a*) Total amount in chamber at end of period.	Gain (+) or loss (—) during period.		(*d*) Amount admitted to chamber.	(*e*) Corrected amount consumed by subject. ($d - c$)			
		(*b*) Volume.	(*c*) Weight. ($b \div 0.7$)					
Dec. 20, 1904.	*Liters.*	*Liters.*	*Grams.*	*Grams.*	*Grams.*	*Liters.*	*Liters.*	
5 a. m. to 7 a. m.	907.28	.....	.....	.....	.....	.....	.....	.....
Dec. 20–21, 1904.								
7 a. m. to 9 a. m.	913.54	+ 6.26	+ 8.94	72.34	63.40	44.38	32.38	0.7296
9 a. m. to 11 a. m.	899.46	— 14.08	— 20.11	36.78	56.89	39.82	30.58	0.7680
11 a. m. to 1 p. m.	898.36	— 1.10	— 1.57	52.49	54.06	37.84	28.25	0.7466
1 p. m. to 3 p. m.	881.96	— 16.40	— 23.43	33.74	57.17	40 02	30.40	0.7596
3 p. m. to 5 p. m.	889.44	+ 7.48	+ 10.69	62.36	51.67	36.17	29.13	0.8054
5 p. m. to 7 p. m.	888.34	— 1.10	— 1.57	57.97	59.54	41.68	30.58	0.7337
7 p. m. to 9 p. m.	881.65	— 6.69	— 9.56	46.66	56.22	39.35	30.53	0.7759
9 p. m. to 11 p. m.	878.59	— 3.06	— 4.37	48.47	52.84	36.99	27.24	0.7364
11 p. m. to 1 a. m.	871.47	— 7.12	— 10.17	39.09	49.26	34.48	26.17	0.7590
1 a. m. to 3 a. m.	871.10	— 0.37	— 0.53	48.38	48.91	34.24	25.00	0.7301
3 a. m. to 5 a. m.	879.10	+ 8.00	+ 11.43	48.42	36.99	35.89	21.18	0 8181
5 a. m. to 7 a. m.	907.04	+ 27.94	+ 39.91	75.36	35.45	24.82	20 92	0.8429
Total	.....	— 0.24	— 0.34	622.06	622.40	435.68	332.36	0.7629

RESPIRATORY QUOTIENT.

The ratio between the volume of carbon dioxide exhaled and the volume of the oxygen inspired, and indicating in marked degree the nature of the materials burned inside the body, is commonly called the respiratory quotient. In the experiments with men, it is computed on the sheets upon which are recorded the data for the determinations of the amount of oxygen consumed, Table 10, and is recorded in column (*h*). In determining the respiratory quotient, the weight of carbon dioxide found is converted to liters by multiplying by the factor 0.5091, column (*e*), Table 9, while the weight of oxygen absorbed by the body is converted to liters by multiplying by 0.7, column (*f*) of Table 10. The ratio between the volumes of carbon dioxide eliminated and oxygen absorbed, $CO_2 \div O_2$, represents the so-called "respiratory quotient."

When carbohydrates are burned in the body, the volume of oxygen consumed is equal to the volume of carbon dioxide given off, since the hydrogen and oxygen in the carbohydrate molecule are in the same proportions as in water, and in the conversion of carbon to carbon dioxide the volume of carbon dioxide is invariably the same as the volume of oxygen required. In the case of the proteids, where not only carbon is oxidized, but also some hydrogen, it is found that the respiratory quotient is generally not far from 0.809, while in the case of fats, where the amount of hydrogen oxidized is quite considerable, the respiratory quotient may fall as low as 0.711. It has been found as a result of experimenting with other types of respiration apparatus, especially those of Zuntz and Chauveau (see p. 3), that the respiratory quotient on an ordinary mixed diet is not far from 0.9. From an inspection of column (*h*) of Table 10 of experiment 70 given herewith, it will be seen that the large proportion of fat in the diet resulted in a marked lowering of the respiratory quotient.

Summary of Calorimetric Measurements.

The records of the heat measurements by means of the respiration calorimeter are summarized in Table 11.

Table 11.—*Summary of Calorimetric Measurements, Metabolism Experiment No. 70.*

Period.	(*a*) Heat measured in terms C_{20}.	(*b*) Change in temperature of calorimeter.	(*c*) Capacity correction of calorimeter.	(*d*) Correction due to temperature of food and dishes.	(*e*) Water vaporized equals total in outgoing air plus excess residual vapor.	(*f*) Heat used in vaporization of water. ($e \times 0.592$)	(*g*) Total heat determined. ($a+c+d+f$)
Dec. 20–21, 1904.	*Calories.*	*Degrees.*	*Calories.*	*Calories.*	*Grams.*	*Calories.*	*Calories.*
7 a. m. to 9 a. m.....	172.35	+ 0.03	+ 1.80	+ 9.22	74.54	44.13	227.50
9 a. m. to 11 a. m.....	132.56	— 0.05	— 3.00	+ 2.87	66.39	39.30	171 73
11 a. m. to 1 p. m.....	122.23	+ 0.03	+ 1.80	+12.02	66.55	39.40	175.45
1 p. m. to 3 p. m.....	141.61	— 0.02	— 1.20	.....	64.67	38.28	178.69
3 p. m. to 5 p. m.....	149.84	+ 0.02	+ 1.20	+ 4.37	64.15	37.98	193.39
5 p. m. to 7 p. m.....	151.31	+ 0 01	+ 0.60	+ 8.23	70.53	41.75	201.89
7 p. m. to 9 p. m.....	148.42	— 0.07	— 4.20	.....	65.48	38.76	182.98
9 p. m. to 11 p. m.....	132.43	+ 0.02	+ 1.20	.....	66.21	39.20	172.83
11 p. m. to 1 a. m.....	115.64	+ 0.05	+ 3.00	.....	72.04	42.65	161.29
1 a. m to 3 a. m.....	112.25	— 0.06	— 3.60	.....	90.50	53 58	162.23
3 a. m. to 5 a. m.....	118.10	+ 0.13	+ 7.80	.....	70.20	41.56	167.46
5 a. m. to 7 a. m.....	98.85	— 0.31	— 18.60	.....	63.78	37.76	118.01
Total.....	1,595.59	— 0.22	— 13.20	+36.71	835.04	494.35	2,113.45

The major part of the heat generated within the apparatus is absorbed and carried away by a current of cold water through the heat-absorbers. The quantity of heat thus brought out is determined from measurement

of the amount of water which flows through the absorbers and the difference between the temperature of the water as it enters and as it leaves the chamber. These determinations are given in column (*a*).

Part of the heat generated within the respiration chamber is brought away as latent heat of the water vapor carried out in the ventilating air current. The amount of heat brought out in this way, being simply the amount necessary to vaporize the water, is calculated from the amount of water vaporized. The amount of water vapor for each experimental period, shown in column (*e*), is taken from column (*g*) of Table 8, and the amount of heat necessary to vaporize it is calculated from the quantities in column (*e*) by use of the factor 0.592 as the latent heat of vaporization of water per gram. These values are given in column (*f*).

In addition to the above, a certain amount of heat is concerned in the changes in temperature of the walls of the respiration chamber and other parts of the apparatus. Each degree of change of temperature for the whole calorimeter is assumed to represent 60 calories of heat. The difference between the initial and final temperatures of each period gives the total change of temperature to be taken into account. These data are shown in column (*b*). Multiplying these values by 60 gives the total quantity of heat involved in the changes of temperature, as shown in column (*c*).

Food materials, dishes, etc., when sent into the chamber through the food aperture, of course deliver heat when they are warmer than the air of the chamber, and remove heat by absorption when they are cooler. The amount of heat thus introduced or removed during the different periods of the experiment, as calculated from the weight and specific heat of each material and the difference between its temperature and that of the chamber, is shown in column (*d*).

The total amount of heat determined in an experimental period, column (*g*), is therefore the algebraic sum of the quantities of heat brought away by the circulating water current, as shown in column (*a*), with the correction due to changes in temperature of the calorimeter, column (*c*), the correction for heat removed or introduced by food, dishes, etc., column (*d*), and the heat latent in the water vaporized, column (*f*).

It should be added that the temperature of the ventilating air current is so regulated as to be the same in entering as in leaving, so that it carries out the same amount of heat as it brings in, and need not be taken into account in the tables.

No corrections have been made for variations in heat measurement due to changes in body temperature, changes in body weight, or to the absorption and radiation of heat by the bed and bedding, as previously

explained. These corrections are chiefly of importance from their bearing upon the question of heat production versus heat elimination, and they are accordingly omitted from the present brief summary.

Intake and Output of Material and Energy.

From the data derived from the preceding tables the balance between the intake and output of material and energy in the body may be calculated. The methods and results of these calculations may be explained as follows:

Gains and Losses of Body Material.

In order to compute the gains and losses of body material as expressed in terms of protein, fat, and carbohydrates it is necessary first to determine the gains and losses of the elements which make up these compounds. This is done by comparing the amounts of the elements in the intake of the body with those of the output, as shown in Table 12.

TABLE 12.—*Gain or Loss of Body Material, Metabolism Experiment No. 70.*

	(*a*) Total weight.	(*b*) Nitrogen.	(*c*) Carbon.	(*d*) Hydrogen.	(*e*) Oxygen.	(*f*) Ash.
Intake.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
Oxygen from air	622.40	.....	.....	.....	622.40	.....
Drinking water	139.00	.....	.....	15.55	123.45	.....
Water in food	1,306.33	.....	.....	146.18	1,160.15	.....
Solids in food	351.57	8.54	216.90	33.70	81.45	10.98
Total	2,419.30	8.54	216.90	195.43	1,987.45	10.98
Output.						
Water in feces	40.48	.....	.....	4.53	35.95	.....
Solids in feces	20.49	0.36	12.04	1.91	1.93	4.25
Water in urine	991.37	.....	.....	110.94	880.43	.....
Solids in urine	40.13	13.04	8.87	2.37	11.31	4.54
Water of respiration	838.30	.....	.....	93.81	744.49	.....
CO_2 of respiration	652.86	.....	178.05	.....	474.81	.....
Total	2,583.63	13.40	198.96	213.56	2,148.92	8.79
Gain or loss	— 164.33	— 4.86	+ 17.94	— 18.13	— 161.47	+ 2.19
Ash of protein	— 0.45	.....	.....	.....	.....	— 0.45
	— 164.78	.....	.....	.....	.....	+ 1.74
Gain or Loss of Body Material.						
Protein	— 29.16	— 4.86	— 15.40	— 2.04	— 6.41	— 0.45
Fat	+ 33.54	.....	+ 25.52	+ 3.96	+ 4.06	.....
Glycogen	+ 17.53	.....	+ 7.78	+ 1.09	+ 8.66	.....
Water	— 188 88	.....	.....	— 21.14	— 167.74	.....
Ash	+ 2.19	.....	.....	.....	.....	+ 2.19
Total	— 164.78	— 4.86	+ 17.90	— 18.13	— 161.43	+ 1.74

The intake of the body is made up of the following: (1) Oxygen from the air, which is found for this experiment in column (*e*) of Table 10; (2) water in drink, which is taken from the record of the amount

of water consumed during the experiment; (3) water of food, which is taken from column (*b*) of Table 6; (4) solids of food, the quantity of which is determined as the difference between the total weight of food material and the weight of water which it contains, as shown by columns (*a*) and (*b*) of Table 6. In such computations milk is considered as food rather than as drink.

The output consists of (1) water and (2) solids of feces and (3) water and (4) solids of urine, which are all obtained by simple computation from columns (*a*) and (*b*) of Table 7; (5) water of respiration and perspiration, which is obtained from column (*g*) of Table 8, and (6) carbon dioxide obtained from column (*d*) of Table 9.

The quantity of oxygen consumed by the subject from the air is directly determined. The quantities of hydrogen and oxygen in the water of drink, food, feces, urine, and respiration are calculated from the composition of water, and the quantities of carbon and oxygen in the carbon dioxide exhaled by the subject are calculated from the composition of carbon dioxide. The quantities of nitrogen, carbon, hydrogen, oxygen, and ash of solids of food, feces, and urine are taken from Tables 6 and 7, respectively.

The differences between the amounts of the elements of intake and those of output show how much of each was gained or lost. Computation of the gains or losses of protein, fat, carbohydrates, and water from those of the elements depends upon the elementary composition of the compounds.

The values for percentage composition employed in these investigations are as follows:

Body material.	N.	C.	H.	O.	Mineral matters (including S).
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Proteids	16.67	52.80	7.00	22.00	1.53
Fat	....	76.10	11.80	12.10	....
Carbohydrates	....	44.40	6.20	49.40	....
Water	....	....	11.19	88.81	....

Disregarding the mineral matters, the following equations may be derived from the above data, letting p = protein, t = fat, r = carbohydrates, and w = water:

$$0.1667\,p = \text{N}$$
$$0.4440\,r + 0.7610\,t + 0.5280\,p = \text{C}$$
$$0.1119\,w + 0.0620\,r + 0.1180\,t + 0.0700\,p = \text{H}$$
$$0.8881\,w + 0.4940\,r + 0.1210\,t + 0.2200\,p = \text{O}$$

Solving these equations in terms of N, C, H, and O, the following formulæ are obtained:

$$\text{Protein} = 6.0\ N$$
$$\text{Fat} = 0.005\ C + 9.693\ H - 1.221\ O - 2.476\ N$$
$$\text{Carbohydrates} = + 2.243\ C - 16.613\ H + 2.093\ O - 2.892\ N$$
$$\text{Water} = - 1.248\ C + 7.920\ H + 0.128\ O + 0.460\ N$$

Substituting for the elements in these formulæ the quantity of each gained or lost as expressed in grams in Table 12, and performing the calculations, gives the weights of the compounds gained or lost. In the following illustration the figures are taken from the data for the first day of the experiment (Table 12). Thus:

$$\begin{aligned}\text{Protein} &= 6\ N\\ &= 6\ (-4.86)\\ &= -29.16\end{aligned}$$

indicating that 29.16 grams of protein were lost on that day. Again:

$$\begin{aligned}\text{Fat} &= +0.005\ C \quad +9.693\ H \quad -1.221\ O \quad -2.476\ N\\ &= +0.005\ (-17.94) \quad +9.693\ (-18.12) \quad -1.221\ (-161.48) \quad -2.476\ (-4.86)\\ &= +0.090 \quad -175.637 \quad +197.167 \quad +12.033\\ &= +33.65\end{aligned}$$

indicating that 33.65 grams of fat were lost on that day. The results for carbohydrates and water are derived in the same way from the other two formulæ.

The results as thus computed are given in the bottom division of column (*a*) of Table 12. The correctness of the computations is tested mathematically as follows: From the total weight of each compound gained or lost and its percentages of the elements assumed in the tabular statement above, the quantities of the elements gained or lost are computed. The total for each element thus derived should be the same as the difference between the income and outgo of the same element.

The gains or losses of material expressed in terms of chemical elements and protein, fat, carbohydrates, and water are summarized in Table 13.

TABLE 13.—*Gain or Loss of Elements and Protein, Fat, Carbohydrates, and Water, Metabolism Experiment No. 70.*

	Nitrogen.	Carbon.	Hydrogen.	Oxygen.	Protein.	Fat.	Carbohydrates.	Water.
	Grams.	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*	*Grams.*
December 20 ...	− 4.86	+ 17.94	− 18.12	− 161.48	− 29.16	+ 33.65	+ 17.34	− 188.80

BODY WEIGHT.

The figures of Table 12 imply that the body lost 164.78 grams of material during the experiment. If there were no experimental errors the body should have weighed 164.78 grams less at the end than at the beginning of the experiment. This calculated balance was checked by actual weighings of the body.

TABLE 14.—*Balance of Gains and Losses of Body Material and Gain and Loss of Body Weight, Metabolism Experiment No. 70.*

	Intake.				Output.					Balance.		
	Food.	Water.	Oxygen.	Total.	Urine.	Feces.	CO_2.	Water.	Total.	Gain (+) or loss (—) of body material.	Gain (+) or loss (—) of body weight.	Difference.
	Gms.	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*
Dec. 20.	1,657.90	139.00	622.40	2,419.30	1,045.80	.....	652.86	838.30	2,536.96	—117.66	— 111.00	6.66

The platform balance, with weighing arrangements, shown in figure 46, was used in this experiment for checking the body weights, and in the next to the last column of Table 14 we have the exact loss in weight as recorded on this particular day by this balance. As a matter of fact, it is seen that the loss in weight as recorded by the balance was 111 grams, which differs somewhat from the amount computed from the figures in Table 12, *i. e.*, 164.78 grams. In this connection it may be stated that the experimental routine, especially with reference to the weighing, was not in a satisfactory condition on the date on which this experiment was made, and consequently the corrections for the differences in amount of urine passed each day at 7 a. m. before the actual weighing account in large measure for the discrepancy noted above.

In Table 14 the balance of intake and output of material in grams is given, and from these figures the loss of body material is calculated to be 117.66 grams, making, therefore, an actual discrepancy between that computed and that found by the platform balance equal to 6.66 grams.

Subsequent experience with the platform balance has shown that with a perfected technique the agreement between the computed gain or loss of body material and that actually found is very close.

INTAKE AND OUTPUT OF ENERGY.

Table 15 summarizes the data regarding the intake and output of energy in the body during this experiment.

TABLE 15.—*Intake and Output of Energy, Metabolism Experiment No. 70.*

Date.	Heat of combustion of food and excreta as determined by use of the bomb calorimeter.			(*d*) Available energy from food. $a-(b+c)$	Heat of combustion of body material gained or lost as calculated by use of factors.			(*h*) Total energy from body material gained or lost. $(e+f+g)$	(*i*) Estimated energy from material oxidized in the body. $(d-h)$	(*j*) Heat measured by respiration calorimeter.	Heat measured greater or less than estimated.	
	(*a*) Food.	(*b*) Feces.	(*c*) Urine.		(*e*) Protein.	(*f*) Fat.	(*g*) Glycogen.				(*k*) Amount.	(*l*) Proportion.
1904. Dec. 20	*Cals.* 2,569	*Cals.* 149	*Cals.* 103	*Cals.* 2,317	*Cals.* −165	*Cals.* +321	*Cals.* +73	*Cals.* +229	*Cals.* 2,088	*Cals.* 2,113	*Cals.* +25	*Per ct.* +1.2

In this discussion the intake of energy is the energy from the material actually katabolized, *i. e.*, broken down and oxidized in the body, including, therefore, not only the energy of katabolized food but also that of the body material lost. The output of energy is that given off by the body as heat, measured either as sensible heat by the respiration calorimeter or as heat of vaporization of water. The intake of energy may be measured in a number of ways. First, we may consider the intake as the potential energy of the food ingested and consider the potential energy of the unoxidized material in the urine and feces as a part of the output. Second, we may correct the potential energy of the food for that of the feces and urine by deducting the amount of energy in these latter, thus obtaining the so-called "available" energy. Without entering into any discussion here as regards the merits of the two methods of computation, we may proceed to the discussion of Table 15. The available energy of the food is calculated from the heat of combustion of the food, column (*a*), the heats of combustion of the unoxidized material in the feces, column (*b*), and urine, column (*c*). These quantities are taken from Tables 6 and 7, respectively. As previously explained, they are the results of actual determinations.

When the available energy of the food is more than sufficient for the needs of the body, more or less of the surplus food may be stored as body material, and the quantity of energy in the material so stored must be subtracted from the available energy of the food to obtain the energy of the material actually metabolized, which is the energy of intake here considered. On the other hand, if the available energy of the food is not sufficient, the body will draw upon its own previously stored material, and the amount of energy thus derived must be added to that available from the food to give the total energy of material oxidized in the body.

It may happen that the body will increase its store of one material while drawing upon that of another. Thus the figures for the experiment under discussion (Table 12) show a gain of glycogen and fat at the same time with a loss of protein in the body. Under these circumstances, the quantity of energy from body material that is to be added to the available energy of food is the difference between the energy of material lost and that of material gained.

CALCULATIONS OF ENERGY OF BODY MATERIAL GAINED AND LOST.

Returning now to the summary of intake and output of energy in Table 15, the total energy of body material gained or lost, as given in column (*h*), is the algebraic sum of the quantities in columns (*e*), (*f*), and (*g*). These latter quantities are calculated from the amounts of body material gained or lost, as shown in Table 12, by use of factors for the heats of combustion per gram of body materials. The factor for protein, 5.65 calories per gram, is that for fat-free muscular tissue from which the non-proteid nitrogenous compounds have not been removed. The factor for fat, 9.54 calories per gram, is the average of the results of several determinations of the heat of combustion of fat from the human body; and the factor for glycogen, 4.19 calories per gram, is likewise the result determined by actual combustion of that material. Applying these factors to the amounts of body material gained or lost, and adding (algebraically) the results, gives the total amount of energy from body material, as illustrated by the following computations for December 20:

Protein,	— 29.16 grams × 5.65 =	— 165 calories.
Fat,	+ 33.65 grams × 9.54 =	+ 320 calories.
Glycogen,	+ 17.34 grams × 4.19 =	+ 73 calories.
Total energy from body material =		+ 229 calories.

The minus sign in column (*e*) indicates that the body has lost the energy from the amount potential in its previously stored material, while the plus sign in columns (*f*) and (*g*) indicates that the energy was potential in body material stored. The total amount of energy derived from the body material that was utilized, shown in column (*h*), is therefore the difference between the amount lost and the amount stored, or, in other words, the algebraic sum of the quantities in columns (*e*), (*f*), and (*g*).

The figures in column (*i*) represent the estimated amounts of energy of the material oxidized in the body. They are the difference between the quantities in column (*d*), the available energy of the food, and those in column (*h*), the energy from the body material stored. Since the

energy of this stored material was obtained from that of the food in excess of that required to supply the needs of the body, the figures of column (*h*) are subtracted from those of column (*d*) to make the total energy of material oxidized.

The output of energy consists of the heat given off from the body either as sensible heat or heat of vaporization of water. Both quantities are measured directly by the respiration calorimeter. The figures in column (*j*) show the amounts of heat thus measured. These are taken from column (*g*) in Table 11. Theoretically, the quantity for intake should be the same as that of the output. It would hardly be expected, however, that results agreeing exactly would be obtained. Column (*k*) shows the difference between the heat measured by the respiration calorimeter and the energy of material oxidized in the body as estimated from the heat of combustion of food, feces and urine, and that of body material gained or lost. This difference is expressed in column (*l*) in percentages of the amounts in (*j*).

CONCLUSION.

Throughout this report the attempt has been made to indicate the experimental limitations as well as the relative accuracy of this apparatus. Believing that improvement in experimental technique is an essential in increasing our knowledge of those processes of physiological chemistry that have special reference to the nutrition of man, we have aimed in the development of this apparatus to secure in so far as possible the accuracy of those forms of physical apparatus ordinarily designated as instruments of precision. The incidental errors of manipulation and computation are by no means wholly eliminated. Indeed, as is to be expected with an apparatus involving so many mechanical details, the number of possible errors is not inconsiderable. We believe, however, that in fundamental principles and practical use it has proved as exact as could well be expected of an apparatus for physiological experimenting.

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