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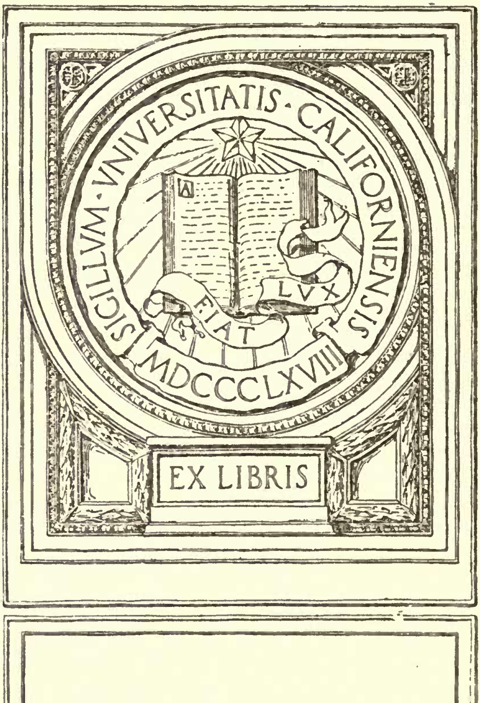
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THE GENERAL PRINCIPLES OF CHEMICAL ENGINEERING DESIGN

BY

HUGH GRIFFITHS

WITH FIVE ILLUSTRATIONS

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INTRODUCTION

THE present work is intended to deal with general principles only, and merely those which apply to chemical engineering, as distinct from other branches. No attempt has been made to exhaust the subject, and the examples given are merely cited to illustrate the points as they arise.

The chemical engineer is frequently described in terms of opprobrium by both the chemist on the one hand and the engineer on the other, and it is sometimes stated that the chemical engineer when in the company of chemists is an engineer, and when in the company of engineers is a chemist. This observation is not surprising, but it simply serves to show that neither the engineer on the one hand nor the chemist on the other understand the scope of chemical engineering, and whilst it is often said that the chemist and the engineer speak in different languages, it might also be stated that the chemical engineer has still another mode of expression.

The principles stated in this monograph are calculated to show a bird's-eye view of the field of problems presented to the designing chemical engineer, and it will quickly be realized that the problems are essentially different from those encountered in either chemical or engineering problems. The lines of demarcation are, of course, not sharp, and chemical engineering spreads itself into chemistry on the one hand and engineering on the other, but the overlap in each case is not so much as to interfere with the work of either the chemist or the engineer.

Still further importance must be attached to the physical aspect of chemical engineering, and it is in this direction particularly that the scientific investigation of chemical engineering requires further development, in order that a scientific knowledge of the functions of chemical plant can accurately be ascertained.

The object of any scientific study is purely economic in the sense that systematic knowledge enables us to transfer experience to a new field with the minimum of mental labour.

The scientific study of chemical engineering has this object, and this only, and it is only by studying the operation and design of plant along the lines of functional analysis that a proper scientific knowledge can be secured.

The practical object of chemical engineering is of course the production of materials at a profit. It is therefore necessary to consider not only factors of a scientific character, but also to take into account economical considerations, upon which the making of profits depends.

In the present work, the field is considered only in general lines, in an endeavour to indicate a method of attack on problems which arise. The detailed treatment of the various points will form other contributions to this series of monographs.

THE GENERAL PRINCIPLES OF CHEMICAL ENGINEERING DESIGN

I

THE ESSENTIALS OF A SUCCESSFUL CHEMICAL PLANT

THE object which is primarily in view in the erection of nearly every chemical works, is the production of some material at a profit. It may be in certain cases that a firm has important secondary reasons for erecting a manufacturing plant, but the main object is always there.

The research chemist with a beautiful process, fresh from the laboratory, is often liable in his enthusiasm to forget that the process must be one which shall be capable of production on the desired scale, in a plant which will work economically, and which will compete successfully. Too often, also, is he ignorant of chemical engineering, and in consequence, after futile attempts at manufacture, he finds his process superseded in favour of one which may be chemically much less efficient, and he is not only disappointed, but discredited and branded as unpractical and a dreamer. Many examples can be found of processes which give first class yields of fine quality products with the minimum of trouble in the laboratory, and yet these are at present not exploited commercially. The reason for this neglect is frequently found in the circumstance that it is almost impossible to work such processes in large batches, either from thermal considerations, or in the difficulty of constructing plant which will withstand the action of the corrosive reagents employed. It may be stated that the pure chemist is not always well informed as to the properties of constructional materials, and surprising though it may appear, very frequently does not know the limitations of such materials from the point of view of corrosion. He is also liable to overlook thermal effects which appear insignificant on a small scale, but which become important as the batch size assumes commercial proportions. The literature of chemical technology is overloaded with descriptions of ingenious processes which, from a purely chemical point of view, are admirable, but which are useless commercially owing to difficulties which arise in conducting them on a commercial scale. A certain well-known process for the manufacture of caustic soda fails completely, because of the difficulty of filtering a certain colloidal precipitate from the liquor at one stage of the process: many chemically perfect processes for the nitration of organic compounds with nitric acid are known, yet these cannot compete with methods in which mixtures of nitric and sulphuric acids are employed, because in the latter case iron vessels can be used, and it is possible in consequence to operate in large batches, whereas with nitric acid alone this would not be so easy, as generally stoneware vessels would have to be used and these cannot be made in very large sizes. These instances could be multiplied almost without limit. In the Research Laboratory considerations of the costs of handling, of water, of power, and of fuel, are liable to be set aside as matters to be dealt with by the unfortunate individual who has to design the necessary plant. Not infrequently processes emerge from the Research Laboratory in a state which is deplorable from this point of view. In the laboratory, for example, products are frequently isolated by steam distillation, which are not sufficiently volatile to make such a method possible on the large scale. The cost of the steam would be prohibitive in such cases. Many similar examples of disregard of physical principles could be given.

The ordinary engineer also finds chemical plant design difficult, and this is not surprising when it is remembered that a chemical plant not only must satisfy every requirement of a " good engineering job," but in addition profits must be made by the production of materials in commercial quantities. Most " good engineering jobs " are simply required to withstand the action of mechanical forces, and—with a few exceptions—are not employed for making money in the coldly direct way required in a chemical works.

Many firms leave all questions of design of chemical plant to their chemists and their engineers, and these combinations are frequently regarded as ideal, but unless there is an unusual catholicity of experience somewhere, the results are often dismal. The reasons mentioned above no doubt contribute to the failure of these combinations in many cases, but it is also to be noticed that many of the factors entering into the design of chemical plant are completely foreign to the training of both the chemist and the engineer. Both very frequently go adrift over economic factors, but possibly most frequent mistakes are due to a lack of knowledge of physics. Unfortunately the amount of accurate physical data available which is of technical value for the design of chemical plant is rather meagre, and the academic training in this subject at present, whilst it may suffice to impart a knowledge of principles, is altogether unsatisfactory from the point of view of technical application.

It has often been stated that more chemical plants have been bungled over the question of heat transmission than anything else. The average student fresh from the University is generally astonished when he is informed that the calculation of a condenser on the basis of his theoretical calculations would be wrong by many hundreds per cent. In this direction, as in many others, the "trained man" has much to unlearn before he is safe on the subject of chemical plant, or perhaps it would be better to say that he has much to learn before he can apply his "scientific" knowledge.

Undoubtedly in many directions there is a great need for research, but nevertheless it is almost invariably possible to calculate the physical elements of the design of chemical plant with very much greater accuracy than would be possible for purely mechanical factors. In the latter case it is usual to employ "factors of safety," or as they are better described, "factors of ignorance." Whereas in mechanical engineering these factors may run into several hundreds per cent., only in very few cases in chemical engineering proper is it necessary to allow such a wide margin.

Assuming that a new process from the laboratory is to be exploited on a larger scale, or a process which has been tested on the "semi-manufacturing" scale has to be extended, it is certain that not only is a descriptive knowledge of the various types of machinery necessary, but also a scientific knowledge of the various factors of chemical engineering design. The factors which have to be considered in attempting to design chemical plant are physical, chemical, mechanical, economic and practical.

Even though a complete knowledge of all these factors is not possible, it is nevertheless of great importance to know "how things vary," and to know also how to take the fullest benefit from experience with similar plant, perhaps of different magnitude. Such a knowledge will enable results to be achieved which no amount of "cut-and-try," or "rule-of-thumb-work," could possibly do.

Whilst this scientific design of chemical plant may be ideal, yet it is unfortunately not always possible for a manufacturer to proceed in a strictly scientific manner in erecting a new plant. Too many chemical processes have been failures on the large scale, and as a result the manufacturer with a new proposition is somewhat wary, and more often than not is very anxious to see what will happen before spending too much of his money. Sometimes not only has the process and the plant scheme to be tested, but also the market for the products may be somewhat doubtful, and in view of the uncertainty, the plant is never at any stage properly designed, but simply grows. Too often some odd items of plant are purchased from a marine store, and these are adapted to the special purpose. Very frequently the plant so produced is highly inefficient, but if by some miracle the process prospers in spite of the plant, then sooner or later a larger production is wanted and the trouble begins. As soon as the extemporized plant is pressed for output it is found that some section is deficient. The faulty member is either duplicated, or substituted by an increased size, with the result that trouble breaks out in some other section of the plant. This process of pruning and grafting proceeds, and if the proposition is a very hardy one, sooner or later, chiefly by replacement of entire sections by proprietary machinery, some approximation to efficient working is secured. This gradual growth of a chemical plant may be very painful to witness and very exasperating to the chemist in his enthusiasm, but it is, after all, a very human procedure, although in most cases one which is most costly, and it would pay better to delay production until all the information had been properly assembled, and a sure foundation formed upon which to build up the development.

Much of the secrecy connected with the prosecution of chemical manufacture relates to matters of chemical engineering alone, as distinct from process and mechanical construction. It has often been stated in connexion with the German dyestuffs for example, that the chemistry of the German works is the chemistry of the text books, but the technique is a totally different matter. This applies to almost every kind of manufacture to some extent, and whilst experience gained in manufacturing practice in the course of time is undoubtedly the best foundation on which to design plant for future work, when new manufactures have to be undertaken problems arise which are difficult to connect up with previous practice.

The object of any scientific study is after all economical in character. The scientific method enables us to utilize results of experience gained in one field, and convey them with the minimum of mental exertion to another field. In order that the chemical engineer shall be able to do this, it is necessary for him to understand principles in order to make his experience of value to him. Sometimes even technically trained men are deceived into jumping to conclusions, and do not convey their experience from one field to another, even in an arithmetical manner. The consideration of a simple example will show what is meant: if one imagines that experiments have been carried out on a small scale, say in an operation necessitating the cooling of a liquid in a tank in contact with the air. For the sake of argument, let it be assumed that it is desired to operate on ten times the output. It is very obvious that it would be altogether wrong to multiply the linear dimension of the small vessel by ten, in order to secure a design for the larger vessel. It would also be wrong to construct a vessel simply of ten times the capacity, as in this case the surface exposed to the atmosphere for cooling would bear a different relation to the bulk, and the time of operation would not be the same. If the vessel cools partly by evaporation of water from the surface, as in the crystallization of inorganic salts, a further complication is introduced, and it will be seen that a little care is required, even in such absurdly simply cases, in utilizing one's previous experience for application to another design.

This kind of reasoning also applies to mechanical considerations in design, and it is certainly extremely easy, unless the basic principles are searched out, to make frequent and costly blunders. It is well known that if an aeroplane, for example, were constructed by copying a smaller model strictly to scale, there would be difficulty later. It is also known to many that since the weight of the various members of a structure increases as the cube of the linear dimension, whereas the section on which strength depends increases as the square of the dimension only, it is not safe to design by simple multiplication of linear dimensions. It is not, however, quite so obvious that the reverse operation may in certain cases lead to dangerous structures, and as we shall see later, a strictly geometrical reduction of, say, an existing chimney about 400 feet high, to a scale giving a height of 20 feet would be a very bad basis for design, and would lead to an unstable structure.

Whilst in these simple cases sufficient has been said to show that what is often described as "common sense," may lead to disastrous results, it may be stated with the firmest confidence, that in chemical engineering work, where the various factors enter in much more complicated relation, this kind of "common sense" is more than ever dangerous, and is one of the surest contributions to disaster.

For the above reasons it is not merely sufficient to possess a pocket-book knowledge of the various subjects, and a warning must be made against the use of formulæ. The confidence which many engineers and practical men place in formulæ and table books is positively staggering. No problem arises but that their procedure is to take into account those factors which are known to them, or which are obvious on the surface, apply the formula, strictly according to instructions, and some kind of result emerges.

In chemical engineering work it is very seldom that the blind application of formulæ will give a correct basis for design, as there are usually many of the complicated influences entering which cannot be calculated by formulæ with accuracy, and a knowledge of principles is necessary in order that the results obtained by the utility formulæ shall be correctly appreciated at their proper worth.

It may readily be seen, therefore, that before any chemical plant can be systematically designed, not only must the process be right in the very broadest commercial sense, and the plant structurally and mechanically sound in every respect, but various other conditions have to be estimated and satisfied if successful operation is to be achieved.

II

PHYSICAL FACTORS

WHILST the physical factors of the design of a chemical plant are of the greatest importance, as they go to control the output which can be secured from a given size of installation, their calculation is often a matter of difficulty, and in some cases it is impossible to separate out the various influences which are operative. In spite of the difficulty of separating out all the physical phenomena, it is very important that the influence of each should be appreciated as accurately as possible, and only by pursuit of the subject in this way is it possible to utilize previous practical experience with benefit.

Apparently some of the simplest cases are really very difficult, but on the other hand it is surprising what can really be done by simple calculation on the basis of physical principles. The application of these principles is not always obvious, and in consequence many valuable opportunities for the collection of technical information of the highest value are neglected, and certainly a new interest is found in one's daily work, when these possibilities are properly realized. It will only be necessary to give a few broad indications of the possibilities in this direction.

From a physical point of view it is important to know the properties of all the materials handled in the plant.

If solids have to be ground or crushed, a knowledge of their physical properties is of the greatest importance, and in this case we have an example of the difficulty of separating out the factors. It is obvious that if the design of grinding appliances is to be placed upon a scientific basis, it should be possible to calculate—having made experiments as to the power required for the production of a certain fineness as expressed in the form of a screen analysis—the power consumption for other finenesses. Reference to the literature will show that there is a sharp difference of opinion in this matter. If liquids have to be handled it is necessary to know what size of pipe to use and what pressure difference will be necessary to maintain the necessary flow. In this case the chemical engineer is by no means so well off as the hydraulic engineer, and whilst the hydraulic engineer is able to select from a multitude of formulæ, some empirical and some scientific, all these relate simply to the case of water, and that only at the ordinary temperature. The chemical engineer may have to deal with liquids varying in viscosity between wide limits, and also under varying temperature conditions. It is not possible for him to employ the same methods as a hydraulic engineer, and only a proper knowledge of principles will enable him to solve the simplest problems in this direction with reasonable accuracy.

The same remarks apply to the flow of gases. Again, the conditions of chemical engineering are very much wider than those met with in other branches of industry, and it would be impossible to give empirical formulæ which would be useful, over every case. This matter of the flow of liquids and gases is of extreme importance, as the tendency is, in modern manufacturing practice, to progress towards continuous methods of manufacture. This being the case, it is necessary to calculate the various sizes of plant with much greater accuracy than would be necessary in an intermittent installation. This question has its bearing on the design of pipe lines, flues, chimneys, and more complex cases can be found in connexion with gas scrubbing, filtration, extraction, and other processes.

The properties of colloidal substances, and the physical properties of colloidal solutions, have a large bearing in chemical manufacture, particularly in such operations as filtration, decolorization, sedimentation, emulsification, and even in the simple operations of mixing and separating liquids. The washing of various precipitated materials frequently gives rise to peculiar problems, and the effect of adsorption in such operations, and in extraction processes, needs only to be mentioned. It has to be admitted that in many of these cases there is a great need for research. In others, occasionally, practice will be found ahead of theory, but many of the little manufacturing tips and dodges can be explained physically. Most chemists are now familiar with the reasons why it is not advantageous to make bricks without straw, yet in manufacturing processes there are similar dodges, these being frequently regarded as great secrets.

Problems dealing with the compression and liquefaction of gases demand a proper knowledge of the various gas laws, and also of latent heats, vapour pressures, specific heats, and the like; in fact, all the data such as can be conveniently shown in Mollier diagrams.

Vapour pressure is a property which should be known quantitatively in an amazing number of operations. Vacuum evaporation and drying, vacuum distillation, condensation, heating under pressure in autoclaves, and crystallizing, may be mentioned as processes in which this property requires to be known. It is not possible to obtain vapour pressure tables of any and every material, but it is comparatively easy to calculate approximate vapour pressures for any substance, the boiling point of which is known, and it is possible to calculate very closely, if in addition to the boiling point the vapour pressure at some other temperature is also known. A knowledge of the vapour pressure relations of a substance enables us to make calculations of partial pressures, and the consideration of these enables the design factors of a surprising range of plant to be calculated.

Drying by hot air, solvent recovery, distillation in steam, may be mentioned in this connexion. It is quite a simple matter, for example, to calculate how much of any substance, the boiling point of which is known, will be carried off with a given quantity of air or steam, under conditions of saturation at any given temperature.

It is unnecessary to insist on the importance of the physical properties of steam, and in this case it is not merely necessary to have a table of pressures and temperatures, but it is also desirable to know something of the physical principles involved in the preparation of the various diagrams. A knowledge of thermodynamics is necessary to understand the principles of gas liquefaction, and also in connexion with refrigeration, which is becoming more and more important in chemical manufacture. Various systems of evaporation are now employed on a large scale, known under the name of Recompression Systems, in which mechanical energy is employed to recompress the steam evolved from the evaporation, so that they may be used again for heating the evaporator. It is obvious that this is simply the principle of the reversed heat engine, and is the same as that underlying the operation of refrigerating machines. In many chemical operations in which refrigeration is employed, it is desirable to know the most economical temperature to which the materials shall be cooled. From the principle of the reversed heat engine, it follows that the farther away the low temperature is from the temperature of the cooling water, the greater will be the consumption of energy for the removal of a given quantity of heat.

Of all the physical factors entering into the design of plant, possibly thermal factors are the most difficult to estimate. Heat has to be paid for, and it is therefore necessary to know how to use it economically, just as it is important to obtain a good yield of the product from the raw materials provided. It is also desirable, and often absolutely necessary, to know with reasonable accuracy times of operation for conducting various reactions, and these generally reduce themselves to thermal problems in the end. In the case of any exothermic chemical reaction, the calculation of thermochemical data presents no difficulty, and the problem involved is generally a question of knowing how to impart to, or extract from, the reaction mixture a certain number of heat units in a given time. In other words; it is necessary to know something about heat transmission. Unfortunately a calculation on the basis simply of coefficient of conductivity is of no value, as this simply gives us information regarding the resistance of the metal wall of a pipe, for example, to the passage of heat. That is to say it gives us information regarding the flow of heat from one surface of the metal to the other. This resistance is, however, almost negligible in comparison to the enormous surface resistance outside of the metal, and a calculation on the simple basis gives a resistance which is too low by many hundreds per cent. It is found in this case that the surface resistances differ very considerably, the rate of transmission of heat, for example, from a hot gas to a cooler metallic surface, being of a different order of magnitude from that from a hot liquid to a cooler metallic surface. The resistance of the surface films is also dependent upon the mechanical disturbance of the fluids in contact with the surface, and in consequence empirical relations between velocity of movement of the fluids, and heat transmission, can be derived. The calculation of heat transmission factors is by no means a simple matter, and it must be admitted that at present there is no final and scientific solution of the problem, although a knowledge of the various influences hindering transmission is certainly of immense value in the design of chemical plant. In this connexion it is customary to employ coefficients of heat transmission, expressed in heat units per unit surface per hour per degree difference in temperature. It will be noted that such a coefficient is dimensionally different from a coefficient of conductivity. The use of this coefficient nevertheless makes the assumption that heat transmission is proportional to temperature difference, yet the latest investigations go to show that this assumption is far from perfect.

Owing to the difficulty of calculating the heat transmission factors of chemical plant, there is an important tendency to employ evaporative methods of cooling, and in this direction may be mentioned the use of vacuum crystallizers in which the cooling is produced without heat transmission devices. Obviously in such cases, a knowledge of vapour pressure and latent heat will form the essential factors of design.

Loss of heat by radiation and by conduction is a matter of importance, and the investigation of more complex cases, such as the heat losses from furnaces, is only possible by physical methods.

Applications of electricity are becoming more and more familiar in manufacture, and in addition to processes involving electrolysis, there is now the application of electrical precipitation of dusts, and the use of electro-osmotic processes for dewatering many materials. The effect of light on certain chemical reactions is also of importance, and there are cases in which this principle is applied on a large scale.

Instances under the above heads can be given almost without limit, over the whole range of chemical manufacture, but no matter how simple the chemical manufacture may be, owing to the circumstance that operation on a large scale makes the use of glass vessels impossible, it is necessary to use various controlling instruments which will let us know what is happening inside the plant. Practically all these instruments are dependent upon physical principles, and some of them are marvels of ingenuity, and occasionally physical principles are called into use which might be quite unexpected.

The various types of distance thermometers, temperature alarms, flow meters, pressure indicators, depthometers, and the like, are familiar in almost every works. Sometimes the ingenious application of physical knowledge will give an instrument of control of extraordinary simplicity. For example, whilst it is possible to secure various types of gas analysis apparatus which will indicate, and even record, variations in the composition of a gas, it is sometimes possible to dispense with these somewhat complicated appliances in favour of a simple physical device. The application of measurement of refractive index of gases, and the use of the interferometer for indicating small variations in composition, finds application on the large scale, and an alarm has been patented for use on synthetic ammonia plants, in which two organ pipes are blown, one with a standard mixture of gases, and the other with the mixture employed in the process, any change in composition being indicated by a slight difference in the pitch of the notes so produced, with the consequent beats becoming audible. It is not possible here to exhaust this subject, but a few general indications have been given which will serve to show how important these physical factors have become in modern chemical plant.

III

CHEMICAL FACTORS

Of the chemical factors entering into the design of chemical plant, only those having a direct bearing on the plant construction will be considered, and it need only be mentioned that occasionally it is necessary to refer back the process to the laboratory for some modification which will effect a simplification in plant. For example, if a process has been worked out in the laboratory, involving the heating of some material under pressure with hydrochloric acid, the chemical engineer would be disposed to ask the research chemist to investigate whether it would not be possible to use sulphuric acid instead, and if such a modification were possible, the construction of the plant would be an entirely different matter.

Of all the chemical factors entering, the most direct depend upon a consideration of the chemical properties of various constructional materials, and how they will withstand the action of the various reagents employed at the temperature and pressures involved in the process. Most chemists, during the early part of their training, have boiled up in test tubes small pieces of various metals with common acids, both concentrated and diluted. In these experiments various results will be remembered, and it is very surprising at first for a chemist to hear that sulphuric acid actually can be concentrated in cast-iron vessels, and whilst such vessels do not last for ever, yet the process is practical in many cases. It is also necessary to know the effect of concentration and temperature upon the rate of corrosion, not merely of pure metals with pure reagents, but with ordinary qualities, such as are met with in practice. The effect of impurities is sometimes very extraordinary. It is, for example, usual to specify the purest quality of lead for preliminary concentration of sulphuric acid, yet it is found that small proportions of impurities in the lead have quite different effects upon the resistance to corrosion, antimony and tin have apparently but little influence, copper is supposed to improve the resistance, but the difference is difficult to detect in practice, whereas bismuth is said to be absolutely fatal.

It is also necessary to exercise care regarding the impurities present in the reagents. Aluminium will, as is generally known, resist the action of strong nitric acid and nitrous fumes, and in works in which nitric acid is manufactured from the atmosphere, aluminium is very popular, and undoubtedly a great success as a constructional material. On the other hand, when nitric acid is manufactured from nitrate of soda, which almost invariably contains a little chloride, opinions are likely to be divided concerning the use of aluminium, and in some plants where the acid is carefully manufactured, and is practically free from hydrochloric acid, it will be found that aluminium pumps can be used for handling the concentrated acid with great success. On the other hand, in another works in which the same method of condensation is not employed, the experience would be altogether different. For similar reasons aluminium fans are quite successful for the ventilation of a nitrating building, or a guncotton plant, but such fans would probably only last a few hours if used for draughting a set of nitric acid absorption towers, where the gases would not be simply a mixture of nitric acid and air, but would also contain chlorine compounds.

Instances of this kind are familiar in every chemical works, though it is sometimes not recognized that there is such a thing as difference in the quality of the constructional materials. Cast iron will withstand the action of ordinary strong sulphuric acid just as well as steel, yet with fuming sulphuric acid, cast iron is not always a success. Again there are different qualities of cast iron, the purest, manufactured from Swedish iron, showing very superior acid-resisting properties to the ordinary kinds, and again, the introduction of silicon into cast iron has a great influence on the resistance to corrosion.

It is therefore necessary to have, not merely a test tube knowledge of the chemical properties of constructional materials, but practical knowledge, if any sort of successful design is to be attempted. Very frequently the temperatures at which operations are conducted in a chemical works are far removed from those within the experience of the mechanical engineer. Autoclaves in a chemical works may be operated at temperatures at which the properties of constructional materials are not well known, and under pressures which are much higher than those ordinarily employed in the case of steam plant. In this case there is a need for research, but it is obviously useless to attempt design on a basis of ordinary engineering data.

Chemical effects are occasionally produced by the materials from which the plant is constructed, namely the constructional materials act as catalysts. In the case of the chlorination of benzene to chlorbenzene, it is advantageous to use an iron vessel, as the vessel acts as a catalyst. On the other hand, if it is desired to manufacture benzyl and benzal chlorides from toluene, we are very careful to avoid even the possibility of a trace of iron getting into the apparatus. Even the use of lead vessels is not attractive, and whilst it is often stated in the books that lead has no action as a catalyst, yet, in practice, in many of these chlorinations, lead has too much catalytic effect. In some hydrolyses of nitro-chlor aromatic compounds either iron vessels or copper vessels can be used, but it is found that the reaction proceeds far more quickly and smoothly in a copper vessel, and this is presumably a catalytic effect. A knowledge of such properties of materials can only be collected by experience on a large scale, and laboratory experiments are not of much value.

Often there is a commercial aspect which is important; for example, if it were desired to convey by rail or ship a large quantity of nitric acid, in the ordinary way the only method which would be possible would be to use glass carboys, and it is extremely doubtful whether many shipping companies would care to risk taking such a cargo. On the other hand it would be possible to use large iron vessels, or even steel drums, if a comparatively small proportion of strong sulphuric acid were mixed with the nitric acid, the effect of this addition being to stop entirely the corrosive action of the nitric acid. It is also important to remember that even a comparatively insignificant mistake may have disastrous results in a chemical works. For example, a valuable aluminium still should not be fitted with an ordinary mercury-in-glass thermometer. If the thermometer were broken, the still would probably be of no further value. Thoughtlessness of this kind is of course very difficult to avoid.

Apart from the question of materials, the most important chemical factors are those of a thermochemical character. Calculations involving heats of combustion, heats of reaction, and of dissolution, enter into a very large number of designs, and in a very large number of cases the time of reaction simply depends upon the being able to remove the heat of reaction at a sufficient rate. Very frequently reactions are carried out on a large scale in a very sluggish manner, owing to the circumstance that the heat of reaction cannot be taken away quickly enough with the plant provided. It is the duty of a research chemist to calculate the necessary thermochemical relations for the use of the chemical engineer, so that the best size of working batch may be settled.

In the laboratory, operations are often comparatively simple, but these give trouble on the large scale. The chemist can make an important contribution towards the success of the plant, by taking a little trouble to find the conditions under which the various products are in the most suitable form for treatment. For example, if a substance is precipitated from solution, it is desirable that the conditions should be the best possible for the production of a precipitate which can be easily filtered, and if necessary washed. It should also be noted that in many cases these precipitates may become colloidal after washing free from electrolytes, with the result that filtration becomes difficult. It is the duty of the chemist to settle these matters, and so contribute towards successful working of the plant at a later stage.

IV

MECHANICAL FACTORS

It is not possible to give here even a summary of the mechanical principles which enter into the chemical engineering design. It may be stated simply that a chemical plant must be structurally and mechanically sound, and must satisfy every requirement of a "good engineering job." It is necessary also to make allowances for corrosion, and from the mechanical point of view the plant must be designed, not merely to stand up as erected, but also to resist the action of the reagents, and still remain in a state of mechanical perfection for a reasonable time. Apart from unusual conditions referred to above, the mechanical factors usually present but little difficulty.

Very closely allied to this subject is the matter of the practical factors and economic factors, and it is also important to be able to calculate approximately the costs of various different constructions for comparison, as in such cases where alternatives present themselves, as we shall see later, a comparison from a business point of view has to be made.

All mechanical constructions in a chemical works should be subject to practical considerations, otherwise the results will be unsatisfactory. For example, occasionally in a chemical works types of construction are required which certainly would not appeal to the ordinary engineer. In the construction of autoclaves for heating substances with a solution of caustic soda under moderate pressure, it is frequently desired to employ riveted steel vessels. There is nothing essentially wrong with riveted steel vessels for this purpose, providing they are constructed in the proper manner, and provided also that both ends of every rivet can be got at, and that it is possible not only to caulk every joint, but also to re-make the joints if necessary.

It is almost a universal experience when drawings of these vessels are sent to the constructors, that they are returned with sarcastic observations regarding the design, simply because the boilersmith does not understand the requirements of the chemical works. There is, in fact, a difficulty in getting engineering firms to construct chemical plant precisely in the manner required, and whilst very often a constructing firm likes to have some latitude regarding the construction, it is necessary to specify anything of a special character with the greatest accuracy. It must nevertheless not be forgotten that in every chemical works there is a large quantity of apparatus which is purely of an engineering character. The design of these portions of the plant usually presents no difficulty, although there is a tendency to scamp the design of the boiler plant, and leave it to the mechanical engineer. It should not be forgotten that the chemical works differs from the power station in many respects, in that the supply of steam required for process work is very large in comparison with the amount required for power production. Furthermore the load is by no means steady, and in some works a very difficult problem is involved in economically designing a plant for the maintenance of a steady supply of steam at the desired pressures. Similar differences apply in other sections of the works.

V

USE OF EXPERIENCE AND DATA

From the complexity of the problems involved in chemical engineering design, it will be obvious that it is not always a perfectly straightforward matter to convey the results of experience from one plant to another, which is not on the same scale, or perhaps not on quite the same operation. Likewise, owing to this complexity, care is necessary in figuring out chemical engineering data from the results of small scale experiments, or of trials conducted in extemporized plant. The danger of applying so-called common sense has already been pointed out, and these observations apply not only to the mechanical, but also to the physical and chemical factors.

In mechanical engineering work it is known that the use of models is only of value when some criterion can be calculated which enables the performance of a machine on a larger scale or under different conditions to be estimated from the results of experiments with the models. The principle relating to this matter has been stated in the purely mechanical field, under the name of the Principle of Similitude. The comparison of geometrically similar structures has been classified under two heads, accordingly as they have to withstand the action of external forces, or systems of forces similarly applied, or accordingly as the comparison is simply made as to their stability when this is mainly or essentially due to the forces of gravitation.

Consider the simplest example under the first head: a load suspended by a wire or rod.

In Fig. 1 we have two suspended cubes, B being geometrically similar to A in all respects: If weight of A = W, then the unit stress in the supporting wires is

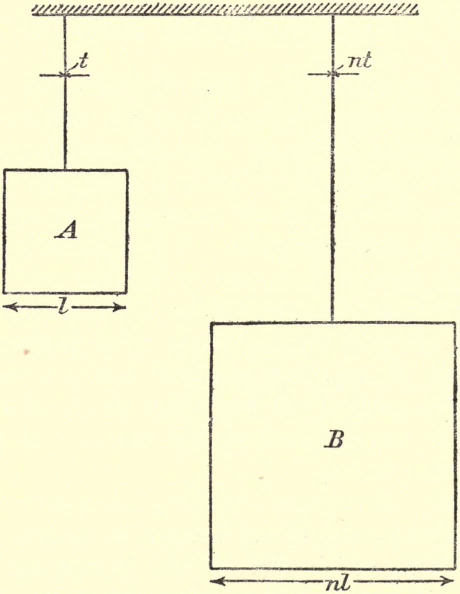

Fig. 1.

$$\text{System A: } W \div \frac{\pi t^2}{4}$$

$$\text{System B: } Wn^3 \div \frac{\pi n^2 t^2}{4} = Wn \div \frac{\pi t^2}{4}$$

i.e. the stress in the larger system support is n times that in the smaller. It is therefore obvious that in such cases mere enlargement of models would be dangerous.

But now let us consider an example of the second kind. In Fig. 2 we have two geometrically similar

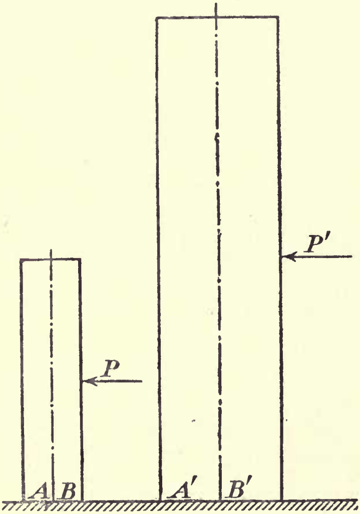

FIG. 2.

columns, and we have to consider their *stability*, each being acted upon by the wind, for example.

The resultant of the wind pressure P′ will be equal to n^2P and the turning moments will therefore be:

System A: $P \times AB$
System B: $n^2 P \times A'B'$

i.e. the turning moments are proportional to the cube of the linear dimensions.

The resisting moments are, however:

System A: $W \times AB$

System B: $Wn^3 \times A'B' = Wn^4\, AB$

i.e. proportional to the fourth power of linear dimensions. In consequence it would be stupid and dangerous to design a small chimney by simply copying a large one on a smaller scale. Such a chimney would not be equal in stability to the larger structure.

These examples are simple, but the same type of reasoning leads to important generalizations which serve to make experience really profitable. They also emphasize the danger of so-called judgment and common sense.

Calculations of similar nature may be used when not only the variation is in respect the linear dimension, but other factors such as speed, and it is very valuable to know "how things vary." For example: The limiting piston speeds of different sizes of engines are the same; furthermore if two engines were built to run at the same piston speeds, with the same steam pressure, the smaller would weigh less per horse-power in proportion to linear dimensions. Two engines built to the same drawing on different scales would prove satisfactory. Other examples are: similar shafts have critical speeds inversely proportional to their diameters, and similar fly-wheels and similar governors give the same degree of regulation.

In another volume of this series the friction of liquids in pipes is considered. The type of calculation employed in all such problems is in principle one of the "similitude" type, the essential point being to determine the criterion on which the comparison must be based.

Similar calculations have an important bearing in estimating the various factors in a chemical engineering design. A well-known example, the case of a nitrating pan, can be considered. In this case, the heat of reaction is taken off by means of cooling surface, and if an experimental pan were used, and a time of reaction of three hours obtained, it would certainly not be possible to obtain this time of reaction in a pan of larger capacity, designed simply by increasing the scale of the smaller pan, as the mass of reacting material will vary as the cube of the linear dimension, whereas the cooling surface will vary only as the square of the linear dimension.

In many types of apparatus there are a large number of different factors to be considered, and the calculations will fall generally into two classes: that in which a scientific and theoretical knowledge of the effect of variations is known, and the other in which the factors may be so complex as to make truly scientific calculation impossible. The data of chemical engineering work will therefore be found in two different classes of formulæ, namely those which are based upon the physical and mechanical laws upon which the operations depend, and the others being simply empirical formulæ, applicable over only a very small range of conditions as a general rule.

In cases where the various physical factors can be separately considered, the useful formulæ will have a general structure similar to the mathematical expression of the various physical laws, but very frequently, and at the present time more often than otherwise, formulæ have to be used which are simply convenient methods of showing variation.

In expressing the specific heat of gases at various temperatures, or vapour pressures of liquids at various temperatures, formulæ of the type $y = A + Bx + Cx^2 +$, etc., are very common, and these do not indicate in any way any natural law, but are simply empirical expressions which serve to fit the facts.

More often than not, as "nature does not proceed by leaps and bounds," the various functions involved in chemical engineering calculations are continuous, and when plotted on squared paper give smooth curves. Plotting on logarithmic paper of such relations will generally give something near a straight line, and substantial accuracy can be secured, at any rate over a restricted range of conditions, by expressing the results as though they gave a true straight line on log. paper, i.e. expressing them in the form of an equation of the type $Y = Ax^b$.

Such formulæ have the merit of being generally applicable, and they also lend themselves to quick calculations on a slide rule. The great merit of "monomial" formulæ of this kind is that although they are purely empirical, they can be very useful as a means of summarizing observations.

Very frequently quite complex phenomena can be concentrated into a useful formula of the type $y = Ax^b\ m^n\ c^d\ f^g$, etc., where the various variables are indicated by the letters x, m, c, f.

It is, for example, possible to construct a useful formula for the amount of water which can be condensed in a coil per hour. In this case the variables on the right-hand side would be mean temperature difference, diameter of coil, number of turns, hydraulic mean depth of tube, and the indices would be different in each case.

It is interesting to know that in another complex physical field, namely gunnery, this type of calculation is very much employed, and although the method has not been extensively and systematically applied very much in chemical engineering, a reference to special investigations on particular sections of the subject will show how useful this method can be. A well-known writer on hydraulics, Barnes, has produced a collection of these formulæ which will cover practically the whole range of problems involving the flow of water at ordinary temperature through any kind of pipe or conduit. This is a fair example of what can be done according to this method.

Data ascertained from experiments are generally calculated out and expressed in the most widely applicable form, and it is important in such cases to keep in mind the nature of the calculations involved.

If, for example, we had a series of observations regarding the heating of an autoclave in a gas-fired setting, and we wish to use this experience for application to problems in which the firing conditions are similar, we should have to ascertain first of all the rate of transmission of heat per unit surface in unit time. This rate would naturally depend upon the temperature, and would in fact be in the nature of a differential coefficient, and would be proportional to the slope of the heating curve at each temperature. It will be realized that the actual phenomenon of heating up is comparatively complex, but provided we wish to apply our data to a somewhat similar case, it would certainly be possible to construct a simple logarithmic formula connecting temperature and rate of transmission. It will be noted that this is not the coefficient of heat of transmission as ordinarily used, as the difference of temperature is not taken into account in the rate. If now we wish to apply our results to another problem, perhaps over a different range of temperature, we shall have to perform in some way or other what is mathematically a process of integration. This is a very simple example of a type of calculation which is constantly occurring in chemical engineering work, and for a large number of problems it is only possible to transfer experience to a new field by such a method.

Our formulæ are very frequently expressions for calculating quickly the values of our differential coefficients under varying conditions, as these express the results in the most widely applicable form.

VI

PRACTICAL FACTORS

The practical factors of chemical engineering design include the various tips and dodges that an intelligent foreman could give relating to the working of a plant, and these factors are of equal importance to those which are calculated on scientific principles. The modification of mechanical factors in view of corrosion and other chemical influences has already been mentioned, but from a practical point of view it is also well to appreciate that unexpected effects are always liable to occur in an ordinary chemical plant, and one of the first things to consider in preparing a design is to be sure that an accident cannot occur. After this has been thoroughly considered, it is just as well to look at the matter once again, and consider what the effect of an accident would be if one were to take place.

In a chemical works, a minor accident is liable to be very serious. The breaking of some small connexion may set free a stream of hot acid or poisonous gas, with deplorable results, and in chemical engineering design it should always be a rule that "it is better to be sure than sorry." Obviously no matter how beautifully constructed reaction vessels may be, if there is the very remotest chance of leakage of corrosive material, structural parts must be suitably shielded or protected from corrosion, otherwise in certain cases it is possible that the whole of a valuable plant might collapse, owing to a small leakage which could not be immediately observed. The most important practical consideration is that the plant must be one which can be easily inspected, easily put into place, and easily repaired, viz., every part must be accessible.

Chemical plant is usually heavy, and from the very nature of the operations occasionally a part has to be taken out and replaced. It is essential therefore to provide reasonable facilities for getting each portion of the plant in and out as required, without dismantling the entire installation or tearing down the buildings. Naturally if this replacement is likely to be frequent, the facilities may be made more elaborate, and in some cases it may be necessary to go so far as to provide an overhead travelling crane for such purposes. In most plants the necessity for a "sky hook" is felt at some time, and if there is any doubt about the life of a heavy vessel, it is good policy to fix a convenient girder overhead, to enable a lift to be made with the minimum of trouble.

In the case of electrolytic plant in which a number of small cells is employed, and where it is constantly necessary to remove cells for repairs or reconstruction, and it is not possible to leave wide gangways, the expense of providing an overhead travelling crane would be money well spent. This matter of accessibility for repairs often may make a difference between commercial success and failure with a new process. Other examples can easily be given. Lead-lined enclosed vessels, such as lead-lined "eggs," should be provided with openings of large size, so that it would be possible to introduce the necessary lead sheets for lining, even with a workman inside, or alternatively one end must be made removable. Vessels of this type are often seen in chemical works which have been riveted up after a portion of the lead lining has been done. This method gives a very nice looking vessel, but after the lead lining is damaged it is not easy to reline the vessel. Occasionally a large vessel will be provided with an extra opening, merely to facilitate handling of replacement parts. Reduction pans used in the dyestuffs industry are, for example, frequently provided with a door on the side, about 4 ft. from the bottom, so that the liner plates may be passed through this hole to a workman inside. It will be obvious that this is a very much more pleasant proceeding than having to pass them through a manhole in the top cover, and also very much safer for the man working inside the pan.

It must not be forgotten that in many chemical plants repairs are troublesome, in that the materials worked with are explosive, or poisonous, or inflammable. Very frequently there is trouble in getting a tradesman to make a comparatively insignificant repair, as he is afraid of being poisoned, or blown up, or burnt. This possibility is not to be forgotten, and it should be remembered that with explosive materials it is frequently necessary to remove the unit of plant, lock, stock and barrel, before any repairs can be attempted, and in some cases the parts have to be burned in a fire before they can be dealt with by the tradesman.

Working with an explosive material, a lead-lined cast iron vessel cannot be considered very admirable, as in the course of time it is possible that a leak will occur in the lead lining and some explosive material find its way between the lead and the iron. This naturally means that the whole of the lining must be removed, and it will be clear that if the material being dealt with were, say, nitro-glycerine, one would not feel too confident in giving a workman instructions to remove the lead lining. In such cases, it is certain that a far better construction would be a vessel of very thick lead, supported on an external cage, or perhaps even a vessel of cast lead of sufficient thickness.

One of the axioms of chemical engineering design is that adequate manholes should be provided where necessary, and that these should be big enough. Many of the manholes provided on chemical plant are far too small, and it is no exaggeration to say that in many works a number of vessels can be found which can only be repaired by selected workmen of small size. A manhole should be big enough for any normal-sized man to jump through without difficulty, and if there is any material of a poisonous or suffocating character handled in the plant, the manhole should be even larger if possible. One hears frequently of accidents in chemical works owing to a man having entered a vessel, for the purpose of cleaning, which had previously contained, say, benzene. In accordance with the rules of such works, he has attached to him ropes, so that if he should become unconscious he may be hauled out. A single experience in attempting to haul an unconscious man through a manhole of ordinary size will suffice to print upon the mind indelibly the feeling that no manhole can possibly be too large. It is just about as difficult to get an unconscious man through a manhole as it is to remove a cork which has passed to the inside of a bottle.

Whilst on this point, it is interesting to notice that the commonest design of benzol distilling plant is according to a scheme illustrated in Fig. 3. With this design, assuming that an ordinary type of rectifying column is employed, before a man could be permitted to enter the still for repair of the heating coils, or for cleaning, it is necessary to steam down the rectifying column very persistently, and to displace as far as possible all vapour. With the design shown on Fig. 4 it will be noted that the connecting pipe from the still to the column may be removed altogether, so that there is no possibility of a down-draught of benzol vapour from a badly cleared column. The first construction is of course sometimes cheaper.

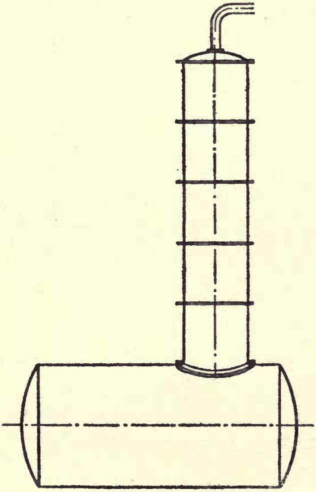

Fig. 3.

The second very important practical consideration is that of safety in working. It will be understood that in chemical works any kind of accident is fraught with serious consequences. It would be impossible to deal with this subject in complete detail, but it is certainly the most false economy to neglect any kind of protection which would give greater safety in working. A few hints may be given from experience, but these do not in any way exhaust the subject. Pipe joints are seldom tight for a very long period against corrosive materials. Such pipes carrying dangerous acids should therefore be put, if possible, in such places that an unexpected leakage does the minimum of injury to plant and workmen. Likewise it is important to give all acid pipe lines a good slope, so that when empty there is very little pressure on the joints. Cocks and valves should never be relied upon to hold back a very

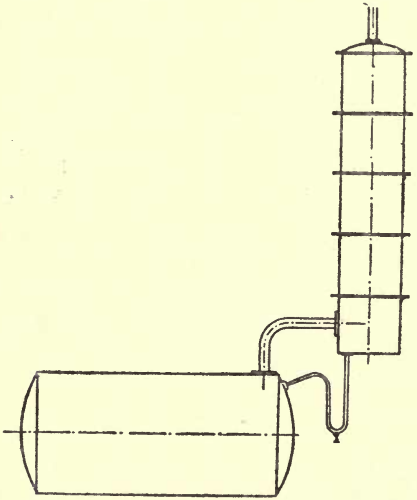

FIG. 4.

large volume of chemical liquid. In some chemical works may be seen large cast-iron vessels of several hundreds of gallons capacity, containing a mixture of nitric acid and sulphuric acid, and these being provided with stoneware cocks, fixed in with acid-resisting cement. In the works the writer has in mind, these vessels were supported on a very heavy wooden staging. The result of this practice can be imagined, when it is stated that on one occasion a careless workman in walking past broke one of the stoneware cocks. Some hundreds of gallons of mixed nitric acid and sulphuric acid ran over the wooden staging, with terrifying results. Similar accidents have occurred even with iron cocks, and it should be remembered that such cocks require attention very frequently, and it is not always possible to empty the vessels simply for the purpose of giving attention to the cock. All these difficulties can be obviated by the use of a plug and seat valve, in addition to the cock, the plug working inside the vessel, and being put in when it is desired to inspect or repair the cock, or in case of accident to the cock.

Following the rule that it should always be the policy to consider the effect when the unexpected occurs, it should also be an axiom to decentralize, as far as possible, accumulations of dangerous material. Fires are liable to occur from unexpected causes.

The electrification of moving belts used in driving machinery may cause sparking and ignition of inflammable vapours or dusts, and where there are moving belts in buildings where dangerous substances are to be handled, it is well to make sure that all parts of the plant are carefully connected to "earth," and many firms go so far as to have the resistance to earth measured frequently.

The circumstance that organic liquids when passed at high velocities through pipes become electrified should also not be forgotten, as several fires have been attributed to this source. Dust explosions are also a possibility.

In a chemical works, in addition to having large manholes, it should also be a practice to have large safety valves wherever possible. More often than not, the safety valves provided to chemical plant are simply the stock appliances which can be obtained from the makers of steam fittings, and are most unsuitable for the work intended. For a large number of purposes the best safety valve is also the simplest. Vacuum stills of the steam heated type, which are used for the purification of organic substances, also require a safety valve to prevent an increase of internal pressure. This may appear to be extraordinary, but it is certain that accidents have occurred with disastrous results owing to the failure of a steam coil in a vacuum still, with a consequent rapid rise of pressure, which could not be relieved viâ the vacuum pump with sufficient promptness. It is important to remember also that safety valves should be as simple as possible, and should be of a type not easily choked.

One of the best safety arrangements for a still is shown diagrammatically in Fig. 5, in which not only is a dead-weight safety valve of very large size provided, but the escape of inflammable vapour into the atmosphere is prevented. This device is used on directly fired stills, in which inflammable substances are dealt with. In this example we have an illustration of the principle that not only is it necessary to provide against accident, but it is also necessary to consider what will happen when the accident against which we have carefully provided occurs unexpectedly. In building a still, it is always arranged that the outlet shall be sufficiently free to prevent any increase in internal pressure, and the safety valve is provided to relieve a sudden and unexpected variation. Under ideal conditions, the safety valve should never be required to function, but in this example provision is made against further possibilities of accident when unexpected conditions arise.

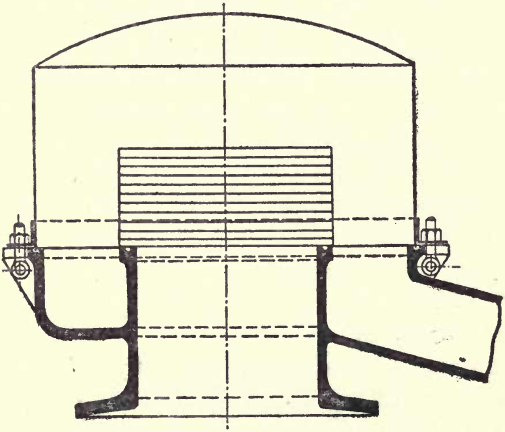

Fig 5.

In erecting plants in which highly inflammable or poisonous substances are dealt with, it is not merely necessary to have the apparatus perfectly tight and free from leakage, but it is also necessary to provide good ventilation, so that if a slight leak does occur, then the escaping vapours may be removed quickly, so that they give no further trouble. In such cases, and in the case of corrosive materials, it is very important that a leak should be visible as soon as it occurs. For this reason the lead-lined tanks for the storage of acid are not always as good as lead vessels supported in a steel frame, where the outside of the lead may readily be seen. Nevertheless this latter construction has the disadvantage, in some cases, that if a leak does occur, it will be uncontrollable, whereas with the former construction it is usually possible to save most of the contents by emptying the vessel as quickly as possible. In a case such as this, the special circumstances have to be considered before a decision could be made, as to which would be the more suitable construction.

Chemical works have a very unenviable reputation in respect of the creation of nuisances. A factory erected near the banks of a river usually has periodical conflicts with the riparian proprietors. The neighbouring farmer also regards the chemical works with great suspicion, and any and every trouble is attributed to the chemical works. Whilst there are legal conditions to satisfy in certain cases regarding the pollution of streams and the pollution of the atmosphere, there are many cases in which there are no such provisions, but it is still necessary, not merely to avoid the creation of a nuisance, but also to avoid as far as possible an evil reputation.

Many chemical works manufacture products the odour of which must be cultivated to be appreciated, and although it may be that an evil smell does no harm, yet it is sure to produce much irritation and annoyance, and much labour and expense is involved in dealing with futile complaints. The chemical works in this respect should try as far as possible to be beyond suspicion, and the plant should be arranged accordingly. Sometimes all that is required in a matter of this kind is to study the lie of the land, and the prevailing direction of the wind. Whilst on this subject it is well to mention that the workman also deserves some consideration, and the more pleasant the plant is to work, generally the less trouble will be experienced with labour. The manufacture of substances such as alphanaphthylamine and picric acid, under the best of circumstances is not inviting, and the more unpleasant the manufacture be, the more the workman must be coddled. In a large number of manufactures again, in this direction, there are legal requirements to satisfy, and these should be carefully considered before any step is made with the plant, and if possible the proposed designs should be discussed with the official inspectors.

In most chemical works handling objectionable materials, respirators and similar devices are provided for the use of the workmen. At best these are most unsatisfactory, and no matter how objectionable the conditions may be, the average workman has a sneaking dislike to these devices, and will dispense with their use the moment supervision is relaxed. It is a commonplace that workmen in acid and chlorine works prefer to chew a piece of damp rag, rather than put on what they scornfully describe as "a muzzle." In view of this, extra precaution in the construction of the plant is necessary, and any design which will necessitate the use of these by the workmen should be adopted only with great reluctance. The same considerations apply to the use of rubber gloves, rubber boots, and goggles.

The human element enters very largely into the operation of chemical plant, and the ideal installation is one which would be "fool proof." Too often the training of workmen to operate a chemical plant is a very difficult matter, and it is necessary for the manager to live close to the works, so that he can be called during the night to deal with any blunder which may have been made. When one inspects many of the chemical plants in operation in this country, one is not surprised that the managing chemist has a very anxious and active life, and it says much for the intelligence of the workmen that accidents are not more frequent.

In many works "spoilt batches" occur with great regularity. Occasionally a workman turns the wrong tap, and an entire charge is lost altogether. "Foolproofness" in a chemical plant is very difficult to secure in most cases, and it is impossible to give a complete set of general rules, as there is certainly no substitute for experience in this direction.

The research chemist should not forget that chemical plant is generally constructed of opaque materials, and whilst in adding a quantity of reagent from a bottle the magnitude of the addition can be seen, yet in chemical plant the results are not visible. Everything which can be done to render the inside of the plant visible should be done. Sight glasses and light glasses should be fitted wherever possible, and "lanterns" or glass sided boxes, or glass syphons should be fitted to the pipe inlets, where liquids have to be run in to reaction vessels. Level indicators, and, in some cases, alarms controlled by floats, may be desirable; temperature indicators and alarms may also be required; float indicators and other instruments of control may all contribute to "visibility." The provision of instruments of control is certainly one of the finest investments in a chemical plant.

One of the commonest mistakes in chemical plant construction is a needless complexity of pipes and valves. It is not surprising that a workman should make a serious mistake by turning the wrong tap, as some of the arrangements of pipes and valves in chemical plants partake of the nature of Chinese puzzles. It is worth while to paint pipes carrying different fluids in distinctive colours, uniformly throughout the entire works, and in many cases it is advantageous to number or even label the different valves, so that a mistake is less likely.

All constructions of this kind require very considerable care and judgment in design, and the important point to bear in mind is that the worker is not a mechanical device, and his attention is liable to wander at times, and it is the duty of the designer to make things as easy as possible for him, and therefore as easy as possible for the managing chemist who has to operate the plant. It should also be remembered that the workman is not always full of enthusiasm, and will not break his neck to attend to things which are not conveniently placed, particularly if he does not understand their importance. Occasionally one sees pressure gauges and thermometers placed in such unfavourable situations that it is necessary for the workman to ascend a ladder before a reading can be taken, and then possibly only with the assistance of a hand lamp. Indicating instruments should be provided with the boldest possible scales, and it is false economy to use the small sizes. Indicating gauges should always have a large dial, and if there is any doubt about illumination, a special light should be fitted, and the instrument should be easily visible to a short-sighted man, standing in his ordinary working position.

Occasionally one sees instances of crass stupidity in the design of chemical plant, but very often these are matters which are liable to be forgotten. One of the worst blunders is in connexion with the distribution of acid by means of compressed air. Occasionally one sees an " egg " of large capacity, provided to elevate liquid to a tank of slightly smaller capacity. In consequence it is necessary for the workman to measure the volume of liquid run into the egg, by dipping repeatedly before blowing. It is occasionally forgotten that it is not easy to blow up half the contents of an egg. In extemporized plant the only remedy for this trouble is to fill part of the egg with lumps of metal, or to cut off a portion of the dip pipe. In any case it is desirable also to provide overflows on high level acid feed tanks, so that if by chance the workman pumps up too much liquid, the excess will run over without damaging the surrounding apparatus and structure. It may be mentioned in connexion with this subject that it is an axiom of chemical engineering never to put a cock on the discharge pipe from an egg.

The above examples are simply chosen at random, and no pretence has been made to exhaust the subject. They are chosen simply to illustrate the various principles, and to give indications of the points which must be thought of in the design of a chemical plant on purely practical grounds.

VII

ECONOMIC FACTORS

As stated at the outset of this monograph, the business of a chemical plant is to make profits, and the efficiency of a chemical plant is measured solely by the magnitude of the profits produced. It is the business of the chemist to control the process in the sense of securing the highest possible yield for a given expenditure of raw materials. It is not to be forgotten, however, that the economic factor is by no means finished, when the question of yield is settled, as cost of manufacture involves several other factors, and is not simply a matter of raw material.

The factors of production costs are: raw materials, including fuel, power and water; labour and overhead charges, repairs, interest and depreciation, not only on plant but also on stocks of raw material.

If a chemist who has worked out a new process approaches his directors with the particulars of his results, he is promptly asked two questions: How much profit can be made? and, How much capital will be necessary? These two questions may differ in importance, but strictly speaking it should be possible to calculate a maximum permissible cost of plant for any given manufacturing proposition.

Economy of raw materials is possible, not only directly, but also by recovery of by-products. Direct economy of raw material is not only a matter of process, but is very frequently dealt with by the plant. In many chemical manufacturing operations "mass action" is involved, and it is necessary to employ an excess of reagent. Occasionally the conditions differ between different types of plant, in such a way that the proportion of excess reagent can be modified. In some cases also it may be possible with one type of plant to omit altogether some expensive solvent. In certain operations in organic chemical manufacture, for example, it is customary to employ aqueous alcohol, in which the materials are slightly soluble, to assist the reaction. In some such cases it is found that the use of very efficient agitators makes the use of alcohol unnecessary, with consequent economic advantage. Very frequently one type of plant is found better than another, and it is a question for decision, if the more efficient is also the more expensive, which shall be used.

Economy of fuel and labour need only be mentioned here. The relative importance of these "raw materials" will depend on the type of manufacture, but it may be stated that generally it is now well worth while to elaborate the plant if necessary to economize in these.

Economy in overhead expenses should not be forgotten, and the most important factors tending to reduce this item of production cost are "fool proofness" of plant, and continuity of operation. Continuously operated plants are becoming more and more popular, and in a very large number of cases the tendency with these plants is not only to diminish labour charges, but also to cut down very materially the necessity for supervision. Whereas in using plant for the manufacture of materials in batches, it is generally necessary to exercise control by chemical examination of each batch. With a continuous plant once the installation has been tuned up, only occasional tests are required, as the variation of physical conditions is in such cases very seldom left to the control of the workmen.

The recovery of by-products is so important as to be in some cases vitally necessary to competitive production. In the Leblanc process of the manufacture of alkalis, it is a commonplace that the by-products are of first importance. From the point of view of design of plant it is necessary to investigate how far the recovery of by-products is worth while, and the question usually resolves itself into a consideration as to whether it is financially sound to go to the expense of the necessary recovery plant for the sake of income from by-products recovered.

The question of capital cost is always a serious one to most chemical manufacturers, and in many cases the tendency is to sacrifice manufacturing efficiency for the sake of reduction of initial outlay. This is largely due to the natural reluctance of the manufacturer to risk his money on a chemical proposition, and it is unusual to find in this country that too much latitude is allowed.

From a scientific point of view, a plant should be designed to give maximum efficiency and maximum output. From a commercial point of view it is necessary to remember that it is desirable to have maximum output from the least expensive plant, and that occasionally efficiency will have to be sacrificed to a greater or less extent for the sake of cutting down the initial expenditure. In purely mechanical constructions it is possible to work out a permissible cost of plant, and the economic value of any proposed elaboration can easily be determined. In chemical engineering work the same determinations are possible if market conditions for products and raw materials are reasonably stable. In considering two alternative designs, one of which is more expensive than the other, the above considerations must be kept in mind.

It should not be forgotten also that where expensive materials are dealt with in manufacture, the interest on the money locked up in these materials may be a serious matter. In such cases it is usually necessary to design the plant so that reaction times will be cut down to the lowest possible figure, and very frequently, by use of continuously operated devices, the bulk of reacting materials can be cut down to a fraction of what will be required in an intermittent plant. As an example may be mentioned cases of crystallizing plant, in which the amount of material locked up in the plant at any time is often more than eight times what it would be in the modern apparatus for crystallization in motion.

One of the most difficult economic factors to estimate in chemical engineering work is the cost of repairs and replacements, and also the economic effect of loss of production due to such repairs being necessary. Owing to the very nature of the materials employed in most chemical plants, repairs are very frequently necessary, and it is very difficult to collect practical data which has anything like general application. It is very useful to possess data, if such can be obtained, regarding the number of charges constituting the "life" of a given type of plant. This life is frequently fixed by the corrosive nature of the materials handled, and in the absence of practical information is very difficult to judge.

Very frequently a choice may have to be made between several different materials of construction. For example, in a certain manufacture, it is found that the life of a stoneware vessel is about 60 charges only, a 12 lb. lead vessel of corresponding size about 100 charges, a copper vessel $\frac{1}{4}$ in. thick about 200 charges, and presumably a platinum lined vessel would last almost indefinitely. In such a case a decision has to be made whether the risk of loss of material, and loss due to cost of repairs, and loss of production time, in the case of the cheaper construction, is sufficient to counterbalance interest and depreciation on the more expensive construction. In such a case it should not be forgotten that when a stoneware vessel is broken it is of no value. A lead or copper vessel can be sold as scrap, whereas a platinum vessel would hardly be diminished in value. Naturally in a case such as this it will be found that different works have made different decisions, accordingly as they have estimated the importance of the various factors.

VIII

THE FINAL DESIGN

SUFFICIENT has been said regarding the various factors entering into a chemical engineering design, to show that there is a very considerable complexity in every case. In view of this complexity it is but seldom that any two chemical engineers will arrive at perfect agreement. Some of the factors cannot be expressed in accurate figures, and there is invariably something which has to be left to the mercy of " horse sense " and intelligent " guesswork."

It will be realized that in a large number of cases, when these factors are considered, there will be an obvious conflict, as for example, in the case of the conflict between capital cost and working efficiency in certain cases. In consequence, the best chemical engineering designs are usually the result of a series of judicious compromises. The greatest care is necessary to avoid hasty decision, and careful consideration and coolness are necessary in order that due place shall be given to each factor which operates.

The human element invariably enters, and is difficult to master. Certain types of construction are greatly favoured by certain engineers, and these sometimes may almost be regarded as obsessions. The late Professor Perry once made the observation that there were some engineers who would make an umbrella of cement.

It is essential that where sufficient data cannot be accurately obtained, a reasonable margin in design must be allowed, and the arrangements must be such that the maximum flexibility of operation will be possible.

Whenever possible each factor should be carefully calculated out, and if there is previous experience to go upon, then the application of the available data must be carried out with the greatest possible care, and not simply in a haphazard direct manner, as would seem obvious at first sight.

In every case the danger of guessing, or designing with insufficient information, should be fully appreciated, and it may be stated that the delay and labour involved in preliminary investigations is always well repaid, as alterations in the finished plant are invariably very costly, and errors may prove disastrous not only to the exploitation of the particular plant, but to the manufacturers themselves.

There is unfortunately a tendency in this country to scamp the designing work, and "worry through" afterwards. This procedure can, in the end, only lead to inefficient working, and the plants so produced are doomed from the commencement to fail against the keenness of modern competition.

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