

Review  
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Prof. F. G. Cottrell  
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F. G. Cottrell

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## New York Section.

Meeting held at the Chemists' Club on  
January 17th, 1919.

MR. C. E. SHOLES IN THE CHAIR.

### PRESENTATION OF THE PERKIN MEDAL.

The thirteenth impression of the Perkin Medal was awarded to Dr. F. G. Cottrell in recognition of his work on electrical precipitation.

Following some introductory remarks by the Chairman and Mr. C. McDowell, Prof. C. F. CHANDLER, in presenting the Medal, said that Dr. Cottrell was born in Oakland, Cal., in 1877. After studying at the Universities of California and Leipzig he became Instructor in Physical Chemistry at the University of California in 1902; later assistant Professor. This position he held till 1911, when he joined the staff of the Bureau of Mines in Washington. Here he was at first the Consulting Chemist, then successively Chief of Physical Chemistry, Chief Chemist, and finally Chief Metallurgist, which position he still holds.

Dr. Cottrell's elaborate and valuable investigations relating to electrical precipitation of particles of liquids and solids began in 1906 with his work on sulphur trioxide fumes, which are not easily absorbed by water. It had long been known that electric brush discharges caused fog to clear. Sir Oliver Lodge had worked along this line. Dr. Cottrell described his first fundamental experiment in 1911 in a paper on "The Electrical Precipitation of Suspended Particles" (J. Ind. Eng. Chem., 1911, 3, 542-550). This marks the beginning of one of the most important contributions to industrial

chemistry. Cottrell says: "The clue to the solution of this difficulty came from an almost accidental observation. Working one evening in the twilight when the efficiency of the different points could be roughly judged by the pale luminous discharge from them, it was noticed that under the particular conditions employed at the time, this glow only became appreciable when the points had approached the plates almost to within the distance for disruptive discharge, while at the same time a piece of cotton-covered magnet-wire which carried the current from the transformer and commutator to the discharge electrodes, although widely separated from any conductor of opposite polarity, showed a beautiful uniform purple glow along its whole length. The explanation lay in the fact that every loose fibre of the cotton insulation, although a relatively poor conductor compared with a metallic point, was still sufficiently conductive from its natural hygroscopic moisture to act as a discharge point for this high potential current and its fineness and sharpness, of course, far exceeded that of the sharpest needle or thinnest metallic wire. Acting on this suggestion, it was found that a piece of this cotton-covered wire when used as a discharge electrode at ordinary temperature proved far more effective in precipitating the sulphuric acid mists, which were then the object of study, than any system of metallic points which it had been possible to construct. Perhaps the greatest advantage thus gained lay in the less accurate spacing demanded between the electrodes of opposite polarity in order to secure a reasonably uniform discharge."

The first installation of his system was made at the Hercules Powder plant, at Pinoli, Cal., where there was a small contact sulphuric acid plant. There he used a 6600-volt alternating current, rectified into a direct current by a motor-driven contact apparatus, and sent this current, by means of pubescent (hairy) asbestos electrodes, through the wet sulphur trioxide fumes, and effected precipitation.

This process, though successful, was not sufficiently profitable to warrant extensive use. It

would probably have died had it not been that the nearby Selby smelter was in trouble. This smelter had a large plant near one of the tunnels of the Southern Pacific Railroad, and with certain winds, the fumes of sulphur trioxide from the silver dissolving house would fill this tunnel with choking fumes, and finally legal proceedings were started to close the smelter plant. At this juncture Cottrell erected a small electrical plant which met the difficulty completely, and is running to-day, yielding dilute sulphuric acid as a by-product. But for these legal proceedings the Cottrell process might never have materialised. The knowledge that fumes and smoke could be "Cottrellised" induced farmers all over the West to sue the smelters, and satisfied the Courts and juries that they were not asking the impossible of the smelters.

The Cottrell process has not only removed the trouble due to sulphuric acid waste fumes of smelters, but it has brought down poisonous arsenic, saved metal dust otherwise going to waste, saved the orange groves from cement kiln smoke, and recovered potash from that cement smoke.

The great expansion which the process has undergone is shown in the recent installation at the Washoe reduction works of the Anaconda Copper Mining Company, Montana. The stack is over 585 ft. high, is 86 ft. in diameter, and the walls are 5 ft. 4 in. thick at the base. The stack contains the equivalent of 6,672,214 common bricks. The smoke is conducted through a vast flue system from the furnaces, and is passed into chambers wherein hang 111 miles of chains, electrified by a high-tension current; the dust particles are repelled by the chains and adhere to large plates between which the chains are suspended. When the plates have become thickly coated, the current is shut off, and the accumulated dust falls into hoppers.

Dr. Cottrell's more recent work has been concerned with securing helium for war balloons; being incombustible, it is an excellent substitute for hydrogen, while it is only slightly inferior in ascensional power. The helium is obtained from certain gas wells, by liquefying out all the other constituent gases.

Dr. COTTRELL, having expressed his deep appreciation of the honour conferred upon him, gave a full account of the history and development of the recovery of helium from natural gas. Dealing first with the separation of air into its components, he said that he had been for many years greatly impressed with the ultimate possibility of producing very cheap oxygen for industrial purposes by liquefaction and distillation of air, but had been equally impressed with the crude thermodynamics which all the earlier systems represented.

Oxygen as sold to-day in steel cylinders is so expensive that it usually fails to suggest even faintly the ultimate possibilities for low-cost production, in which latter case it would be piped at moderate pressure straight from the separating plant to the furnace. Thus, \$200 a ton is a very low price for even moderately pure oxygen in steel cylinders to-day, whereas on the very large scale where unit cost of plant, overhead and sales expenses and the like are greatly reduced and compression into cylinders, transportation of same, etc., are completely eliminated, the power consumption for the actual separation would become the largest and dominant factor of ultimate cost. The individual steps in the process of liquefaction and separation of gaseous mixtures may all be made thermodynamically reversible to much the same extent in practice as are those of the steam engine and the air compressor. The chance for inventive skill lies chiefly in the selection of these individual steps from the alternatives long since clearly recognised and their combination into a consistent series. The difference in efficiency of present commercial processes resides in the acumen with which this choice and combination have been carried out and in the mechanical perfection of the apparatus in which the system is embodied.

The final measure of theoretical efficiency is, of course, the degree to which reversibility in the thermodynamic sense has been approached. No energy has to be supplied in the separation of air to overcome chemical affinity, but it is necessary to overcome what we may call the force of diffusion of the two gases in effecting their separation. Thus, figured mechanically, the work necessary to

separate five volumes of air at atmospheric pressure into one volume of oxygen and four volumes of nitrogen, each at atmospheric pressure, is simply that of bringing each of the partial pressures of the two gases as they existed in the mixture up separately to that of the original mixture. Or, it is the work necessary to compress the oxygen from five volumes at  $\frac{1}{5}$  atmosphere to one volume at one atmosphere plus that to compress five volumes of nitrogen at  $\frac{1}{5}$  atmosphere into four volumes at one atmosphere, all isothermally. Or, to put this even more concretely, if the heat inter-changers and stills were thermodynamically perfect in their operation, it would only be necessary to compress the original air isothermally to a pressure of approximately 10 lb. per sq. in. above atmospheric, to effect its complete separation into pure oxygen and pure nitrogen, each at atmospheric pressure. Per ton of oxygen separated this works out at 60 h.p.-hr. on the basis of isothermal compression. This is, of course, the theoretical limit for a perfect reversible cycle, which cannot be attained in practice, but we may hope to approach it to much the same degree that we have the corresponding limit in the steam engine and the air compressor—say 50 per cent. as at least a legitimate goal for early endeavour. It seems doubtful whether any large-scale air-separating plants at present in service are greatly exceeding 10%. But even 10% would mean oxygen at a power cost of only 600 h.p.-hr. per ton, which in itself should present startling possibilities to the minds of most chemists and metallurgists.

That there has not been more actual development is chiefly due to the magnitude of the project, requiring as it does the closest co-operation and support of the whole undertaking from both the users and producers of the oxygen. The transition from the present bottled oxygen stage of the industry to that of production directly at and as a part of the large metallurgical plant, let us say, where it is to be used, means not only a complete re-design and development of larger production units but a complete reorganisation of sales and business policy. Some experiments in this direction were indeed undertaken in Belgium before

the outbreak of war, but were on an entirely inadequate scale to furnish conclusive results.

Let us consider for a moment the tremendous efforts already expended to concentrate up to the limit the ores and all the other raw materials entering a furnace and then remember that we are still adding the oxygen with four times its weight of inert nitrogen, all of which reduces the intensity of the chemical reactions and causes waste of valuable fuel, to say nothing of additional expenses due to excessive size of equipment.

But to return to the narrative. In 1916, as a result of a memorandum handed to me by Director Manning of the Bureau of Mines concerning a new process for air separation, I came in touch with Mr. Fred E. Norton, of Worcester, Mass., who had in 1913 entered the employ of Mr. E. A. W. Jefferies to undertake the engineering development of a process of air separation patented by the latter and which he had arranged with the General Chemical Co. to test at one of their plants. After spending between \$50,000 and \$100,000 on this project the General Chemical Co. decided to drop it. Messrs. Jefferies and Norton then pooled their patents as the Jefferies-Norton process and, with the financial help of a few friends, continued experimental development. The parts of their process particularly attracting my attention were those Mr. Norton had introduced after cessation of the work at the General Chemical Co. and which radically changed the fundamental cycle upon which he in common with others had been working previously.

I found that, after making application for patents, they had discussed the work very freely with those who should be best able to judge of its merits and possibilities, but had made little progress toward securing practical and financial backing toward large-scale development. Following our custom in the Bureau in such cases, an effort was made to put Mr. Norton and his associates in touch with people who might have sufficient use for such a process to justify their aiding in its further development, but I fully realized the difficulties and uncertainties in the way of definitely securing such co-operation.

At the same time as the above development, but quite unknown to me, another thread of the story was being spun in England. On February 28, 1915, Sir William Ramsay wrote to Dr. R. H. Moore, of the U.S. Bureau of Mines: "I have been investigating blowers, i.e., coal damp rushes of gas, for helium for our Government. There does not appear to be any in our English blowers, but I am getting samples from Canada and the States. The idea is to use helium for airships." The importance of this proposed use of helium for balloons and particularly for airships of the Zeppelin type lies in the inertness and non-inflammability of helium and the fact that it is of all known substances the next lightest to hydrogen, having about 92% of the latter's buoyant effect. It also shows only about half the rate of diffusion and consequent wastage through the balloon fabric. At the time of the receipt of Sir William's letter the United States was not in the war, and nothing immediately came of the suggestion in this country. Dr. Moore remembered, however, that in 1907 Dr. H. P. Cady, of the University of Kansas, had found more than 1% of helium in some natural gases from Kansas. In 1917, following a meeting of the American Chemical Society, Dr. Moore brought the matter to the notice of Dr. Parsons, who promised to have it presented to the War Department.

News of Ramsay's suggestions also reached this country through other channels and eventually came to our attention. Professors Satterly and Patterson, of the University of Toronto, commenced experimentation on the subject January 1, 1916. Col. G. A. Burrell, who headed the research department of the Gas Warfare Service at the American University, states that Cady's experiments had also suggested similar possibilities to him.

However, no definite step toward securing action seems to have been taken in the United States until June 1, 1917, on which date Messrs. Moore and Burrell, of the Bureau of Mines, explained the subject to Colonel Chandler, in charge of the balloon service for the Army. He was intensely interested, and asked that a report be made to him, giving all

available details. He also took the matter up with Mr. G. O. Carter, in charge of hydrogen plants for the Navy, who had had several years' practical experience in the Linde Air Products Co. with the liquefaction and separation of gases by their process. Mr. Carter also immediately appreciated the importance of the subject, and urged this upon the attention of his superiors in the Navy.

Up to this time in the whole world there had probably not been more than 100 cub. ft. of helium separated as a pure gas, and its price in the small lots in which it was sold was about \$1700 per cub. ft. About this time I was called into the conferences and was much impressed by the weight which the British Admiralty apparently laid upon the cost of separation of the gas as a determining factor in its practical availability. I was given to understand that they had figures on the basis of the well-known commercial processes for separating gases by liquefaction and distillation, and were unable to see how production could be hoped for from these at less than \$60 to \$80 per thousand cubic feet, which they felt to be practically prohibitive for the programme they then had in mind. At this stage Mr. Norton was asked to act as a consulting engineer of the Bureau of Mines and prepare plans and estimates for an experimental plant, the supervision of which for the Bureau of Mines devolved on Mr. Burrell.

In due course a report was transmitted to the War Department, and although this report was as yet fragmentary and based on very inadequate data concerning the practical conditions to be met in the field, the Aircraft Board, on July 31, 1917, recommended an allotment of \$100,000, half each from the Army and Navy, which became available for the use of the Bureau of Mines on August 4. A detailed survey of field conditions, to determine the best available supply of natural gas for the purpose, was at once begun, as also the preparation of working drawings for the experimental separation plant. The work was commenced by Mr. Burrell, and by him carried through its early critical stage. The general supervision of the project was for a short period at one time placed in the hands of Prof. W. H. Walker. Mr. Burrell

next communicated with the two well-established operating companies controlling, respectively, the Linde and Claude systems of gas liquefaction and distillation, to determine whether it would be possible to work out a plan of general co-operation and pooling of information and facilities for this specific war purpose. This did not, however, prove practicable, though both companies expressed themselves as anxious to co-operate individually with the Government and to undertake independently the erection of plants of their own respective designs at cost, or even less, and have ever since done all that was in their power to make the work as a whole a success.

At this juncture a special commission from the British Admiralty, headed by Commander Cyprian D. C. Bridge, arrived in America to collect data and exchange ideas on what was being done, and from the resulting conferences the possible importance of the work in hand became so evident that the Aircraft Board on October 17, 1917, recommended that a further allotment of \$500,000 be made jointly by the Army and Navy to permit of immediately starting the construction of complete plants under all three processes. In accordance therewith, Mr. Norton was directed to prepare plans for a somewhat more complete plant embodying his process than had originally been contemplated as a first step. This brought the total estimated cost of the plant to about \$150,000. Owing to official delays, however, it was not until February, 1918, that the additional \$100,000 became available for the Norton project. In the meantime contracts had been closed with the Linde Air Products Co. and with the Air Reduction Co. for the construction and experimental operation of a Linde and a Claude plant respectively, each for an estimated daily production of about 7000 cub. ft. of helium, and construction was well forward on each. These plants were to be at North Fort Worth, Texas, and to utilise a natural gas containing about 0.9% by volume of helium; of this gas the Lone Star Gas Co. was bringing some 20,000,000 cub. ft. daily through its pipe line from the wells at Petrolia, more than a hundred miles north-east of Fort

Worth, to that city for domestic and industrial consumption. After careful study of field conditions it was decided to erect the Norton plant at Petrolia in direct proximity to the wells, a procedure which had not been deemed practical for the two other plants on account of their larger demands for power and water supply.

Parallel with the Bureau of Mines work on processes of extraction, Dr. A. F. Rogers, of the U.S. Geological Survey, undertook a reconnaissance of all natural gas fields in the United States with regard to their possible helium supply, as this might be judged from sampling and analysis of existing wells combined with a study of geological conditions. The Bureau of Standards also undertook the determination of certain physical properties of the gases, more especially the latent and specific heats and specific volumes of methane over a wide range of pressures and temperatures, and the diffusion of helium through balloon fabrics. The data will be published shortly by the Bureaus.

In order to co-ordinate properly all the different agencies concerned, the conduct of the helium work as a whole was about this time placed in the hands of a committee consisting of one representative from each of the three departments chiefly concerned. Mr. G. O. Carter, as chairman, represented the Navy, Dr. Harvey N. Davis the Army, and Mr. Geo. A. Orrok the Interior.

The Linde plant, costing in round figures \$300,000, was the first to be started. It commenced operation March 6, and on March 22 produced gas containing 28% of helium. By April 21 this purity had reached 50%, the yield being at first small, but both quantity and purity were steadily increased up to a maximum daily production on September 6 of 7755 cub. ft. of 67% purity, with an average production of, say, 5000 cub. ft. at over 70% purity; the gas was then further purified in a second step to about 92 or 93% purity.

The Claude plant, costing about half as much as the Linde, commenced production some weeks later than the latter, and has also gradually increased its production and the purity of its product. Although up to date these are still considerably

behind the performance of the Linde plant, a new still is just being installed at the Claude plant which it is hoped will materially improve both yield and purity.

Due to present pipe line limitations coupled with heavy consumption of fuel gas at this time of year, it has been necessary for some months past for the Lone Star Gas Co. to substitute for part of the Petrolia gas some from other fields carrying less helium, so that the helium content of the gas at present being treated at Fort Worth has fallen to between 0.4 and 0.5% by volume, which proportionately cuts down the production at both plants.

At the time of signing the armistice the first shipment of 147,000 cub. ft. of 93% helium was on the dock about to be loaded aboard ship for Europe.

The Army and Navy have now jointly entered upon a larger production programme under the immediate direction of the Navy, and have allotted some \$5,000,000 for the purpose, including the construction of a new pipe line and additional units of the Linde plant at Fort Worth. General Squire states plants are under construction to give at least 50,000 cub. ft. a day at an estimated cost of not more than 10c. per cub. ft. If present expectations of the Norton process are fulfilled this cost may be still further greatly reduced.

The Norton, or Bureau of Mines, plant at Petrolia was completed as far as initial construction is concerned in the middle of October, and since that time its various parts have been successively undergoing tests and adjustments. The multi-tubular heat interchangers and large expansion engines, which were among the new departures in this plant, over which most anxiety was originally felt, have thus far worked very well, and now seem to be performing their allotted tasks to complete satisfaction. A good deal of difficulty was at first encountered by occasional floods of oil and salt water from the gasoline extraction plant, which immediately clogged up the interchangers. This has now been eliminated by installing adequate settling chambers and traps. It is hoped that helium production will soon be attained, but as this

plant has a rated production capacity of several times that of either of the other two, each change or adjustment in its parts requires rather more time, apart from the fact of the entire novelty and experimental character of many of its parts.

In studying the different systems of gas liquefaction and separation it is very essential at the outset to distinguish clearly between the production of liquid as an ultimate product and the utilisation of liquefaction and re-evaporation as a mere step in a separation where the ultimate products desired are still gases and at essentially the temperature of the original mixture fed to the apparatus. In the former case a very considerable expenditure of work is represented in what may be termed the refrigerative properties of the liquid delivered. But in the second case, where the liquid is not drawn off from the apparatus and its amount therein remains constant, the part continually evaporating serves to condense nearly an equivalent amount of the incoming gases. Also the cold gases furnished by this evaporation take up heat from and cool the fresh incoming gas while they themselves are returning to room temperature.

#### *Ideal equal pressure process.*

The continuous process of liquefaction and re-evaporation of a single gas may be illustrated diagrammatically, as in fig. 1. Ideal conditions would consist in perfect heat interchange horizontally between the two legs of the U-tube, A and C, and perfect heat insulation lengthwise along each of these and from their surroundings. If these conditions were fulfilled and the whole system once brought to a steady state by, let us say, refrigeration of the bottom of the U-tube by some extraneous source of initial cooling while gas was slowly passed through it, we may imagine a certain amount of liquid condensed at the bottom of the U and a uniform gradient of temperature established along its two legs. Now, if the initial extraneous source of refrigeration were removed but gas still passed slowly into the system, the gas would progressively cool in A, liquefy at B, re-evaporate at B, and warm back to the atmospheric

temperature in passing up C. Under these ideal conditions, with a single gas, the slightest imaginable difference in pressure between A and C should serve to perpetuate the process!

Whatever heat leakage there is, however, either through the walls of the insulating chamber or down the legs of the U-tube, represents a loss not of energy itself but of its availability for the purposes in hand: *i.e.*, of thermodynamic potential, the practical result being the necessity of expend-

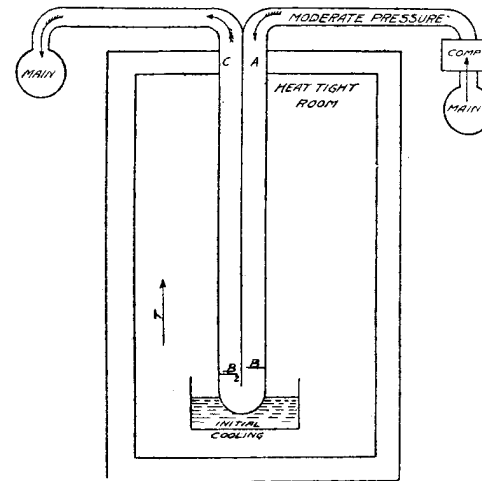


FIG. 1. IDEAL EQUAL PRESSURE SYSTEM.

ing mechanical work to compensate for these heat leaks. If, in addition to this, we are dealing with a mixture instead of a single pure gas, the constituents will in general liquefy and re-evaporate with varying ease, tending to set up temperature differences between adjacent parts of the two legs of the U and thus requiring a further expenditure of work to operate the cycle. Looked at from the point of view of gas separation, the first of these effects represents pure loss, but the second is due,

at least in part, to overcoming the "force of diffusion" in separating the gases, and should thus be counted as useful work.

The problem is, therefore, to provide just enough refrigeration at the proper temperatures and places to cover these two demands after they themselves are reduced to as low a value as possible in the design of the apparatus and by use of the best heat insulation attainable.

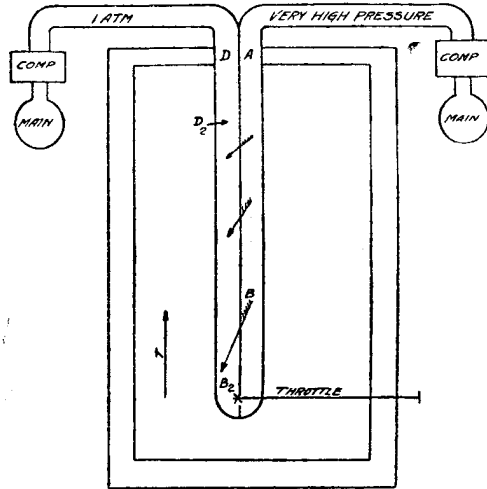


FIG. 2. LINDE SYSTEM, SELF-COOLING.

The three systems for gas separation now before us differ perhaps most strikingly of all in the way in which they produce this refrigeration.

#### *Linde system.*

In the case of the Linde, fig. 2, the gas mixture to be separated is pumped at very high pressure (say 1500 to 3000 lb. per sq. in.) into leg A and allowed to expand through a regulating throttle to a lower pressure at  $B_2$  and return through D, the

refrigeration being usually credited to the "Joule-Thompson effect." The specific heat of highly compressed gases is usually less than that of the same gas at lower pressure, so that a given weight of gas passing down leg A under high pressure in falling from one temperature to another will give up fewer calories of heat than the same weight of gas coming up the leg D will absorb between the same two temperatures. Thus it is evident that on the whole more heat will be carried out of the system by the issuing gas than is brought in by the incoming, with resulting refrigeration.

The fact that these differences of specific heat only become important at considerable pressures and the pressure created for this purpose is practically wasted at the throttle, as far as useful mechanical effect is concerned, makes this process decidedly inefficient from a thermodynamic standpoint; *i.e.*, from the question of power consumption. Its chief merit lies in its extreme simplicity and freedom from moving parts. It is the type of system first developed both in the laboratory and commercially. As cooling proceeds, liquid finally forms at  $B_2$ . For the purpose of separating the constituents of the mixture the leg D is developed into a "column still" on the same principle as those used for rectification of ordinary liquids, but, to avoid confusion, not shown in the present cuts.

#### *Claude system.*

In the Claude system, schematically represented in fig. 3, another principle is introduced. It was early pointed out by Lord Raleigh and others that if some sort of expansion engine could be substituted for the free expansion throttle in systems of the Linde type and the work of these engines expended outside the heat-tight room, greater refrigerative effect would be produced even if all the mechanical work so produced were allowed to go to waste, for in its mere production it would have already extracted an equivalent amount of heat from this room. As, for the purposes in hand, these engines must work at very low temperatures, grave mechanical difficulties were seen in the problems of lubrication, brittleness of valves, stoppage by frozen impurities from the gas and the



like. George Claude, of Paris, was the first to solve these difficulties, at least in a commercial way. By use of an expansion engine Claude was able to drop the initial gas pressure to from 400 to 600 lb. per sq. in., or even lower in some of the larger units recently erected for air separation. At these pressures the effect depended upon by

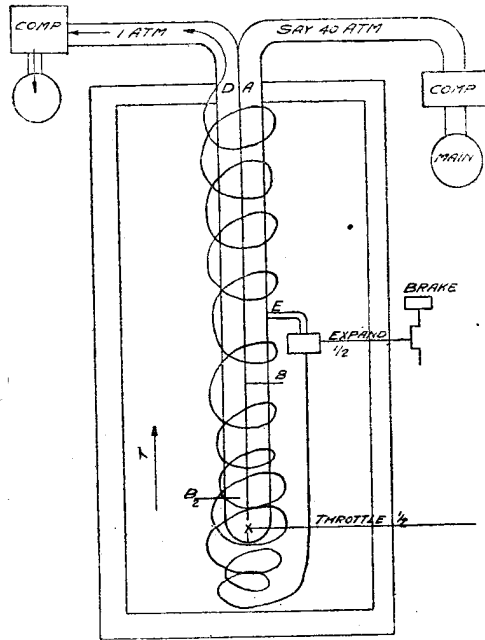


FIG. 3. CLAUDE SYSTEM, EXTERNAL WORK FOR COOLING.

the Linde system practically disappears, so that, in practice, the Claude system works essentially on a wholly new principle rather than by the superposition of this upon that of the Linde process.

However, as Claude confined himself to one

expansion engine (though this is in many cases compound, having a high and a low pressure cylinder), it was necessary for him, with the moderate initial pressure used, to locate the engine's gas intake at a level in the interchanger sufficiently low so that the exhaust would reach the lowest temperature desired in the system and still be able to absorb quite an appreciable amount of heat at this temperature.

With the one engine taking its gas from the incoming side of the U, it is also evident that for efficient liquefaction only a part of the gas can be expanded through the engine, for, if liquefaction takes place in its cylinders, expansion to that extent is lost. The remainder of the gas must, therefore, be retained under pressure in the U and cooled down and liquefied by heat exchange with the expanded gas returning as indicated by the spiral line around both legs of the U. The gas after liquefaction in leg A is let into leg D through the throttle, and there under the lower pressure rapidly drops still further in temperature by its own evaporation. Here it undergoes fractional distillation as explained above.

#### Jefferies-Norton system.

Coming finally to the Jefferies-Norton system, fig. 4, it will be noted that this differs from the Claude in at least three important points, viz.: (1) The system employs more than one engine (in the illustration three, AE, BE, and CE), each working through a different temperature range. The number of these temperature steps depends upon conditions, increasing with the total range of temperature to be covered and also with decreasing initial pressure employed. (2) The pressure in the outgoing leg of the U is only enough lower than in the incoming leg to allow for proper control of flow, unavoidable friction, head of liquid in the still trays and the like. (3) The engines work upon the gases after their liquefaction and distillation, thus permitting all the gas to be so treated. Incidentally, this also insures freedom from easily frozen impurities entering the engine valve chambers and cylinders and in many cases

greatly simplifies the whole problem of initial purification of the gas to be treated. Engine C corresponds in a way to Claude's one-engine system, but as the initial pressure used in the system can, on account of its greater efficiency, be much less than in the Claude, the temperature range over which this engine works will be much

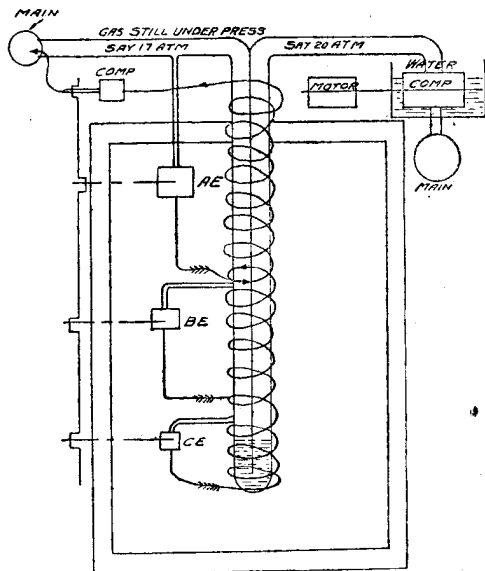


FIG. 4. JEFFERIES-NORTON SYSTEM, TEMPERATURE COMPOUNDED.

less than in the latter. Since, when expanding a given weight of gas between two definite pressures, the work obtainable from it (and consequently the number of calories its expansion will extract from the system) is greater the higher its temperature, engine A will extract the most heat from the system and deliver the most power to the crank-

shaft per unit of gas used, and engine C the least, which still further emphasises the importance of this development.

Rough analogies, though suggestive, are often dangerous to accuracy in scientific and technical explanations, but without laying any great stress upon it, the following may here be helpful to those not especially familiar with this subject. It was pointed out at the start that a considerable amount of the refrigerative effort which has to be expended in any of these processes is to remove the heat which, despite the best insulation, still leaks in from without. Now in this sense the expansion engines of the last two processes may be thought of as engaged partly in pumping out this heat from the refrigerated system back to the outside, much as mine pumps are kept busy pumping out the water which leaks into a mine. Just as water may be coming in at various levels in the mine, so heat is leaking into parts of the system at all levels of temperature. The one engine of the Claude system is analogous to the mine with a single pumping station at the bottom where all water entering at any part of the mine is allowed to drain clear to the bottom and is then all pumped from there to the surface, while the Jefferies-Norton system is analogous to the installation of several pumping stations at different levels so that water from the upper levels is pumped out over the shorter lifts, thus saving power.

The really salient feature brought out in these diagrams is perhaps the progressive approach toward the ideal of thermodynamic reversibility and the high degree to which this is fulfilled in the basic principles of the Jefferies-Norton system.