Helium Liquefier

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A plant for the liquefaction of helium on a large scale has recently been completed in the Cryogenic Engineering Laboratory of the Massachusetts Institute of Technology. The chief characteristics are:

Rate of liquefaction	25–32 l/hr
Power required	45 kw
Helium circulated	215 g mols/min (185 cfm)
Operating pressure	12.5 atm
Refrigeration	Expansion engine plus liquid nitrogen
Liquid nitrogen consumed (If no liquid nitrogen is used, rate of helium liquefaction is 10 l/hr)	20–40 l/hr
Heat exchanger	Hampson type
Actual work expended (N_2 plant included)	3.1 kwhr/l
Computed requirement (actual liquefier but with N_2 plant and helium compressor assumed reversible)	0.87 kwhr/l
Computed requirement (entire process reversible)	0.24 kwhr/l

BECAUSE OF THE EXTREMELY LOW BOILING POINT of helium, 4.22° K or −452° F, special techniques are required to create and maintain the necessary environment for the production of the liquid phase. The quantity of heat that must be removed from a given amount of gaseous helium originally at room temperature in order to bring about its liquefaction is not unusually large, but the work required to extract heat from condensing helium and to discard it at room temperature is about 800 times greater than that necessary if the refrigeration level were the freezing point of water. Furthermore, the problem of adequate insulation against the leakage of heat is acute.

The minimum work required to convert one gram of gaseous helium at one atmosphere and room temperature into liquid helium at 4.22° K can be conveniently determined by considering the change in entropy which the helium undergoes. If we assume that waste heat can be rejected to cooling water at 300° K (80.3° F), for instance, the gain of entropy by the cooling water is exactly equal to the loss of entropy by the helium, the liquefaction being accomplished reversibly. This is shown graphically in Fig. 1. By virtue of the definition of entropy the area of the field *ABCDE* represents the heat removed from one gram of helium when it is cooled from 300° K to 4.2° K and condensed at one atmosphere. The area

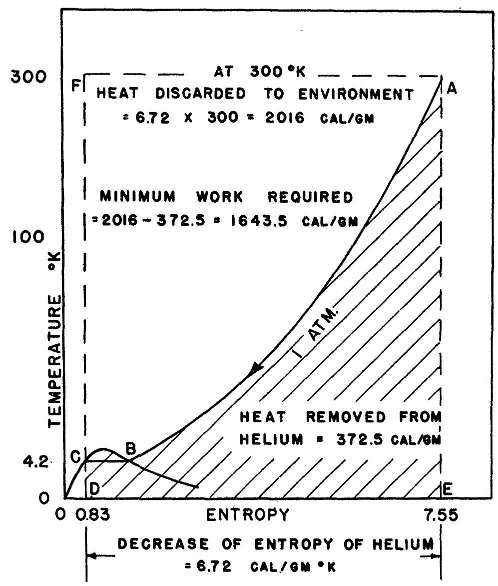

FIG. 1. Temperature-entropy diagram of cooling process.

of the rectangle *AEDF* is a measure of the heat discarded to the surroundings. The difference between the two must be the work put into the system to bring about the liquefaction. It will be observed that the minimum expenditure of work exceeds by fourfold, and more, the heat taken from the helium. Expressed as kilowatt hours per liter of liquid helium (125 g) the result is 0.24.

In the design of apparatus for the attainment of high efficiency in the liquefaction of helium it is necessary to consider the nature of the refrigerative load. A process such as the manufacture of ice, for example, is concerned mostly with latent heat. The refrigeration requirement can be met efficiently by the evaporation of a liquid refrigerant at the proper temperature level. If provision is made for reasonably effective transfer of heat, the entropy gained by the refrigerant in the evaporator does not greatly exceed that lost by the water being frozen, thus fulfilling a condition for high efficiency.

The reduction of warm gaseous helium to the liquid

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state at 4.2° K is a different problem. From one gram of helium at 300° K and one atmosphere, 367 calories of heat must be taken to reduce its temperature to the boiling point, 4.22° K. To effect condensation, only 4.8 calories more must be withdrawn. The refrigerative load is, therefore, distributed over an enormous temperature range. The ordinary refrigeration cycle that employs a liquid refrigerant is unsuitable for this type of service. No single refrigerant exists that can span so great a range of temperature. Even if such a refrigerant could be found, the cycle would be quite inefficient, because all the heat would have to be pumped from the lowest temperature level instead of a descending series of levels as the stream of helium is progressively cooled. The entropy gained by the refrigerant would greatly exceed that lost by the helium.

The only practicable way, probably, to cool a stream of fluid substantially, reversibly utilizes a second stream of the same or other fluid in an adiabatic counterflow heat exchanger. This principle is employed in the liquefying cycle described below. The second stream of cold gas is provided by the adiabatic expansion in an engine of a part of the first stream. In its idealized form the cycle is shown in Fig. 2. A

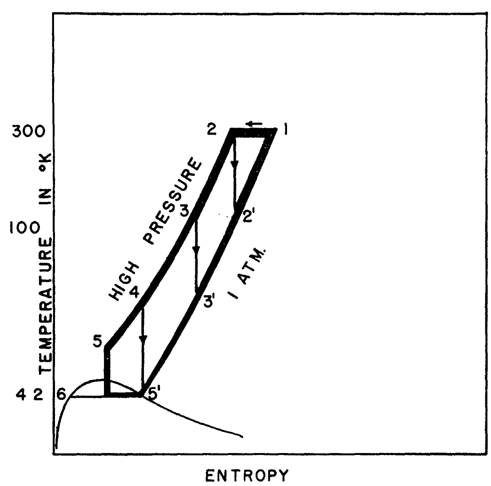

FIG. 2. Idealized cycle for cooling a helium stream.

large stream of helium circulates in the direction of the arrows. A small fraction of the stream is removed as liquid at 6, an equivalent amount of gaseous helium being added to the stream at 1. Isothermal compression (1 to 2) occurs in the compressor. Cooling of the compressed gas (2 to 5) is accomplished in the counterflow heat exchanger by the transfer of heat to the colder outgoing stream of low pressure gas (5′ to 1). A fraction of the stream of compressed helium at 2 is expanded in an engine to 2′, where it joins the main stream of low pressure gas. The drop in temperature is a result of the external work done. Since helium is an almost perfect gas at higher temperatures, the preferred rate of flow through the first engine (2 to 2′) exactly equals the rate of liquefaction. Under this condition the mass rate of flow in the high pressure channel of the heat exchanger (2 to 3) equals that in the low pressure channel (2′ to 1), and, consequently, the temperature drop from 2 to 3 equals the temperature rise from 2′ to 1. Assuming the heat exchanger to be perfect, no net gain of entropy occurs in this part of the heat exchanger, and thus far the process is reversible. For the next stage of cooling, a second fraction of the stream of compressed helium is split off at 3 and expanded in a second engine to 3′. At lower temperatures the effect of pressure upon the specific heat of helium is not negligible. If the temperature drop from 3 to 4 is to equal the temperature rise from 3′ to 2′, the mass rate of flow through the second engine (3 to 3′) must exceed slightly the rate of liquefaction. By so doing, complete reversibility in this section of the heat exchanger can be closely approached. A third engine is indicated by the path 4 to 5′. Finally, the remainder of the stream is expanded in a fourth engine. Even with a perfect heat exchanger and a perfect engine, however, this stage of the process is quite irreversible. Because of the rapidly rising specific heat of the high pressure stream, the unliquefied portion of the flow through the final engine plus the flow from the third engine (5′) must exchange heat with a fluid that is considerably warmer. There is, therefore, a large net increase in entropy in this section of the heat exchanger. The number of engines required in the cooling cycle just described depends upon the magnitude of the ratio of the pressures involved—the greater the pressure ratio, the smaller the number of engines. With high and low pressures of 12 atmospheres and one atmosphere, respectively, 5 engines would be indicated, and the work required would be 0.30 kwhr/l of liquid helium as compared to 0.24 kwhr/l for a reversible process.

Description of Liquefier

A flow diagram of the actual cycle chosen is given in Fig. 3. It differs from the idealized cycle of Fig. 2, not only because the heat exchangers and expansion engines are necessarily imperfect, but also because practical considerations have influenced the choice of apparatus and procedures. For the sake of compactness of the liquefier and greater production of liquid from available compressed helium, liquid nitrogen is employed to the extent of its utility. The transfer of heat from gaseous helium to liquid nitrogen evaporating at a constant temperature is irreversible, of course, and a net increase of entropy is incurred. A final difference lies in the substitution of a throttle valve for the fourth engine of the cycle of Fig. 2.

In the flow diagram shown in Fig. 3, compressed helium (about 12 atm) from the compressor is treated for entrained oil in an oil trap and for vaporized oil in a refrigerated heat exchanger 3. Thereafter the stream divides, about 8 per cent going to heat exchanger 4, in which it is cooled to 80° K by means of liquid nitrogen and then expanded in engine E_1, the remainder going to the principal heat exchanger 5. The temperature of the gas in heat exchanger 5 ranges from room temperature at the upper end to 15° K at the bottom. At the zone of exchanger 5 where the temperature is 40°–45° K a second fraction (about 15 per cent of the whole) of the compressed helium is led off for expansion in the second engine, E_2. At the lower end of exchanger 5 a final division of the stream occurs. About 52 per cent is used in expansion engine E_3 and 25 per cent flows through the small exchangers 6 and 7 to the expansion valve D.

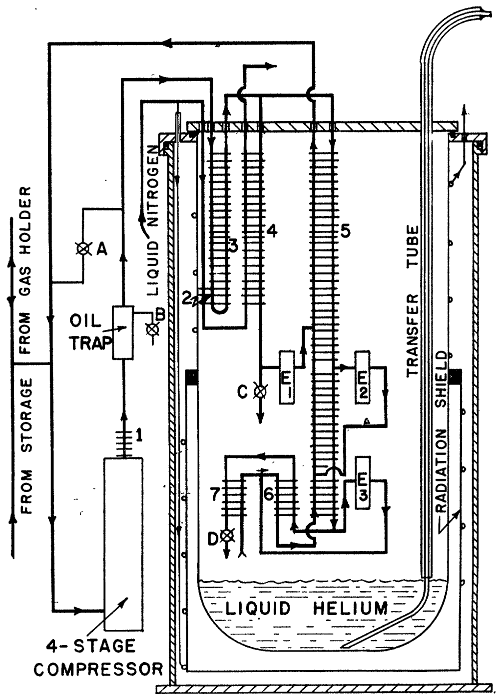

FIG. 3. Flow diagram of helium liquefier.

All the helium that enters exchanger 4 passes through engine E_1, the pressure falling to substantially one atmosphere and the temperature falling from 80° K to about 45° K. The expanded helium joins the low pressure stream in exchanger 5. All three engines are served by a single crankshaft and are identical in size. The bore is 2 inches, and the stroke is 2 inches. Each engine is comprised of a single cylinder. Although the three engines receive compressed helium from the same supply line and discharge their spent gas into the same low pressure conduit, they operate at different temperature levels and embrace different sections of the heat exchange system. Helium enters E_2 at about 45° K and is discharged at about 25° K. The inlet temperature of E_3 is about 15° K, and the outlet temperature is estimated to be about 9° K.

Liquid helium forming at the throttle valve *D* drops into the bottom of the Dewar vessel in which the heat exchangers and engines are suspended. Space for 30 liters is provided.

Certain features of the earlier helium cryostat (*1*) have been retained. The heat exchangers and engines, which hang from a steel plate, are surrounded by an atmosphere of helium rather than by the insulating vacuum. Minor leaks from the high pressure stream can be tolerated. The helium atmosphere is contained by a large metal Dewar vessel, the vacuum jacket of which is continuously pumped. The lower half of the inner wall of the vacuum jacket is enclosed by a nitrogen-cooled radiation shield.

The engine cylinders and pistons are made of nitrided nitralloy and are so closely fitted that piston rings are unnecessary. The piston rods are relatively long and slender, and are made to operate in tension to promote perfection of alignment of the piston within the cylinder. There exists a thermal gradient in the helium atmosphere surrounding the heat exchangers and engines, the temperature being approximately 295° K at the top and 4.2° K at the bottom. As far as practicable, the cylinders of the engines are located at the proper elevation for matching temperatures inside with outside in order to reduce convection to a minimum. The stuffing boxes for the piston rods and valve pull rods and the running gear of the engines are placed on top of the lid of the Dewar so that heat generated in these parts can be kept out of the cold region.

The piston rods and valve pull rods are attached to the ends of horizontal walking beams (*2*), as in ancient steam engines. The beams are 2 feet in length, are pivoted at one end, and at the point immediately above the crankshaft are fitted with ball bearings to act as cam followers. With a stroke of only 2 inches the end of the piston rod travelling in an arc of 2-foot radius is not pulled away from the vertical by an appreciable angle. Speed control is achieved by centrifugal action of a split flywheel within a brake drum. The two halves of the flywheel are fitted with brake shoes. Speed is adjusted by changing the compression of a spring. This adjustment may be made while the engine is running.

The Heat Exchange System

The heat exchange system begins with the intercoolers and aftercoolers of the compressor, indicated in Fig. 3 as 1. These are made of internally finned tubing that has two channels, one for helium flowing in one direction, the other for cooling water flowing in the opposite direction. Considerable care must be used to avoid excessive heating of the helium during compression. In low pressure liquefiers such as the one being described, a large volume of the gas is circulated through the compressor (in which it becomes saturated with oil), heat exchanger, and expansion engine again and again before a given portion is completely liquefied. High temperatures during compression would partially decompose the lubricating oil. The volatile fractions resulting from the decomposition would eventually cause stoppage of the heat exchanger in the cold zone or leakage of the valves of the expansion engines. By the use of four stages of compression, even though the highest pressure is only 13 atmospheres, and by reduction of the temperature of the helium between stages to within a very few degrees of that of the cooling water, damage to the lubricating oil is avoided so completely as to make unnecessary the use of charcoal or other absorptive purifying agent.

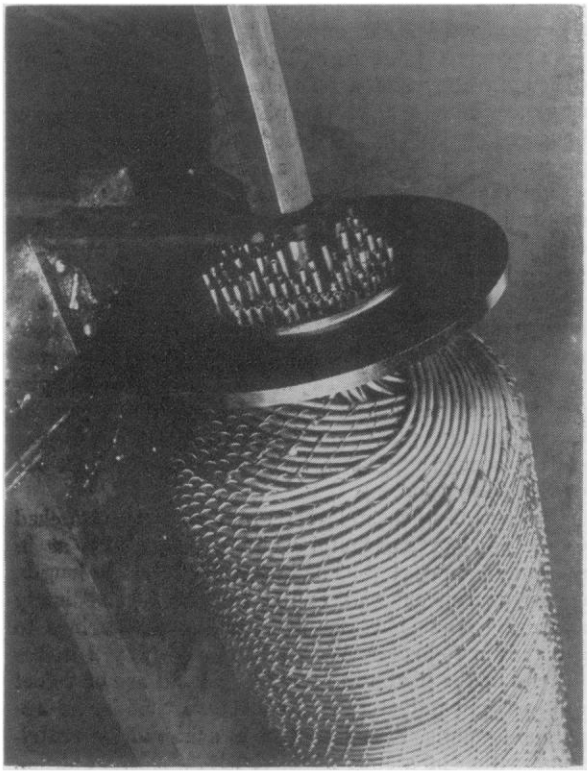

FIG. 4. Hampson type exchanger under construction.

Heat exchanger 2 is a zone of limited contact between a stream of liquid nitrogen and the cold end of heat exchanger 3. Its sole purpose is to provide sufficient refrigeration to maintain the lower end of exchanger 3 at approximately 200° K. Heat exchanger 3 is similar to exchanger 1 in that it is made of internally finned tubing. The entire stream of compressed helium is cooled as it flows downward from room temperature to approximately 200° K and is immediately warmed up again during its return passage in the same exchanger. The purpose of this treatment is to condense oil vapor carried by the helium stream. Condensed oil collects in a chamber at the lower end of exchanger 3. The chamber is drained periodically.

In heat exchanger 4, as indicated earlier, a small fraction of the compressed helium is cooled substantially to the boiling point of nitrogen by indirect contact, first with gaseous nitrogen, and then with liquid nitrogen. Thereafter this stream of compressed helium is expanded in engine 1. Heat exchangers 4, 5, 6, and 7 are all of the Hampson type as to method of construction. Fig. 4 is a photograph of a partially completed exchanger. A bundle of small brass tubes (1/8" O.D., 1/10" I.D.) provides passage for the compressed helium. Low pressure helium (nitrogen in the case of exchanger 4) flows outside the tubes within the enclosing shell. Exchanger 4 contains 18 tubes approximately 23 feet long. The number of tubes in each helix, counting from the innermost outward, is 1, 2, 2, 3, 3, 3, 4. The outside diameter of the shell is 3 inches, and the length is 36 inches.

Exchanger 5 contains 130 tubes approximately 60 feet long and 30 tubes 40 feet long. There are 26 layers of helices, the number of tubes per helix varying as indicated by the following sequence of numbers: 2, 2, 3, 3, 3, 4, 4, 4, 5, 5, 5, ... 10, 10, 10. The tubes are spaced from each other by winding around each tube a spiral of 0.019-inch copper wire. The 160 tubes are manifolded together at the upper end of the heat exchanger. The outermost 30 tubes (40 feet long) are brought together at their lower ends to supply compressed helium to engine 2. All the gas flowing through these tubes must pass through E_2. The remaining 130 tubes are brought together at the bottom of the heat exchanger. The diameter of exchanger 5 is 9.5 inches and 7.25 inches at top and bottom, respectively, and its length is 47 inches.

Exchangers 6 and 7 are identical. Each contains 30 tubes 11 feet long.

The Hampson type of heat exchanger was chosen because of its compactness. As constructed, it is rather wasteful of refrigeration, but it has made possible a noteworthy condensation both in diameter and height of the assembly. Furthermore, the accessibility of the engines for maintenance is considerably greater than in the earlier model. There is, of course, no cold space for experiments. The machine is a simple liquefier.

Multiple engines operating at different temperature levels, in addition to their primary function of almost reversible cooling of the fraction of gas ultimately liquefied, also provide substantial compensation for the inefficiency of the heat exchanger. By making the mass rate of flow of helium through E_1 and E_2 greater than the rate of liquefaction, the portion of exchanger 5 above the discharge of E_1 and the portion lying between the inlet and discharge of E_2 are substantially unbalanced. The mass rate of flow of low pressure helium upward is greater than that of the high pressure stream downward. The net effect is to bring the temperature of the incoming high pressure helium very close to the discharge temperature of the respective engine. Stated differently, by the expenditure of a slight amount of additional work in the compressor to provide excess flow of helium through E_1 and E_2 a mediocre heat exchanger can be made to approximate, so far as cooling the incoming gas is concerned, the performance of a perfect exchanger. In operation, the temperature of the efficient gases is approximately 12° C lower than that of the entering gas—an excessively large difference. At the zones where the gas discharged from the three engines, respectively, joins the low pressure stream, the temperature difference between incoming and outgoing helium is estimated to be only one to two degrees. The principle of unbalancing a heat exchanger in order to secure a closer temperature approach at one end or the other is, of course, well known.

The short sections of exchanger 5 lying between the discharge of E_1 and the inlet to E_2 and between the discharge of E_2 and the inlet to E_3 provide valuable protection against mismatching of temperatures resulting from failure of heat exchanger and engines to meet design criteria.

of liquefaction. If valve D is opened too wide, the temperature of the compressed helium entering E_3 rises above 16° K. Conversely, if valve D is too nearly closed, the temperature in question becomes too low. When a favorable adjustment has been secured, the rate of liquefaction is 32 liters per hour. For small batches of liquid helium, cooling the apparatus represents substantially the whole cost of production. For large batches of 25–50 liters the average cost per liter is quite small. This conclusion is predicated on the assumption that the evaporated helium will be saved

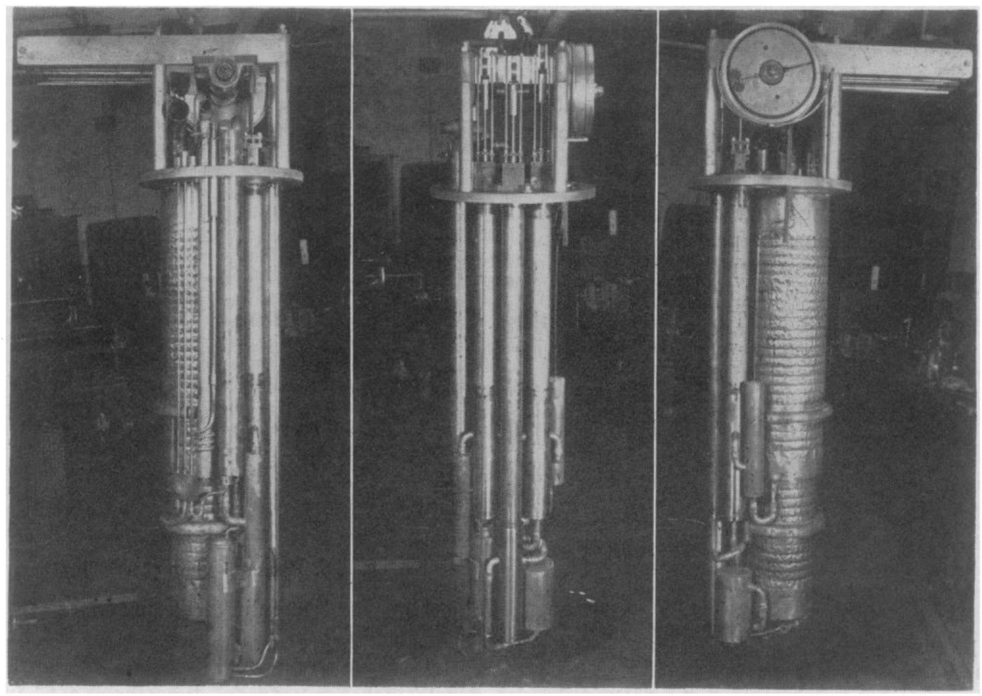

FIG. 5. Three views of the heat exchanger–expansion engine assembly.

for further use. If the gas is allowed to escape to the atmosphere upon evaporation from the liquid state, the value of the helium itself must be considered. Prevailing retail rates of bottled helium are such that the helium in one liter of the liquid phase is valued at almost $3.00. This figure exceeds by far the cost of reducing the helium to the liquid state.

Performance

The cool-down time of the liquefier is relatively short if liquid nitrogen or liquid air is available, ranging from 40 minutes when started within 24 hours after a previous run to 1 hour and 45 minutes if the apparatus must be cooled from room temperature. In the latter case approximately 40 liters of liquid nitrogen would be consumed.

The cool-down period can be shortened by partially opening valve C, which allows cold helium from exchanger 4 to enter the space surrounding the heat exchange system. Its only means of escape is the low pressure channel through exchangers 7, 6, and 5 in the order mentioned. Cooling is thus applied directly to the lower end of the heat exchanger. Efficient use of valve C demands considerable attention from the operator. For that reason it is rarely used.

Once the liquefaction temperature has been reached, expansion valve D is adjusted to maintain the inlet temperature of engine 3 at 14° to 16° K, experience having shown this condition to give the highest rate

Liquid nitrogen is not indispensable to the successful operation of the helium liquefier. Without it, of course, more time is required for cooling the apparatus, and the rate of liquefaction drops from 32 liters to 10 liters per hour. Whenever liquid nitrogen is employed it serves a dual purpose. About 95 per cent of the stream flows to exchanger 4 for cooling helium, the remainder to the radiation shield. No reservoir is provided in either place. A small stream of nitrogen flows continuously from an external storage vessel through the apparatus. It is vaporized and warmed approximately to room temperature during passage.

Production rates given above refer to liquid stored within the liquefier. During transfer to external vessels losses are incurred. About 6.5 liters are required to cool and fill a 4-liter glass Dewar.

Helium-filled gas thermometers have been provided for temperature measurement. One is clipped to each inlet and each discharge pipe of the three engines. This method of application was chosen to permit easy assembly and disassembly of the engines without damage to the calibrated thermometers. The result is, however, quite unsatisfactory. The thermometer bulbs seem to be influenced more by the helium atmosphere surrounding them than by the fluid flowing through the tube against which they are pressed, even though a 1-inch layer of insulating material is wrapped around each assembly.

Although absolute temperatures are unknown, the thermometer indications are useful during operation. As was mentioned earlier, an indicated temperature of 14°–16° at the inlet of engine 3 is a concomitant of high production.

The engine efficiency is estimated to be 80 per cent. This estimate is based upon the performance of similar engines fitted with thermocouples, the junctions of which were exposed directly to the gas streams entering and leaving the cylinder. The efficiency of the expansion engine is necessarily very high; otherwise the results achieved would not be possible.

Although the principal heat exchange is considered relatively inefficient, it has desirable qualities in addition to compactness and convenience. Its resistance to flow on the low pressure side is extremely low. This contributes to its inefficiency but favors engine performance and reduces flashing of liquid helium during transfer. Increasing the length of the exchanger would improve efficiency but would increase the cool-down time and provide more bulk to be insulated. More elaborate preparation of suitable fixtures for use in its construction would undoubtedly have given a more uniform distribution of tubes throughout the volume of the exchanger, with a probable improvement of efficiency.

Three views of the expansion engine–heat exchanger assembly are given in Fig. 5. Note the split flywheel and water-cooled brake drum for work dissipation. Although the power of the engine is almost 2 kw, its

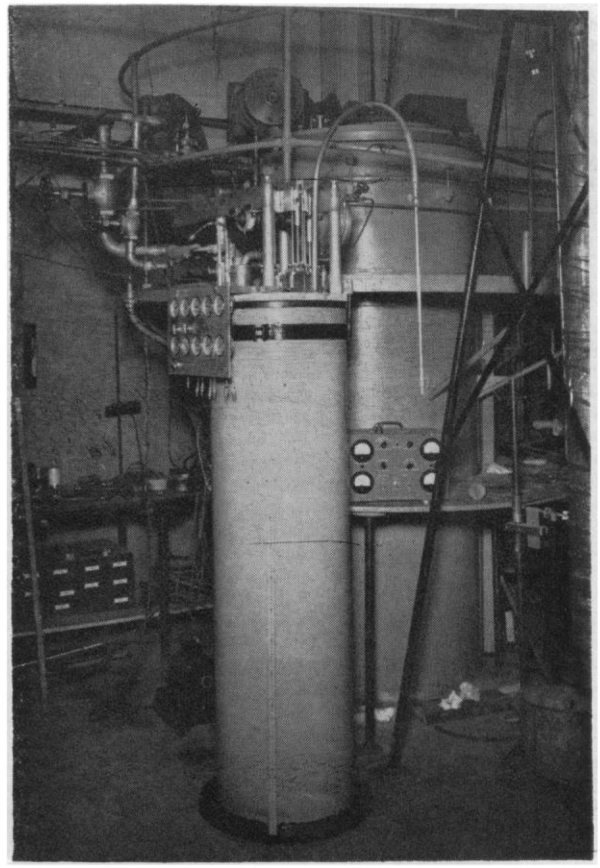

Fig. 6. External view of the liquefier.

recovery would complicate the machinery to an objectionable extent. Fig. 6 shows the complete liquefier. The outer wall of the vacuum jacket is an iron cylinder 18 inches in external diameter and 64 inches tall. The large cylinder seen beyond the liquefier is the helium refrigerator.

References

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2. Collins, S. C., and Smith, L. B. *Technical Report 48 L. I. R., Mass. Inst. Technol.*