

## INDUSTRIAL METHODS OF LIQUEFACTION AND PRACTICAL APPLICATIONS OF LOW TEMPERATURES.

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The title of this paper was not selected by myself. Were I to deal with every subject which might legitimately be collected under such a comprehensive umbrella, I should require far more time than has been allotted to me. I have therefore decided to deal only with the subject of the separation of the constituents of air, with special reference to low temperature liquefaction.

When people talk of separating the constituents of the air, nine out of every ten have in view only the extraction of oxygen from the atmosphere, and, as I have been engaged in extracting vastly more than my fair share for the last thirty-five years, the subject is one on which I should be able to speak with some degree of authority. In fact, the history of the British Oxygen Company, with which I have been associated for the whole of that period, is so intimately bound up with the industrial development of oxygen that it is impossible, at any rate for me, to consider these subjects apart.

Therefore, for historical accuracy, before dealing with low temperature extraction of oxygen from the atmosphere, I propose to refer very briefly to the barium oxide process for effecting the same purpose, as it was undoubtedly by that process, in the hands of the British Oxygen Company, that the oxygen industry was founded.

The British Oxygen Company was established in 1886 as the Brins Oxygen Company, to take over an alleged process for the production of oxygen, patented by two French brothers whose name was adopted as the title of the Company. The Brin process was based on Bous-singault's discovery in 1851, that at a temperature of about  $540^{\circ}$  C. the monoxide of the metal barium would absorb oxygen readily from the atmosphere with the resulting formation of dioxide, and that at a higher temperature of about  $870^{\circ}$  C. the oxygen thus absorbed would be given off again and the barium restored to the monoxide condition ready for the cycle to be repeated.

As a natural consequence of Boussingault's discovery many efforts had been made to establish a commercial process for the production of oxygen based on this apparently unalterable property of barium oxide. In spite, however, of its chemical simplicity, many practical difficulties arose which remained unsurmounted until the advent of the Brins Oxygen Company. Even then it was only after prolonged and costly experimental work which resulted in the Brin process being practically thrown overboard, that the barium method of abstracting oxygen from the atmosphere became an established success. I described the process fully in a paper I read before the Institution of Mechanical Engineers on January 31st, 1890, and I

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cannot do better than refer to that paper anyone who may be still interested in the process.

Here it is sufficient to say that the fundamental changes which we effected were: (1) working at a constant furnace temperature of about  $650^{\circ}\text{C}$ ., change of pressure being relied upon for determining the respective

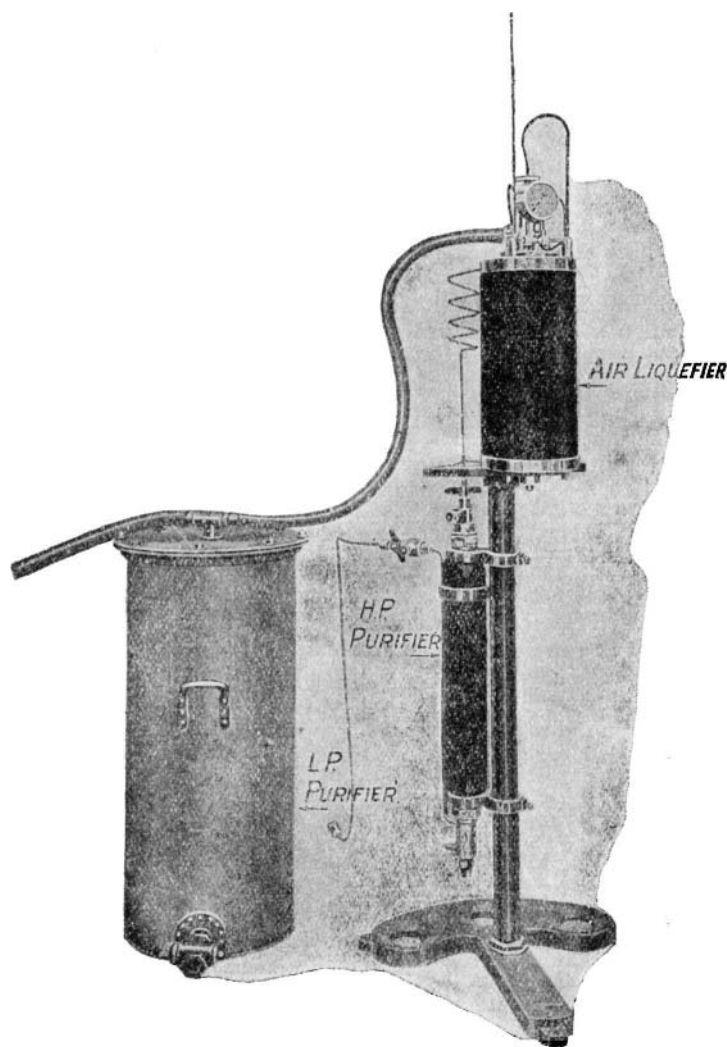


FIG. 1.—Hampson's Air Liquefier.

phases of oxidation and deoxidation; (2) short operations lasting only a few minutes, and (3) the automatic reversal of the various valve gears involved in operating the process.

The process was exclusively employed by the British Oxygen Company for nearly twenty years in their London, Birmingham, Manchester, and Glasgow factories, and a considerable number of plants, varying in capacity

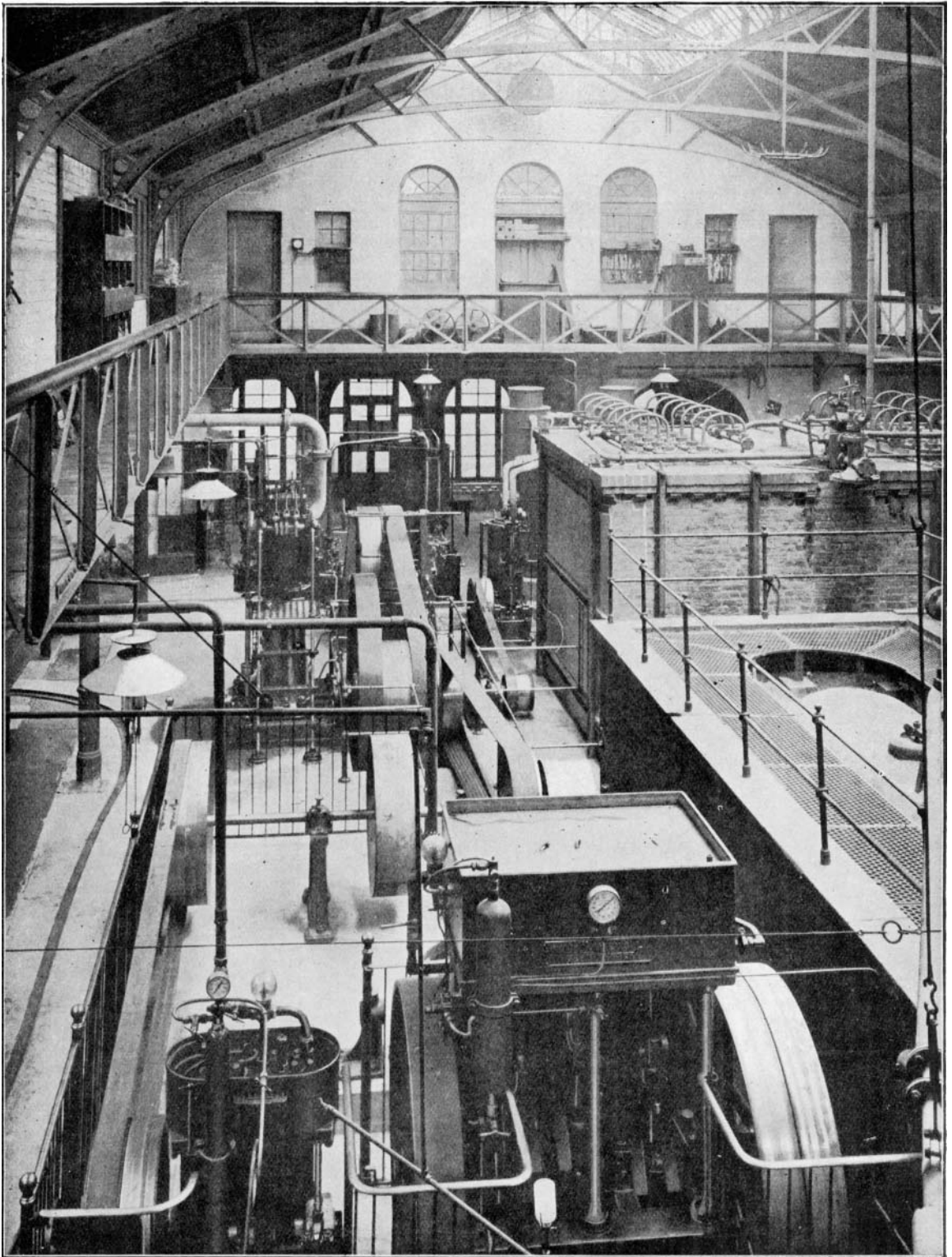


FIG. 2.—Westminster Works, B.O. Co., 1906.

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from 5000 to 30,000 cubic feet of oxygen per day, were also erected by them to provide oxygen for industrial applications. A fact which is especially worthy of mention is that the first plants for the commercial production of oxygen in Paris, Berlin, and New York, were of the barium oxide type and were erected by the British Oxygen Company.

I am afraid not a single barium plant remains in existence to-day although in point of economy the process does not compare unfavourably with liquid oxygen plants of the smaller type, and it was abandoned mainly because it was incapable of producing oxygen of equal purity.

As early as 1896 the British Oxygen Company, as the makers of Hampson's apparatus for the liquefaction of air, became connected with low temperature research. The Hampson apparatus (Fig. 1), which is based on a nozzle, or free internal, expansion, is so efficient in its temperature interchange, that when expanding about 700 cubic feet of air from a pressure of 150 atmospheres to atmospheric pressure, it begins to produce liquid in about 6 minutes with a yield of about 1 litre of liquid per hour.

For the production of liquid air on a commercial scale, this apparatus is too small to be of any value. On the other hand it is specially designed for the quick production of liquid for research purposes and it has been adopted for that purpose in many educational establishments and research laboratories throughout the world.

The success which attended the introduction of this apparatus, coupled with the still more important work of Professor Carl von Linde in the liquefaction of air, pointed to a method for the separation of its constituents which might develop into a rival to the barium process; consequently, the British Oxygen Company, like other concerns equipped with facilities for the production of liquid air, were quietly experimenting between 1896 and 1903 with various methods for separating the constituents of liquid air by partial evaporation.

It must, however, be admitted that the problem remained entirely unsolved until the process of rectification was disclosed by Professor Linde in the latter year. From that date onwards rectification has been the fundamental principle underlying every patented method for separating the constituents of liquid air.

The British Oxygen Company were not long thereafter in realising that their barium process for producing oxygen was at length seriously threatened by the introduction of rectification for separating the constituents of liquid air. We therefore concluded an arrangement with Professor Linde under which we acquired his British and British Colonial rights in rectification.

In 1906 we erected in our Westminster Works a Linde plant capable of producing about 500 cubic feet of oxygen per hour. It is illustrated in the photograph, Fig. 2.

This photograph is of some general interest, because it shows on the left-hand side the first liquid air plant erected for the production of oxygen in this country, and on the right-hand side a portion of the last, and best, of many barium oxide plants erected by the Company. Professor Linde himself was so struck with the efficiency and mechanical simplicity of this latter plant that, largely on his recommendation, the two plants were worked side by side for many months before it was finally decided to substitute liquid air for barium oxide plants in the production of oxygen throughout the Company's factories.

In 1908, as the outcome of prolonged litigation, which established Linde's claim to the rectification of liquid air, the Company entered into an agreement with the Société l'Air Liquide of France under which we



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acquired the Claude British and British Colonial patents (with the exception of Canada), for the separation of oxygen and nitrogen from liquid air. In many of our factories we have to-day Linde and Claude plants working side by side. We therefore claim to have had exceptional facilities for comparing the two systems on which the important oxygen industry of to-day has been developed in all parts of the world.

I now propose to describe and illustrate diagrammatically the essential features of the Linde and Claude systems, and as I am dealing with the subject from the industrial rather than the scientific point of view, I shall confine myself mainly to facts and figures which are based on practical experience. I must therefore assume the production of liquid air to have reached the stage where Linde's adaptation of the Joule-Thomson effect and Claude's expansion engine enabled that liquid to be produced in commercial quantities. I must also assume the physical laws involved in its production to be generally understood.

The Linde plant shown on the left of Fig. 2 represents the earliest type employed for the separation of oxygen from liquid air. Such plants consist essentially of an air compressor; a suitable purifier for eliminating carbon dioxide; a drier for removing moisture from the air; a fore-cooler, which is kept cold by means of an ammonia or a carbon dioxide machine; and finally, the separator containing the counter current heat interchanger and the rectification column.

The working of such a plant is as follows: Air is drawn by the compressor through a lime or caustic soda purifier in order to remove carbonic acid. It is then compressed, under conditions as nearly isothermal as possible, to a pressure of about 135 atmospheres and passed through a drier containing calcium chloride in order to remove moisture. It then

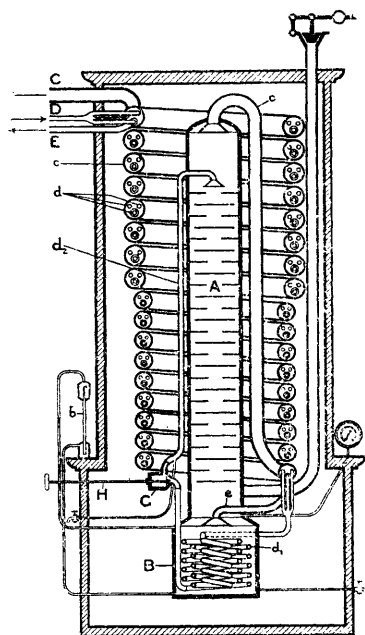


FIG. 3.—Linde's single column type separator.

enters the fore-cooler where it is cooled to a temperature of about  $-30^{\circ}\text{C}$ ., any remaining traces of moisture being deposited there as ice, and finally passes to the separator of which a sectional elevation is shown diagrammatically in Fig. 3. The main pipe *D* conveying this compressed air to the apparatus is split up into three small pipes *d* at the point where it enters the counter-current interchanger coil *C*. It passes down these pipes, which are reunited into a single pipe *d*<sub>1</sub> when they leave the interchanger and this pipe *d*<sub>1</sub> which is coiled in the vaporiser *B* as shown, is attached to the inlet of the valve *G*. At this point, by the adjustment of the regulating valve spindle *H*, the air is caused to expand from a high to a low pressure and is discharged at this low pressure through the rose-ended pipe *d*<sub>2</sub> into the top of the rectification column *A*. The expanded air fills the column and then flows through the only two possible outlet pipes *c* and *e* which surround the

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small pipes  $d$  thus forming a counter-current interchange of heat, as the outgoing expanded air ascends the interchanger coil through which the high pressure air is descending in the small pipes  $d$ . The expanded cold gases, having thus abstracted heat from the incoming compressed air, leave the separator at C and E as indicated in the diagram, nearly at atmospheric temperature.

It is at the valve G that Linde obtains the Joule-Thomson cooling effect and this is made cumulative by means of the counter-current heat interchanger. The apparatus is completely enclosed in a wooden casing and all spaces are packed with suitable insulating material, consequently, after starting the plant with everything at atmospheric temperature, the separator gradually cools down until some of the expanded air begins to liquefy and collect round the coils in the vaporiser B. The quantity of liquid thus collected is registered outside the apparatus by means of an ordinary coloured liquid which is contained in a glass tube  $b$  enclosed in a pressure equalising circuit as indicated. Once this stage is reached liquid begins to accumulate rapidly in the vaporiser B, and the initial pressure of the compressed air may be gradually reduced by increasing the opening of the valve G.

As the liquid begins to accumulate round the coils in the vaporiser B, the compressed air transmits some of its latent heat to the liquid. The latter is thereby evaporated whilst the compressed air is itself liquefied in proportion to the amount of heat thus extracted. The vapours thus produced flow upwards through the rectification column A whilst the liquid formed in the compressed air pipe coil  $d_1$  ascends through the pipe  $d_2$  and is discharged through the rose-end at the top of the rectification column. The temperature gradient necessary for efficient rectification then rapidly becomes established in the column, and the final stage is reached under which the separation of oxygen is effected. The pipes C and E of the counter-current interchanger then begin to fulfil their proper functions, the nitrogen vapours being delivered through the former from the top of the column and the oxygen vapours through the latter from the top of the vaporiser. The separated gases leave the apparatus at C and E respectively at or near atmospheric temperature, having abstracted heat from the incoming compressed air whilst passing up the counter-current interchanger.

The action which takes place in this, the simplest type of rectification column, must now be briefly explained as exactly the same principle is involved in all others.

Linde relies for his temperature gradient on the difference between the boiling point of nitrogen and oxygen. The former is  $-196^{\circ}\text{C.}$ , and the latter  $-183^{\circ}\text{C.}$  Liquid air is discharged into the top of the column at an intermediate temperature of about  $-194^{\circ}\text{C.}$  As it passes down nitrogen, being the more volatile component, immediately begins to evaporate off and the liquid gradually becomes richer in oxygen, with a somewhat higher temperature. As this rich oxygen liquid accumulates in the vaporiser it is evaporated by the compressed air passing through the coil until it is practically pure oxygen with a temperature very nearly  $-183^{\circ}\text{C.}$  There is thus a temperature gradient of about  $11^{\circ}\text{C.}$  established between the top and the bottom of the column. Liquid air passing down the column is brought into intimate contact with the rising vapours of oxygen and an exchange of material takes place. At each stage some of the rising oxygen is condensed and some of the nitrogen in the descending liquid is evaporated, whilst the liquid gradually gains in temperature

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until by the time it reaches the vaporiser its composition is that of practically pure oxygen. The gas on the other hand which passes off from the top of the column through pipe C is mainly nitrogen at a temperature about  $11^{\circ}$  C. lower than that of the oxygen at the bottom of the column. The oxygen which rises in the column to effect the material exchange with the nitrogen of the descending liquid, is carried back to the vaporiser together with most of the oxygen contained in the original liquid; thus there is a constant accumulation of oxygen which passes off as vapour through the pipe E. The gases taken separately from the top and bottom of the apparatus through the counter-current interchanger, are made to abstract heat from the incoming compressed air on its way to be liquefied.

When normal oxygen-producing conditions are established, the air supply from the compressor becomes reduced from 135 atmospheres to about 55 atmospheres, the latter pressure being found sufficient to make good all thermal losses due to friction, leakage of heat from outside, and imperfect interchange in the counter-current system.

This type of separator is easy to operate and from an economical point of view has been found satisfactory hitherto for use in relatively small oxygen producing plants. A defect, however, of rectification in this form is that although oxygen of high purity can be produced, at least 7 per cent. of oxygen is contained in the waste nitrogen. Bayly's well-known experiments in 1900 demonstrated that the vapour in equilibrium with any liquid mixture of oxygen and nitrogen always contained more nitrogen than the liquid and that when the evaporating liquid is air, the proportion of oxygen present in the vapour is 7 per cent. Therefore, in any rectification column, such as this early Linde type, where liquid air enters at the top, a loss, amounting to about one-third of the oxygen in the air, is inevitable.

With large plants this becomes a serious matter, and I believe I am correct in stating that Claude was the first person to design a separator which obviates this loss. I will, therefore, now, in order to maintain chronological accuracy, briefly describe a type of Claude plant capable of producing 4,000 cubic feet of oxygen per hour, which is largely employed by the British Oxygen Company at the present time in nearly all of their factories in this country.

The outstanding features of Claude's plants are: (1) Cooling by means of an expansion engine. (2) A selective system of rectification rendered possible by a preliminary partial separation of oxygen and nitrogen. (3) A combined system of heat interchange and drying which renders chemical abstraction of moisture from the air unnecessary.

The working of the plant is as follows: Air is drawn by a compressor through purifiers to remove carbon dioxide as in the Linde plant. It is then compressed to a maximum pressure of about 33 atmospheres and passed through two vertical tubular heat interchangers in series. In passing through the second of these it meets in counter-current the cold separated oxygen and nitrogen passing outwards from the separator and a very complete interchange of heat takes place. Here also most of the moisture is thrown down as water and drawn off at intervals, the remainder being arrested in the form of ice round the tubes at the top of the interchanger. Meanwhile the first interchanger which had previously performed the same function, is being thawed out by the air passing through it, in order to be ready for subsequent use. Thus these interchangers are operated as such alternately, being changed over at intervals of 8 hours. The compressed air leaves the second interchanger at a tempera-

ture of about  $-100^{\circ}\text{C}$ . 60 to 70 per cent. of the cooled air goes direct to the expansion engine where, in expanding to about 4 atmospheres, it performs external work against a dynamo brake and issues from the engine at a temperature not far removed from its point of liquefaction. The remainder of the air passes under full pressure into an interchanger, termed the liquefier, where it is liquefied by meeting in counter-current all the cold oxygen and nitrogen passing from the separator to the second, or operating, interchanger previously described. The cold vapour from the expansion engine and the liquid from the liquefier both enter the outer compartment A of the liquid collecting vessel shown in the diagram (Fig. 4) at the bottom of the vaporiser, the liquid supply being controlled by the valve shown, which performs the same function as the valve G in the Linde apparatus already described.

By this skilful combination of internal and external expansion, Claude is able to obtain a high efficiency from his expansion engine. For this latter purpose it is obviously desirable to keep the compressed air as warm as possible. By passing the cold gases through a liquefier a twofold purpose is served. First, a moderate supply of liquid air for making good cold losses is assured by very effective heat interchange, coupled with the Linde method of internal expansion. Second, the heat usefully abstracted by the cold gases from the compressed air passing in counter-current through the liquefier, raises their temperature to a point which prevents them abstracting, at a later stage, too much heat from the compressed air passing through the main interchanger to feed the expansion engine.

Reverting to the diagram, it will I hope now be obvious that a regular and adjustable supply of liquid air and intensely cold vapour is fed to the outer compartment A below the vaporiser. The vapour thus ascends the vertical nest of tubes B (leading from the top of this compartment), which are immersed in baths of liquid oxygen C and D. In these tubes the vapour undergoes progressive liquefaction and oxygen being the less volatile constituent, it is the more readily condensed and flows back as liquid into the compartment. A partial scrubbing effect, or rectification, also takes place, consequently the vapour passing out at the top of the tubes is very rich in nitrogen. This rich nitrogen vapour travels down a similar nest of tubes leading to the inner compartment E of the bottom vessel which it reaches partly in the liquid condition. Thus in practice liquid containing about 40 per cent. oxygen is obtained in the outer compartment and liquid containing about 4 per cent. oxygen is obtained in the inner one. A pressure of 4 atmospheres is necessary in these compartments, and the tubes communicating with them, in order to raise the liquefying point of the oxygen-nitrogen mixtures above  $-183^{\circ}\text{C}$ ., the temperature of the liquid

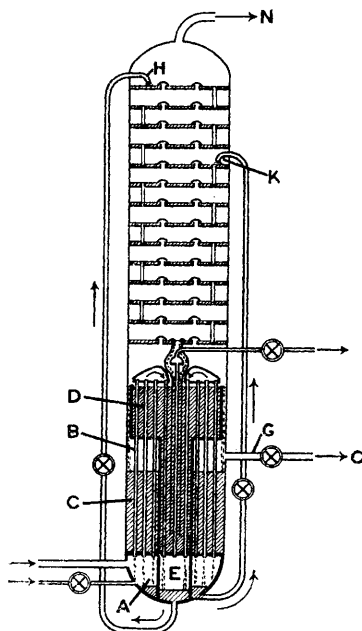


FIG. 4.—Claude's separator.



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oxygen bath, so that liquefaction may take place and that latent heat may pass to the liquid oxygen and evaporate it to a corresponding extent. Above the vaporiser, as in the Linde apparatus, is the rectification column. The liquid, rich in nitrogen, is conveyed from the inner compartment E to the top of the column at H. The liquid containing about 40 per cent. oxygen is conveyed from the outer compartment A to the column at the point K where the composition of the ascending gases should correspond to that of a gas mixture in equilibrium with a 40 per cent. oxygen liquid. Rectification with the correct temperature gradient then proceeds as already described in connection with the Linde separator (Fig. 3) with however the important difference that, as rich liquid nitrogen replaces liquid air at the top of the column, a correspondingly lower temperature is maintained there, thus extending rectification, with the result that nearly all the oxygen is abstracted from the air. The waste nitrogen is taken away to the liquefier interchanger from the top of the column and oxygen through the pipe G above the lower of the two communicating oxygen baths, which latter are so arranged that a uniform supply of good quality is assured.

An interesting addition to the separator is a small nest of tubes in the centre of the vaporiser through which a quantity of rich nitrogen from the inner compartment E can be withdrawn as indicated. After this additional scrubbing a relatively small, but useful, quantity of gaseous nitrogen of 99.5 to 100 per cent. purity, can be obtained as a by-product.

All parts of the apparatus subject to temperatures below that of the atmosphere, are efficiently insulated and when working conditions are established, air is delivered by the compressor at a pressure of 26 atmospheres. 33 atmospheres, already mentioned as the maximum pressure, is the initial pressure employed to hasten cooling down. This is less than a quarter of the initial pressure required by Linde and other plants, which is not only a fine tribute to the efficiency of Claude's expansion engine, but this relatively low maximum pressure enables lighter material and more efficient design to be employed in the interchangers and elsewhere.

A striking feature of the expansion engine is that it works without any cylinder lubrication. Specially treated leather, from which water and fatty matter have been removed, is employed as piston packing and it is found that, at the low temperatures involved, leather in this condition remains pliable and the engine gives no more trouble than an oil lubricated machine.

We find that these plants under daily working conditions produce oxygen of 98.5 per cent. purity for an expenditure of about 185 B.H.P. per hour or 46 B.H.P. per 1000 cubic feet of oxygen. The labour required for working the plant is no more than is required for a plant one-tenth the size. We do not employ larger plants than these as we find them to be a unit of convenient size for our oxygen factories.

We do not employ Linde plants of larger capacity than 2000 cubic feet of oxygen per hour, but so far as the separator is concerned, these and all larger Linde plants are now similar in most respects to the Claude design.

In producing cold with these larger plants, Linde does not employ an expansion engine doing external work but still relies on the Joule-Thomson effect produced by internal expansion of the air. On the other hand he economises power by compressing only one-third of the air used to a constant pressure of about 135 atmospheres and the remaining two-thirds to 4 atmospheres. Thus like Claude he admits liquid and gaseous air to his separator and appears to obtain similar results with very little more

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expenditure of power. Fig. 5 is a diagrammatic illustration of Linde's separator.

This consists of two rectification columns, one above the other. The lower, like the condenser tubes in Claude's apparatus, works under a pressure of 4 atmospheres and the upper under atmospheric pressure. The high pressure air at 135 atmospheres enters the bottom vaporiser at C and is liquefied in exactly the same manner as in the single apparatus illustrated in Fig. 3, entering the lower column, after expansion, through the rose-end shown. This supply of liquid air, like that of the Claude liquefier, makes good all cold losses. The low pressure gaseous air enters the bottom vaporiser at B and passing through a separate coil is discharged into the lower column about the centre, as shown, from which point it rises to a nest of tubes D surrounded by a bath of liquid oxygen, as in the Claude apparatus. Here partial liquefaction takes place, and the liquid falls back over the plates with a scrubbing effect on the rising vapours. Most of the oxygen is thus removed and accumulates as liquid in the lower vaporiser. The remaining gas, practically pure nitrogen, passes over to be condensed in the external tubes as indicated. Thus liquids, rich in nitrogen and oxygen respectively, are supplied as in the Claude apparatus to the upper column, in the positions shown, for final rectification. Both nitrogen and oxygen are drawn off as indicated through a counter-current coil interchanger similar in construction to that shown in Fig. 3, in order to abstract heat from the incoming high and low pressure supplies of air, the whole being similarly insulated. In these plants, as in the smaller, Linde employs an auxiliary fore-cooler which is kept cold by an ammonia or carbon dioxide machine, but he also employs the fore-cooler for separating out moisture from the air.

I am not able to speak from personal experience of a Linde plant of greater capacity than 2000 cubic feet of oxygen per hour. This latter plant, however, absorbs about 106 B.H.P. per hour, or 53 B.H.P. per 1000 cubic feet of oxygen produced. Both Linde and Claude oxygen separators have been manufactured up to a capacity of about 9000 cubic feet of oxygen per hour. With such plants the power consumed per 1000 cubic feet of oxygen produced, is about 33 B.H.P. I believe the Linde Company have also manufactured larger units, for which they claim still lower consumption of power, but the design and construction of efficient heat interchangers for large oxygen plants is likely to put a limit to their size and I venture to doubt whether a plant with much lower consumption of power than 30 B.H.P. per 1000 cubic feet of oxygen is possible with due regard to economy in other directions.

Whilst on the subject of large plant units, reference may appropriately be made to the well-advertised Jeffries Norton process which we have repeatedly been assured would produce oxygen at 6d. or less per 1000 cubic feet.

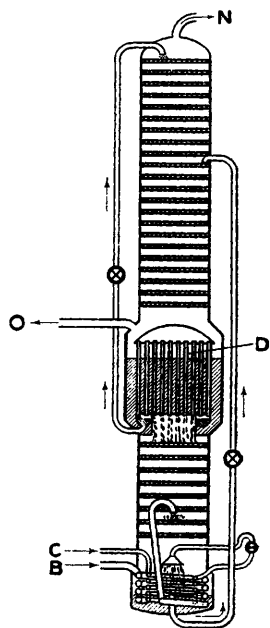


FIG. 5.—Linde's double column type separator.

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The process appears to be based on the fact that heat interchange should take place between high pressure gases, in order to recover power by expansion more effectively than is the case in existing systems, where heat is transmitted from a high to a low pressure gas.

In Fig. 6 I give a very free diagrammatic illustration of the process as I understand it. Air at a pressure of say 20 atmospheres enters the system at A and on its way to the rectification column B (which is operated at only a slightly lower pressure) it is made to pass through two interchangers, as diagrammatically illustrated, in order to heat up outgoing nitrogen and oxygen. The former of these first passes through its interchanger under full pressure. It is then split up as shown, about 60 per cent. being heated by suitable external means at D to a temperature of about  $550^{\circ}\text{C}$ . This hot and fully compressed gas then passes to a motor E, which it drives, generating sufficient power, it is claimed, to work the whole system. The remaining 40 per cent. of nitrogen, in order to help in counteracting heat influx, is expanded in the engine C, the expanded gas on its way out of the system being again employed as shown to abstract heat from the incoming compressed air. The separated oxygen leaving the rectification column under pressure passes as shown, to the expansion engine P, and the expanded oxygen on its way out of the system, is employed to abstract heat as indicated from the incoming compressed air.

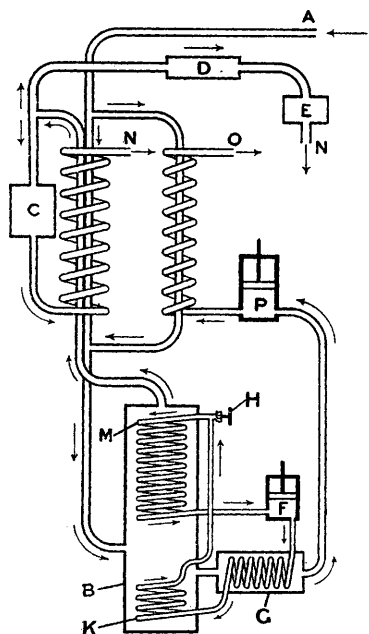


FIG. 6.—Diagram of the Jeffries Norton process.

I have already shown that in order to maintain the correct temperature gradient in rectification columns, it is necessary to have oxygen vapours at the bottom and nitrogen vapours at the top, but when the pressure in the column is nearly the same as that of the compressed air entering it, then the condensation of the latter in liquid oxygen cannot be effected and normal rectification cannot be set up. In order

to get over this difficulty and transfer heat from the top to the bottom of his column, Norton places a coil K in the liquid oxygen bath at the bottom of the column through which an independent supply of oxygen, raised by the compressor F to a pressure above that prevailing in the column, is caused to flow after being first cooled by the outgoing oxygen vapour in G. The circulating oxygen is then condensed in the oxygen bath and afterwards expanded through the valve H to a temperature low enough to condense nitrogen. It is then drawn through the coil M to be recompressed by the compressor F in the enclosed circuit.

The Norton process has had the advantage of Government support in the U.S.A. where a large plant for the separation of helium from natural gases was erected in Petrolia, Texas. The plant was never successful and I understand it has now been abandoned, a plant erected

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by the Linde Air Products Company of the U.S.A. during the war at Fort Worth, Texas, being employed instead. I have not heard of any Norton plant being successfully operated for the production of oxygen and although the process has clever features and is refreshingly original, I am afraid most engineers who have had experience with very low temperatures, will regard it as somewhat impracticable.

There are many other makers of oxygen plants to-day, mostly of small size. Nearly all are based on the original Linde apparatus (Fig. 3) and I am not aware of any possessing novelty in design. Only one maker that I know of employs the Claude expansion engine. In that case, some of the air from the main compressor at a very high pressure and without previous cooling below atmospheric temperature, is sent through the expander and then through a heat interchanger to the centre of the column. This has certain advantages in the production of liquid air but I do not think it can be economically adapted to the production of oxygen. It is apparently claimed as an advantage of the system that ordinary oil can be used for lubricating the cylinder of the expansion engine. It is, however, a greater advantage of the Claude system that oil need not be used at all.

Cylinder lubricating oil is a source of trouble in liquid oxygen plants in two respects. (1) Traces are always liable to be carried forward and tend to foul up both interchanger pipes and the column, thus necessitating periodical and difficult cleaning. (2) The other, and more serious trouble, is in connection with the air compressor cylinders. The heat generated in each stage of compression, in spite of very efficient cooling, necessitates the use of special high flash point oils and precautions to ensure that the flash point temperature is not exceeded. It has been proved, however, that any lubricating oil heated in the presence of compressed air beyond its flash point, breaks down into simpler substances including free carbon and acetylene. These substances, particularly acetylene, are liable to be carried forward in the air and to accumulate as solid particles in liquid oxygen baths, thus producing conditions which have given rise to numerous explosions which have been almost invariably traced to the presence of acetylene. In our oxygen factories, until the cause became obvious, these incidents were amongst the most disquieting of our experience, but since we have got to the root of the trouble, we have greatly reduced the risk by introducing suitable safeguards on our air compressors. We have also taken precautions not to store carbide or use acetylene within 100 yards of our air intake. Thus we are forced to be very inhospitable in our own factories to a gas which has otherwise proved a valuable business ally.

Hitherto I have dealt only with plants producing a gaseous oxygen product. Liquid oxygen can always be drawn from such plants but they are not the most convenient construction for the purpose.

It is obvious that when some of the oxygen is drawn away in the liquid state its value in the interchangers for abstracting heat from the incoming air is lost. This has to be compensated for by increased pressure. Hitherto the demand for liquid oxygen has been practically restricted to rescue work and aircraft uses, but its employment for explosives, developed by the Germans during the war, is likely to extend and create a demand for plants primarily designed to produce liquid oxygen. The Société l'Air Liquide recently supplied a plant for this purpose to certain mines in Lorraine where German plants had hitherto been used. It works at a pressure of 60 atmospheres and produces 75 litres of liquid oxygen per hour for an expenditure of 140 B.H.P.; less than 2 B.H.P. per litre. We are also supplying to South Africa a much smaller plant working at a higher pressure



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which will produce liquid oxygen for an expenditure in power of 2·5 B.H.P. per litre and will alternatively produce gaseous oxygen. These results compare favourably with any others I have seen, but I am hopeful that we shall still further improve upon them in the near future.

The price of oxygen in the liquid state must always be more than in the gaseous owing to the greater expenditure of power involved in its production and losses due to evaporation in its use. We sell the liquid at infrequent intervals and small quantities, as drawn from the oxygen plants in our factories, at prices down to 1s. 4d. per lb. in Dewar vessels of small capacity, but to a regular and large consumer very much better terms could now be offered.

In Lorraine, where I have seen liquid oxygen extensively used in the iron mines for blasting purposes I was told that it cost 1 fr. 50 per litre, which, at the rate of exchange prevailing at that time, corresponded to about 7d. per litre in this country. Either of the liquid oxygen plants to which I have just referred would be easily capable of producing the liquid at this figure.

In recent years, thanks to improved methods of constructing metallic Dewar flasks, the transport of liquid oxygen has become much simplified. In flasks of 25 litres capacity and upwards the loss due to ordinary evaporation I am told should not exceed 5 per cent. in 24 hours, although in the mines a much larger percentage is of course lost by evaporation whilst the cartridges are being impregnated with the liquid immediately before they are used.

As regards the cost of gaseous oxygen, this varies with the size of plant employed to a larger extent than in the case of the liquid. As evidence of the extent to which this occurs it is only necessary to compare the cost of producing gaseous oxygen by means of present day liquid air plants of maximum and minimum sizes. For this purpose a plant producing 500 cubic feet of oxygen per hour may be taken as the smallest practicable unit, and for the other extreme I will take a Claude plant producing 9000 cubic feet of oxygen per hour, for that is the largest size of which I can speak with adequate personal knowledge.

Assuming power in each case to cost 1d. per B.H.P. (a somewhat high figure for the larger plant) then working continuously to their full capacity, with adequate power, labour, material and a fair proportion of all the usual standing charges, including interest on capital and depreciation, the cost of oxygen produced by the small plant would be 19s. and by the large one 4s. 6d. per 1000 cubic feet.

If these plants were worked intermittently so as to produce annually only half of their full output, the standing charges would tell greatly in favour of the large plant. I estimate that the cost of oxygen would then be with the small plant 27s. and with the large 6s. 3d. per 1000 cubic feet.

These costs are for gas into the gasholder. In the case of oxygen factories supplying the gas in cylinders it is obvious that with requisite supervision, heavier overhead charges, relatively small plants in operation and a fluctuating demand the cost of oxygen must always be very appreciably higher than in works where the gas can be used direct from the holder.

Throughout their factories in this country the British Oxygen Company have now plant capable of producing an aggregate of 2 million cubic feet of oxygen per day. Our present sales fluctuate between 4 and 5 million cubic feet per week, which is less than half the total capacity of our plants. Our present average price for oxygen in cylinders is about 38s. per 1000 cubic feet, although to many large consumers the price is substantially lower.

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This price I believe compares favourably with that prevailing in other countries with the probable exception of Germany, where in any case the collapse of the mark renders comparison difficult.

The secret of cheap oxygen is large liquid air units worked to their full capacity. By having increased the size of our factory units since the war we are able now to sell oxygen below our pre-war price. The oxygen business has become a good barometer of trade. It has suffered severely during the prolonged industrial depression, but the demand has been perceptibly increasing within the last two months. If this continues, as everybody must hope will be the case—for it will indicate improved general conditions in trade—then it will be obvious, from the figures I have given, that with an increased output still further reductions in the price of oxygen in cylinders should become possible.

The amount of oxygen sold in this country for medical purposes of every kind probably does not exceed 1 per cent. of the total output in cylinders. About 3 per cent. is used for limelight and experimental purposes. All the rest goes to industry. Of the industrial uses for compressed oxygen the most important is now metal cutting. This must represent over 50 per cent. of the total demand, and is about equally divided between scrap-cutting, or destructive work, and much important constructive work. The latter is perhaps one of the most promising outlets for oxygen. When the oxygen cutter is employed in conjunction with self-feeding profiling machines, now constantly being designed for various classes of work, it is found to operate almost with the precision of a saw and with far greater rapidity. Oxy-acetylene welding ranks next to metal cutting, amongst the industrial applications of oxygen. About 25 per cent. of the gas sold in cylinders is employed for that purpose and it is becoming obvious that oxy-acetylene welding can easily hold its own in a great variety of work against electric welding and other processes. The remainder of the oxygen sold in cylinders is mostly employed for lead burning purposes and for obtaining high temperatures in special metallurgical operations.

In the wider fields of industry where the use of oxygen has often been suggested, as for instance in the enrichment of air for blast furnaces, and in conjunction with steam, for the continuous gasification of fuel, it is doubtful whether the stage has yet been reached when oxygen can be produced cheaply enough even in large plant units to be economically employed. In Germany oxygen is used in the manufacture of nitric acid and acetic acid, but otherwise neither in that country nor any other, so far as I am aware, has the use of oxygen yet developed to any appreciable extent in the chemical industry.

It must be admitted that industrial development throughout the world is still mainly confined to the cylinder trade. In this country, in spite of trade depression, the quantity of oxygen distributed in cylinders at the present time must approach 300 million cubic feet per annum (of which upwards of 225 million are supplied by the British Oxygen Company). In France I believe the annual output is about the same as here, but it is stated to be three times as much in the United States of America and more than twice as much in Germany.

At the outset of this paper I expressed the intention of limiting myself to an interpretation of its title which would permit me to deal exclusively with the separation of the constituents of the air. I wish, however, to explain that I had not advanced far with my subject before I realised that I should have to limit myself still further and abandon the consideration of all constituents except oxygen if I attempted any historical review of the

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industrial production and use of that gas. I have therefore confined myself to the subject on which I am best informed and have devoted this paper exclusively to oxygen. I offer no apology for this because I believe that the industrial importance of oxygen to-day warrants independent consideration.

During the war the supply of oxygen was described by a prominent member of the present Government as a matter of paramount national importance. This was certainly no exaggeration at that time and since the war the economic value of oxygen in the industrial applications I have mentioned, has been recognised to the full. Unfortunately exaggerated claims and statements are very apt to breed misconceptions in these difficult days of abnormal exchanges and keen international competition. I am therefore grateful to this important society for affording me an opportunity of placing on record what I believe to be a reliable statement of the present position in the oxygen industry.