REFRIGERATION AT TEMPERATURES BELOW THE BOILING POINT OF HELIUM

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I. INTRODUCTION

The growing need for continuous refrigeration at or near the normal boiling point of helium has led to the practice of coupling a helium liquefier with the apparatus to be cooled in such a manner as to return the cold helium vapor to the heat exchange system of the liquefier and thereby recover substantial amounts of refrigeration.

The value of such an arrangement is demonstrated in Fig. 1. A small liquefier of 4 ℓ/hr capacity containing a somewhat better than average heat exchanger is connected to a liquid storage vessel by means of a two-channel transfer line. The rate of accumulation (or loss) of helium is measured by the rise or fall of an external gas-holder. With the liquefier running and all vapor, that is, the unliquefied portion of the Joule-Thomson stream plus that formed as a result of added heat, returning to the compressor by way of the liquefier, the relation between the rate of heating and the net transfer of helium to or from the storage vessel is given by the upper curve. The lower curve shows the corresponding relation when the liquefier is not in operation and there is no recovery of refrigeration. In the first case the useful refrigeration at 4.4°K varies from 4.8 W·hr/ℓ of liquid at low rates of heating to 3.5 W·hr/ℓ when the heating rate is 38.5 W. In the second case the ratio is 0.78 W·hr/ℓ of liquid helium — about one-fifth as great.

The helium liquefier used for this experiment required a flow of helium of 35 SCFM with adiabatic expansions at two temperature levels from 14 atm to 1 atm. Liquid nitrogen was not used.

It is significant that so long as the average heating rate is below 18 W the rate may be as high as 50 W for a part of the time.

II. REFRIGERATOR FOR LOWER TEMPERATURES

In response to the need for continuous refrigeration at the 1.85°K by Professors Fairbank and Schwettman of Stanford University for their superconducting accelerator, a small experimental refrigerator was constructed and successfully operated at Arthur D. Little.[1] The refrigeration cycle used in this machine is given in Fig. 2. The heat exchanger for recovering refrigeration from the low-pressure vapor (10-14 mm) represented the chief problem to be solved. The volume of gas to be treated was enormous and the pressure available to drive it through the heat exchanger was very small. The design finally chosen consisted of a vertical stack of pancake coils of finned tubing connected in series in such a manner as to cause the high-pressure stream of incoming helium to flow in a spiral path from the center of one pancake to the periphery and from the periphery of the next pancake to its center and so on. The low-pressure stream flowed vertically upward through the finning which presented a short path of large cross section.

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1. S.C. Collins, R.W. Stuart, and M.H. Streeter, Rev. Sci. Instr. 38, 1654 (1967).

High-pressure helium enters the special heat exchanger at three temperature levels, room temperature, 79°K and about 7°K. The warmer sections of the heat exchanger are, therefore, unbalanced and the recovery of refrigeration is far from complete. The lowest section in which the mass rate of flow of incoming and outgoing helium was the same was made relatively long for high efficiency so as to conserve refrigeration of high intrinsic value.

During the test continuous refrigeration in the amount of 10 W at 2.0°K and 15 W at 2.2°K was maintained. The major limitation on refrigeration was the capacity of the vacuum pump available for use. For the helium circulated in the special exchanger the refrigeration obtained was approximately 22 J/g, a figure very close to the maximum available.

III. STANFORD REFRIGERATOR

A large refrigerator of this type has now been made for use in the Stanford accelerator. It has a capacity of 300 W at 1.85°K. The cycle is slightly different (Fig. 3), in that conditions for heat transfer in the range from 16° to 8°K were made more favorable by shunting a portion of the high-pressure stream to the main heat exchanger for further cooling by the gas discharged by the No. 2 expansion engine. The heat capacity of helium at 10-15 atm is much higher at the 16° to 8°K range than that of the low-pressure outgoing gas.

In Figs. 4, 5 and 6 various stages of the manufacture of the low-pressure heat exchanger for the Stanford refrigerator are shown.

IV. REFRIGERATOR OF THE FUTURE

Because of the cost of the power to operate a large refrigerator continuously it is readily apparent that any increase in the efficiency of the refrigerator will greatly extend its usefulness.

There is undoubtedly room for improvement in every component of a refrigerator for very low temperatures. The vacuum pump is probably the most inefficient element. A major effort will be required to do much about it but such an undertaking seems well worthwhile.

Industrial compressors use approximately 50% more power than the theoretical minimum but further improvement will likely be slow and costly considering the advanced state of the art.

Only slight improvement in the efficiency of expansion machines seems possible.

Heat exchangers vary greatly in efficiency. In general there is room for much improvement. Such improvement will, of course, add to the cost of the refrigerator.

The most promising possibility for greater efficiency lies in the use of more stages of expansion. This principle is illustrated in Table I. Expanding portions of the stream of high pressure helium at five temperature levels is highly effective.

A flow diagram of a refrigerator having five stages of expansion is given in Fig. 7. Ordinarily the complexity would be considered too great, but recent models of expansion engines have demonstrated a degree of reliability which justifies the use of multiple cylinders. The power produced by the expansion engines should be about equivalent to that required to drive the vacuum pumps. The net power requirement of the system is estimated to be three times that of a Carnot cycle.

TABLE I. Effect of number of thermal stages of expansion on the available refrigeration. Helium flow was 74 SCFM at a pressure of 15 atm.

Number of Stages of Expansion	Refrigeration at 4.4^{o}K (W)
1	12 obs.
2	37 obs.
3½ (N_2)	58 obs.
5	75 calc.

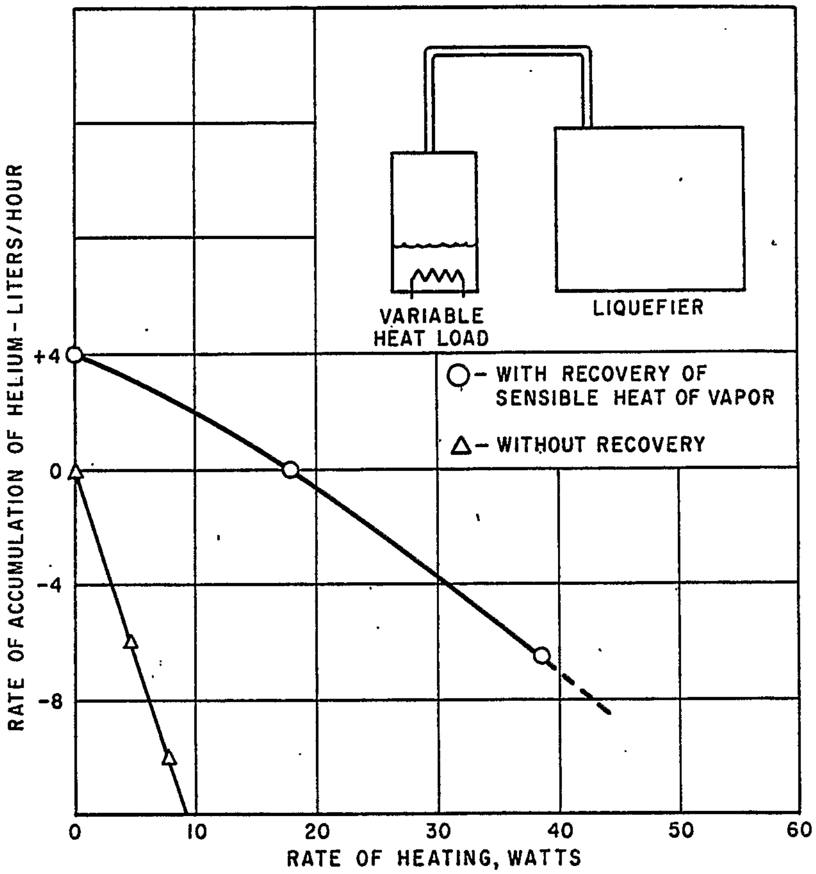


Fig. 1. Refrigeration at 4.4^{o}K.

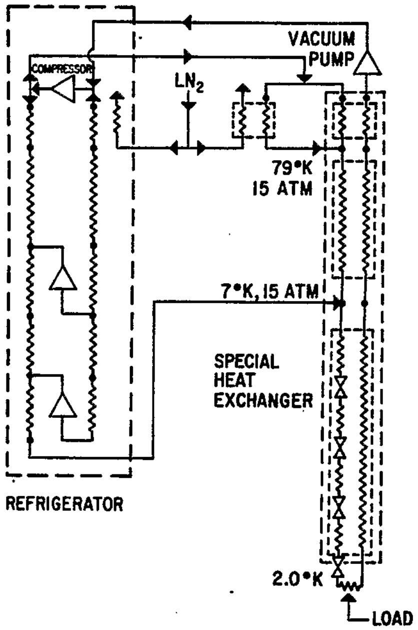


Fig. 2. Flow diagram of experimental refrigerator for 1.85°K.

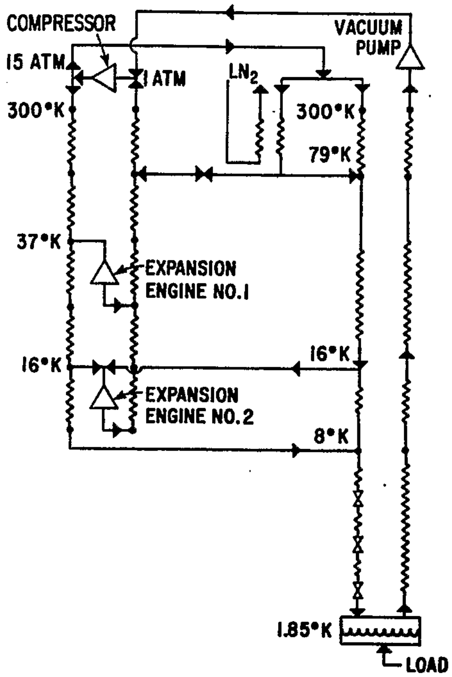


Fig. 3. 300 W, 1.85°K refrigerator cycle.

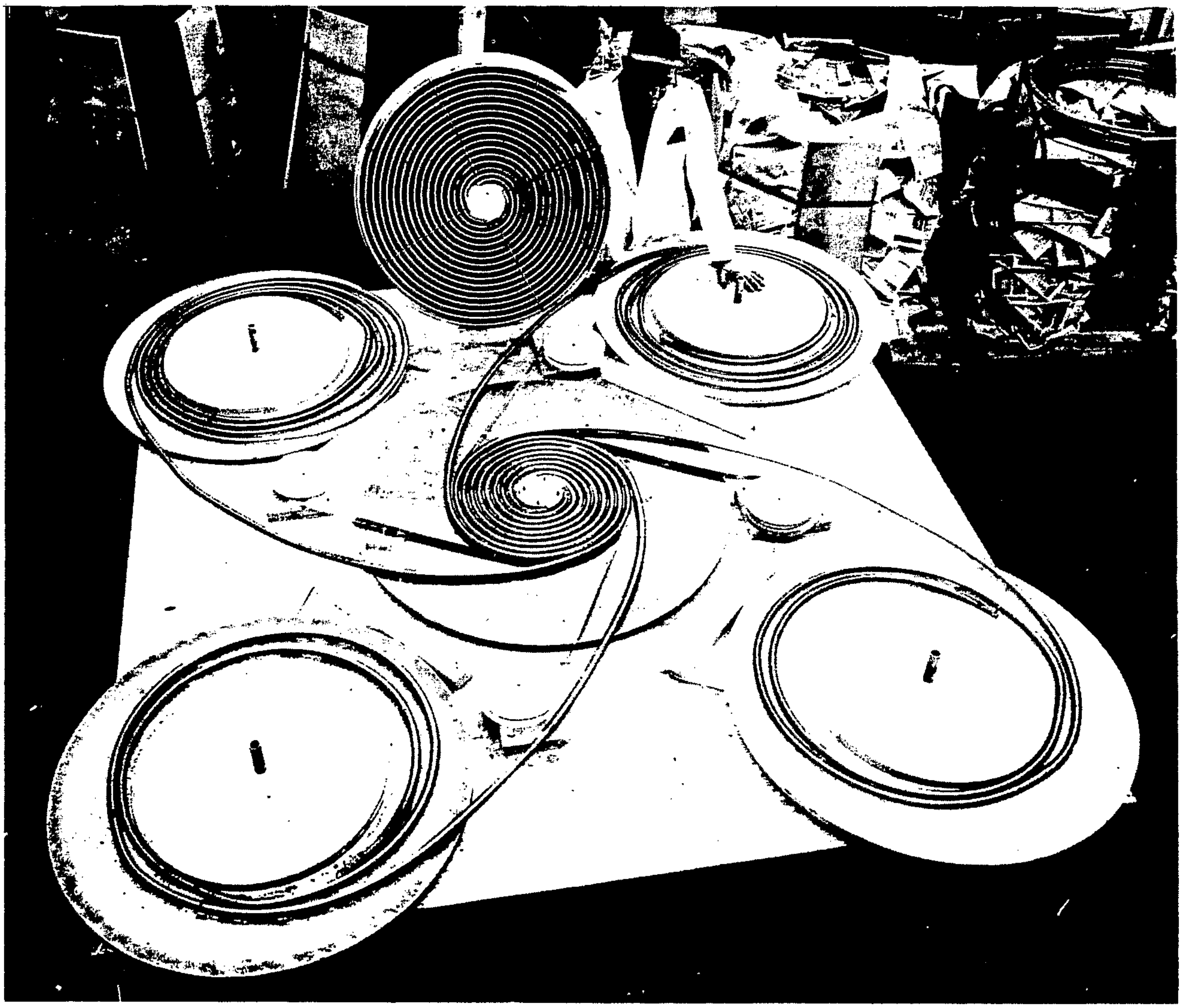


Fig. 4. Heat exchanger pancake under construction.

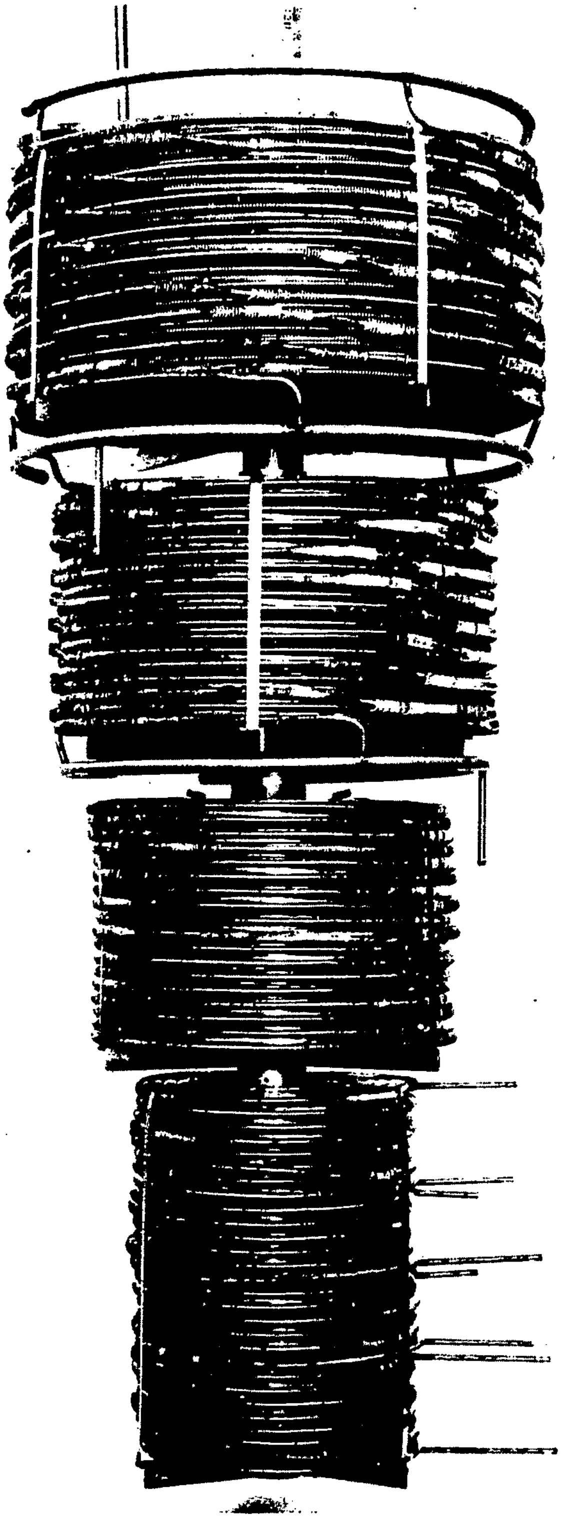


Fig. 5. Low-pressure heat exchanger ready for jacket.

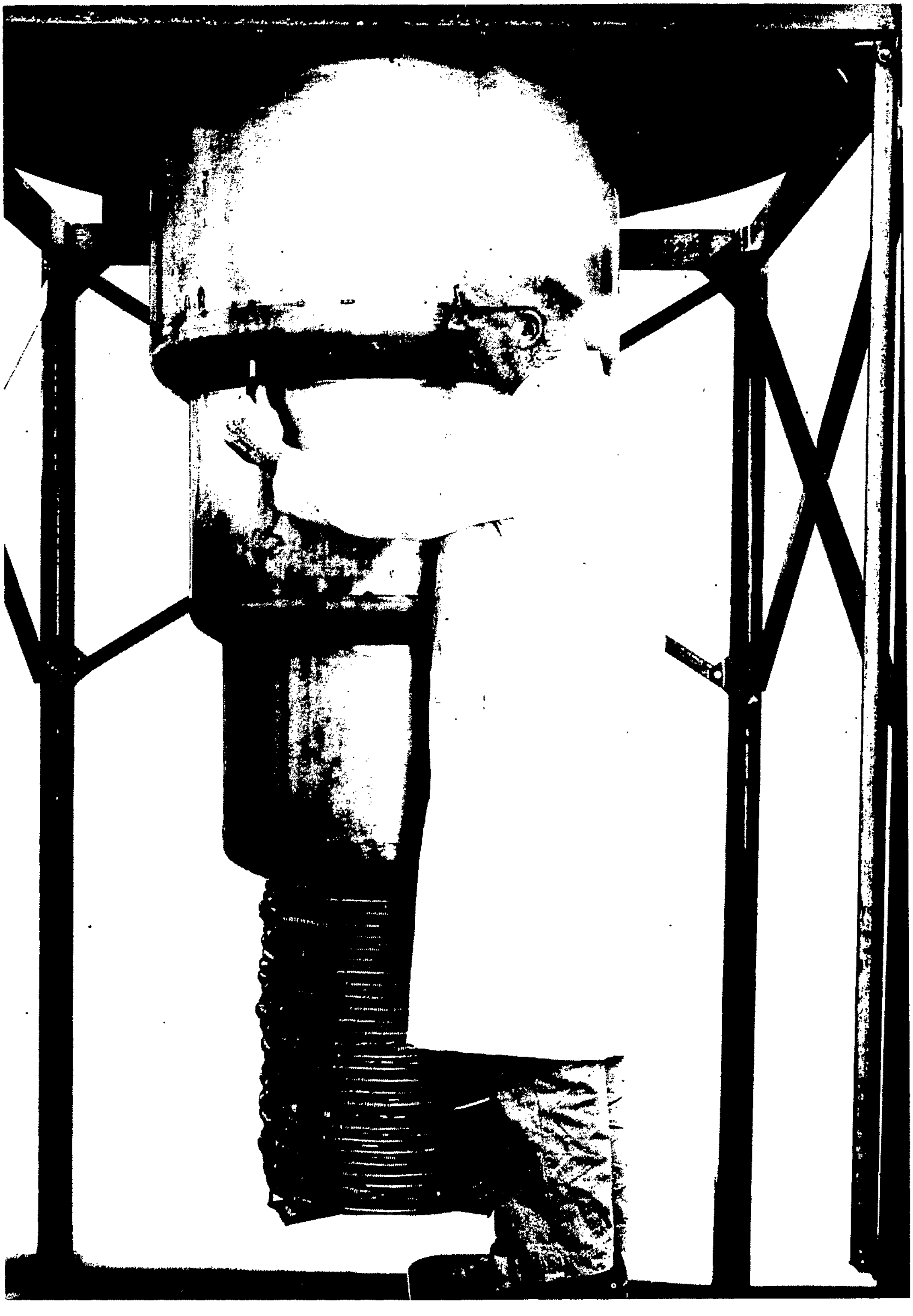
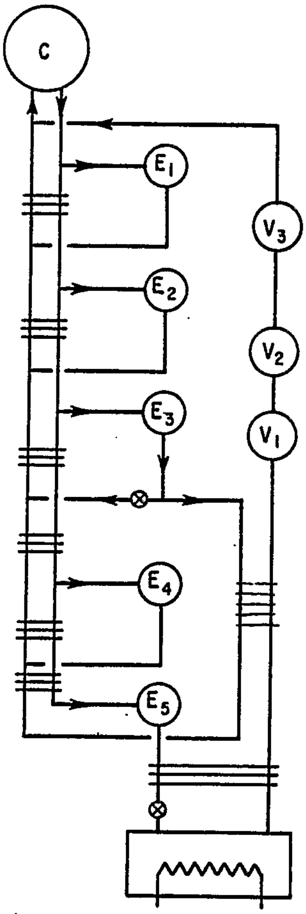


Fig. 6. Low-pressure heat exchanger receiving jacket.



POWER REQUIREMENTS	1.5° K	1.8° K
COMPRESSOR	3050 kW	2410 kW
VACUUM PUMP	318	272

Fig. 7. Proposed cycle for 5 kW, 1.5°K refrigerator.