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LARGE SCALE REFRIGERATION SYSTEMS FOR THE TEMPERATURE RANGE OF 1.0 to 1.85 K *

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ABSTRACT

The feasibility of converting the two-mile electron accelerator to a superconducting machine is actively being explored at the Stanford Linear Accelerator Center. Within the framework of that program a study of possible systems to provide the necessary refrigeration within the 1.0 K to 1.85 K temperature range is being made. In this paper the implications of the conventional approach are reviewed. It is shown that by reducing ambient temperature pumping equipment through the use of ^{3}He as an intermediate heat transfer fluid, thermodynamically efficient systems can be realized. Cryogenic compressors are reviewed: they do not appear to be economically feasible for continuously operating systems. Implications of helium ejector expanders are discussed and the general aspects of the continuing program presented.

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INTRODUCTION

The two-mile electron linear accelerator at the Stanford Linear Accelerator Center has now been in operation for a number of years and has proved to be a powerful tool of high energy physics research. During the years in which the accelerator was being built, and particularly in the last few years, a number of significant developments in technology have taken place. These developments have opened the way towards achieving higher energies at lower cost per unit power input than has been hitherto realized, in particular by the remarkable progress in the technology of superconductors.

The superconducting linear accelerator is one of the approaches for applying the new technology to the extension of the accelerator art towards higher energies, greater intensity, better duty cycle or other goals of importance to high energy physics. It is recognized that many of the objectives within the scope of superconducting technology could also be attained by a conventional approach but at the expense of tremendous effort and astronomical cost. Clearly the incentive for the present study is economical as well as technical.

It should be stressed that the technical feasibility of a long, high gradient superconducting accelerator has not yet been fully demonstrated. In parallel, and more germane to the present discussion, it has become apparent that the same can be said of the technology required to furnish and to maintain large volumes of liquid ^{4}He at temperatures below the λ-point. A refrigerator providing 300 W at 1.85 K has recently been commissioned at the High Energy Physics Laboratory at Stanford University(1). However, the installation of a number of such machines along an accelerator is neither an efficient technical solution, nor is it economically viable.

This paper then has two functions: It is a report on the outcome so far of a continuing study, and it is intended to stimulate interest and to draw attention to the unusual technical problems that are encountered in this low temperature region.

REFRIGERATION SYSTEM REQUIREMENTS

The basic accelerator parameters have been presented elsewhere(2). The estimated heat loads at three temperature levels are summarized in Table I, based on operation at 2856 MHz, the present frequency of the accelerator, a duty cycle of 6 percent at an energy of 100 GeV. The difference in the passive loads at the three temperatures is due to the absence of the 6 K conductive heat intercepts and shields at 1.85 K. It turns out that to provide the necessary plumbing for a 6 K intercept system greatly outweighs in complexity and in cost the necessary increase of about 10 percent in the cooling requirements at 1.85 K. However, at the lower temperatures, where the active load is of the same magnitude as the static heat input, a considerable saving can be effected by introducing the intermediate intercept system.

1.85 K REFRIGERATION SYSTEMS

^{4}He 1.85 K Refrigeration System

A simplified flow diagram of the ^{4}He refrigerator is shown in Fig. 1. It is based on a two-expansion engine Claude cycle providing two stages of isobaric refrigeration at the 60 to 70 K and 8 to 15 K temperature levels for a Linde-Hampson cycle, furnishing refrigeration at 1.85 K.

As the existing subdivision of the accelerator into thirty sectors has been retained, the refrigeration system envisions 16 refrigeration stations, 16 vacuum pumping stations and one compressor station. Of these, one complete refrigerator and vacuum pump station would be on standby at the beam injection end of

Table I. Estimated Heat Loads (in watt)

	1.0 K	1.5 K	1.85 K
Passive Load			
Waveguide connections	78.0	78.0	360
Dewar	1.0	1.0	144
Supports	1.9	1.9	24
Phasing and tuning mechanism	24.0	24.0	240
Accelerator connections	0.6	0.6	15
Helium connections	0.5	0.5	115
Instruments	24.0	24.0	48
Miscellaneous	10.0	10.0	300
Total Passive Load	140.0*	140.0*	1,246**
Active Load			
RF loss (at 100 GeV and 6 percent duty cycle)	150	1,500	12,000
Beam loss	10	100	1,000
Total Active Load	160†	1,600†	13,000
Total Heat Load	300	1,740	14,246

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[*] Does not include the two intermediate heat shields at 70 and 6 K required to reduce the refrigeration loads at 1.0 and 1.5 K.

[**] Does not include the intermediate heat shield at 70 K required to reduce the refrigeration load at 1.85 K.

[†] Based on a theoretical extrapolation of mixed experimental results at temperatures between 1.5 and 2.0 K.

the accelerator. Each refrigeration station consists of one 1200 watt He I precooling unit shared in parallel by two 500 watt, 1.85 K He II refrigerators.

The refrigeration scheme has been described in greater detail elsewhere(3). From the outset it was clear that the cost of such a system would be high and that the efficiency was limited by the performance of the best available vacuum pumping equipment. The total power per unit of refrigeration is 970 watt/watt, based on manufacturers' quoted requirements for pumps and compressors. The appendix presents the estimated costs that would be involved in implementing the system.

Modified Systems

The vacuum pumps represent a very substantial cost both for the initial equipment and for the subsequent operation and maintenance, as the appendix shows. The following alternatives have been considered, in an effort directed towards a reduction in the number of pumps.

1. Independent ^{3}He refrigeration loops. The helium isotope of mass 3 has a vapor pressure of about 114 torr at 1.85 K.
2. Ejector expanders.
3. Cryogenic vacuum pumps or compressors, to operate in the temperature region of 10 to 40 K and 10 to 760 torr.

Naturally any thermodynamically reasonable combination of the above alternatives was also considered. A summary of the permutations examined is given in Table II. In each case the starting point was the 1.85 K refrigerator of Fig. 1. It is recognized that this refrigerator concept may not be the most efficient one, nor be universally applicable to all temperature levels. However, its quasi-independent circuits simplify analysis and offer a better insight into the thermodynamic interaction of the various subsystems.

Table II. Summary of Refrigeration Systems

System	^{4}He SYSTEM			^{3}He-^{4}He HYBRID SYSTEM		
	Temperature (K)			Temperature (K)		
Combination	1.85	1.5	1.0	1.85	1.5	1.0
Ambient Temperature Pumps	System Expensive	System Very Expensive	NO	System Likely	System Possible	System Likely
Ambient Temperature Pumps and Ejector Expander	System Expensive	System Very Expensive	NO	System Possible	System Likely	System Possible
Cryogenic Compressor	NO	NO	NO	NO	System Uneconomical	System Uneconomical
Ambient Temperature Pumps and Cryogenic Compressor	System Uneconomical	NO	NO	System Uneconomical	System Uneconomical	System Uneconomical

The Hybrid ^{3}He-^{4}He Refrigerator

The use of ^{3}He would eliminate at least two vacuum pump stages, but it introduces two relatively undesirable features: the Joule-Thomson effect is about 25 percent smaller than that of ^{4}He, so that correspondingly larger mass flows must be used, and its latent heat of vaporization is also somewhat less. The other possible source of trouble is the ^{3}He-^{4}He heat exchanger at the cold end: as the properties of superfluid ^{4}He must be exploited in the accelerator bath, this must be a liquid-liquid heat exchanger. The transfer of heat from the ^{4}He to the ^{3}He baths requires temperature differences which imply certain losses. These aspects have been ignored, as well as the problems associated with thermal boundary resistance at the He II metal interface (Kapitza resistance)$^{(4)}$, and the heat transfer process through the bulk of the superfluid helium under the very high heat loads encountered.

Figure 3 represents a hybrid 1.85 K refrigerator with a ^{3}He loop. The original concept of separated function refrigerators and the room temperature vacuum pumps for ^{3}He as well as the central compressor installation for ^{4}He has been retained. However, to reduce the ^{3}He inventory in the system, two adjacent sectors share a local ^{3}He compressor, fed by both sets of vacuum pumps. The loop is optimized in the low pressure region of the inversion curve of ^{3}He at about 5 atm. The vacuum pumps maintain the pressure in the ^{3}He-^{4}He heat exchanger at about 95 torr and furnish the loop compressor with gas at approximately 340 torr. The other differences as compared to the ^{4}He refrigerator are the ^{3}He-^{4}He heat exchanger in the accelerator dewar bath, the increased rate of flow of ^{3}He of 35 g/sec, and the elimination of at least one Joule-Thomson stage.

It should be emphasized, that the ^{3}He loop has almost no effect on the total installed horsepower. Its virtue lies in the reduction of the amount of necessary pumping equipment and in the parallel decrease in the dimensions of the low pressure return heat exchangers.

Ejector Expanders

Using the arguments first advanced by Rietdijk(5) as the starting point, it has become apparent in the course of the present study that the ejector is probably not well suited to an application requiring large mass transfers and correspondingly high pumping rates. The compression characteristics of an ejector, and hence its efficiency, seem to drop off rapidly at moderately large secondary flows. This statement must be qualified by the fact that with decreasing temperatures, the mass flow decreases also and hence the required pumping rate. High pumping rates are required at 1.85 K. Nevertheless, it is estimated that in the case of the ^{4}He refrigerator, a reduction of approximately 20 percent in the size of the vacuum pumps can be achieved. In the hybrid ^{3}He-^{4}He cycle this reduction is somewhat greater as the efficiency of the ejector has a tendency to increase with the back pressure. Unfortunately, as still not enough is known about the performance of the ejector to obtain a realistic assessment of the costs involved in the design of an ejector-based cycle, the appendix does not reflect this decrease in cost.

Cryogenic Compressors

Figure 4 relates the first stage suction pressure of ambient temperature pumps to their installed cost and horsepower for the ^{4}He system. It would appear that any device which raises the initial inlet pressure can effect a tremendous saving in the capital cost. However, excluding mechanical limitations, a cryogenic compressor becomes feasible only when at least a part of the heat of compression is removed. Table III lists some of the theoretically attainable values of temperature rise and heat of compression under various inlet and exhaust pressures, for a single stage compressor. The inlet temperature was held constant at 10 K. Even under ideal conditions it is uneconomical to compress ^{4}He to atmospheric pressure, even if up to fifty percent of the heat of compression is allowed to remain in the circulating gas. To provide about 6 kW total precooling per sector at 10 K is out of the question. Likewise, if the compression ratio exceeds about 3.5, both for ^{3}He and ^{4}He, the precooling demands are just too great.

This leaves the last entry for each gas in the table. To provide a total of about 1.6 kW of precooling per sector may not present undue technical difficulties, but the effect of a cold ^{4}He compressor with a nominal compression ratio of 3.2 supplying a three-stage vacuum pump is to approximately double the flow in the precooling loop. This results in a doubling of the associated compressor horsepower, thereby increasing appreciably the total power requirements. The cost reduction obtained as a result of the elimination of the first stage of vacuum pumps is balanced by the added precooling refrigerator and compressor cost.

Similar arguments apply to a comparable ^{3}He compressor. It therefore makes thermodynamic and economical sense to use the hybrid ^{3}He-^{4}He system with two stages of warm return gas vacuum pumps.

As it is thermodynamically expensive to remove large quantities of heat at low temperatures, it might appear to be more sensible to put the compressors at higher temperature levels. Reciprocating pumps of this type, having an intake temperature around 40 K and compressing directly to ambient have been discussed(6). This arrangement leads to other problems. Not only is the loss of refrigeration very large, but the physical size of reciprocating pump of given

Table III. The Cryogenic Compressor: Theoretical Heats of Compression and Maximum Temperature Rise for Several Intake and Exhaust Pressures, at 10 K

	Pressure		Heat of Compression	Isothermal	Adiabatic
	Initial (torr)	Final (torr)	joule/gram	Cooling, 10 K (kW)	Temperature Rise (K)
^{4}He	12	760	203	5.46	50
	12	120	90	2.42	28
	12	40	39	1.05	18
^{3}He	100	760	66	2.31	22
	100	380	38	1.33	17
	100	340	32	1.12	16

capacity increases rapidly at the higher temperatures. It can be shown that for intermittent operation, and when liquid nitrogen for precooling is available in large enough quantities, such compressors do have certain attraction. However, as these conditions certainly do not pertain to the accelerator operation as presently envisioned, the concept was abandoned.

1.0 AND 1.5 K REFRIGERATION SYSTEMS

As Table I shows, going to lower temperatures theoretically eases the refrigeration problem. While it is still premature to predict where the optimum operating conditions of a superconducting accelerator will be, it is nevertheless important to examine the means whereby such low temperatures can be reached and maintained for very long periods of time and on such a large scale.

What exactly are the alternatives in this temperature range? As Table IV illustrates, ^{4}He probably has limited use below 1.85 K; its vapor pressure is too small to permit efficient Joule-Thomson heat exchanger design. Flashing from an intermediate, higher temperature has been considered, but the efficiency of the process is rather low, and mass flow rates tend to increase, which in turn places greater demands on the vacuum pumps. Consequently, the use of ^{4}He below 1.85 K has not been pursued further.

On the other hand, ^{3}He has clear advantages, again in hybrid combination with ^{4}He. The refrigerator of Fig. 3 is adaptable equally well to 1.5 K and 1 K. In this configuration the dewar has an intercept shield at 6 K, the calculated heat load being 42 watt per sector. Even with this additional load, the total primary ^{4}He flow is only about 30 g/sec per refrigerator. The major contribution to the flow, some 20 g/sec, is due to the radiation and heat intercept shielding at 70 K. In this system, due to relatively small flow of ^{3}He, ejector expanders are quite likely to be used. The work on ejectors has not yet progressed to the point where

Table IV. Comparison of ^{3}He and ^{4}He as Fluids for Service At and Below 1.5 K

	^{3}He		^{4}He	
Temperature K	1.0	1.5	1.0	1.5
Vapor pressure (torr)	8.7	50.7	0.12	3.6
Heat load per sector (watt)	10	58	10	58
Mass flow* per sector (g/sec)	1.0	4.9	0.6	3.2

*Assumes 80 percent liquefaction.

definite predictions can be made, but the relatively low primary driving pressures are seen to be a disadvantage. The ejector should be optimized for the Joule-Thomson regime, which in the case of ^{3}He lies uncomfortably close to 1 atmosphere. In order to extract as much from the pressure potential as possible, with the low driving pressure, very small nozzle diameters must be used. Not only are these susceptible to mechanical damage, but with decreasing size of the device, wall effects which are almost impossible to take into account properly, begin to play an increased role. However, already a modest 20 percent boost in the back pressure covers almost all pressure losses in the return stream heat exchangers.

As far as cryogenic compressors are concerned, there appears to be no real economic or technical advantage in using them at these temperature levels.

A 1 K refrigerator is really not that different from one at 1.5 K. The vapor pressure of ^{3}He is still quite acceptable and the mass flow rates have shrunk to laboratory scale. No attempt has been made in the present study to consider very low temperature and pressure heat exchangers: it may well turn out that a continuous Joule-Thompson process cannot be sustained. The continuous flashing of liquid ^{3}He from a higher temperature, ejector-controlled, stage has been examined briefly. In spite of its low efficiency, this could provide the necessary refrigeration by virtue of the small mass flows involved.

CONCLUSIONS

The analysis, both thermodynamic and economical, of refrigerators representative of the projected needs to keep a 100 GeV linear electron accelerator at 1.85 K has shown that a hybrid ^{3}He-^{4}He system using ambient temperature pumps and compressors is probably the most economical and could be built without undue difficulty and with present technology. Next in order of cost is a

^{4}He system using ambient temperature vacuum pumps. Both systems would undoubtedly benefit from ejector-expanders, though to what extent cannot yet be predicted.

For 1.5 K and below, hybrid ^{3}He-^{4}He systems must be used as the vapor pressure of ^{4}He is too low. This is a mass flow region where ejector expanders may be appropriate. The temperature of 1 K probably represents the threshold below which the conventional approach cannot be used, but it is believed that down to this temperature, perfectly acceptable and economical refrigerators can be built, again based on the hybrid ^{3}He-^{4}He concept.

At the temperatures and load levels which have been reviewed, the cryogenic compressor does not appear to be viable.

REFERENCES

1. S. C. Collins and M. H. Streeter, "Refrigerator for 1.8^{o}K," in Cryogenic Engineering Proceedings of the first Cryogenic Engineering Conference, Tokyo and Kyoto, Vol. 1, Heywood Temple Industrial Publications Ltd., London (1967), p. 215; also G. Robinson, private communication (1970).
2. W. B. Herrmannsfeldt, G. A. Loew and R. B. Neal, "Two-Mile Superconducting Accelerator Study," Report No. SLAC-PUB-626, presented at the Seventh International Conference on High Energy Accelerators, Yerevan, Armenia, USSR (August 1969).
3. G. Ratliff and S. J. St. Lorant, "Refrigeration System," Section K in Feasibility Study for a Two-Mile Superconducting Accelerator, R. B. Neal, editor, Stanford Linear Accelerator Center, Stanford University, Stanford, California (1969).
4. G. L. Pollack, Rev. Mod. Phys. 41(1):48 (1969).
5. J. A. Rietdijk, "The Expansion-Ejector, A New Device for Liquefaction and Refrigeration at 4 K and Lower," in Liquid Helium Technology Proceedings of the International Institute of Refrigeration, Commission 1, Boulder, Pergamon Press, New York (1966), p. 241.
6. S. C. Collins, private communication (1969).

APPENDIX

Equipment Costs, Installed and Tested

Compressors	
3 stage, 3 each at 18,000 SCFM, helical rotary	$ 1,050,000
Refrigerators	
1,000 watts at 1.85°K, 16 each	6,600,000
Vacuum Pumps	
4 stages, 10 torr to 1.5 atm, 16 each	4,700,000
Purifiers	
Dual, full-flow, < 1 ppm impurities, 12 atm	500,000
Piping, Storage	
430,000 SCF at 12 atm	1,050,000
Instrumentation, Special	
Pressure and level control, remote reading and data logger	500,000
Engineering	1,400,000
	$ 15,800,000

Conventional Facilities

Compressor Building	$ 300,000
Refrigeration Equipment Facilities	355,000
Cooling Water	350,000
Electrical	2,000,000
	$ 3,005,000

Operating Costs

Added First Year

Helium fill 450,000 liters at $ 2/liter	$ 900,000
Spare parts, all equipment	500,000
	$ 1,400,000

Yearly Costs (60 Percent Load Factor Used)

Power	$ 320,000
Nitrogen for purifier	55,000
Helium, 1 percent makeup	10,000
Water, cooling tower makeup	5,000
Labor, shift and maintenance	275,000
Materials	250,000
	$ 915,000

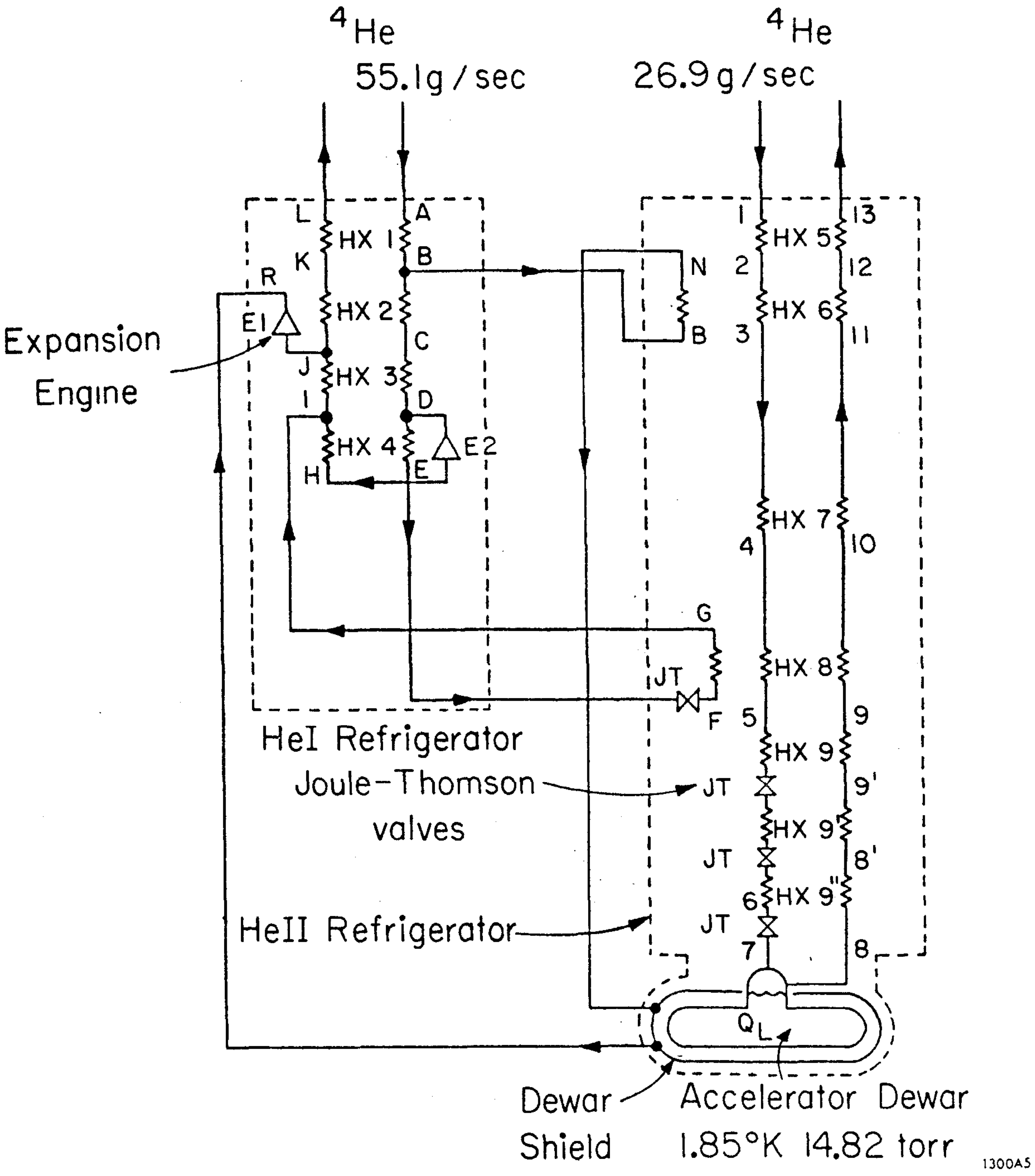

FIG. 1--1.85 K refrigerator schematic flow diagram.

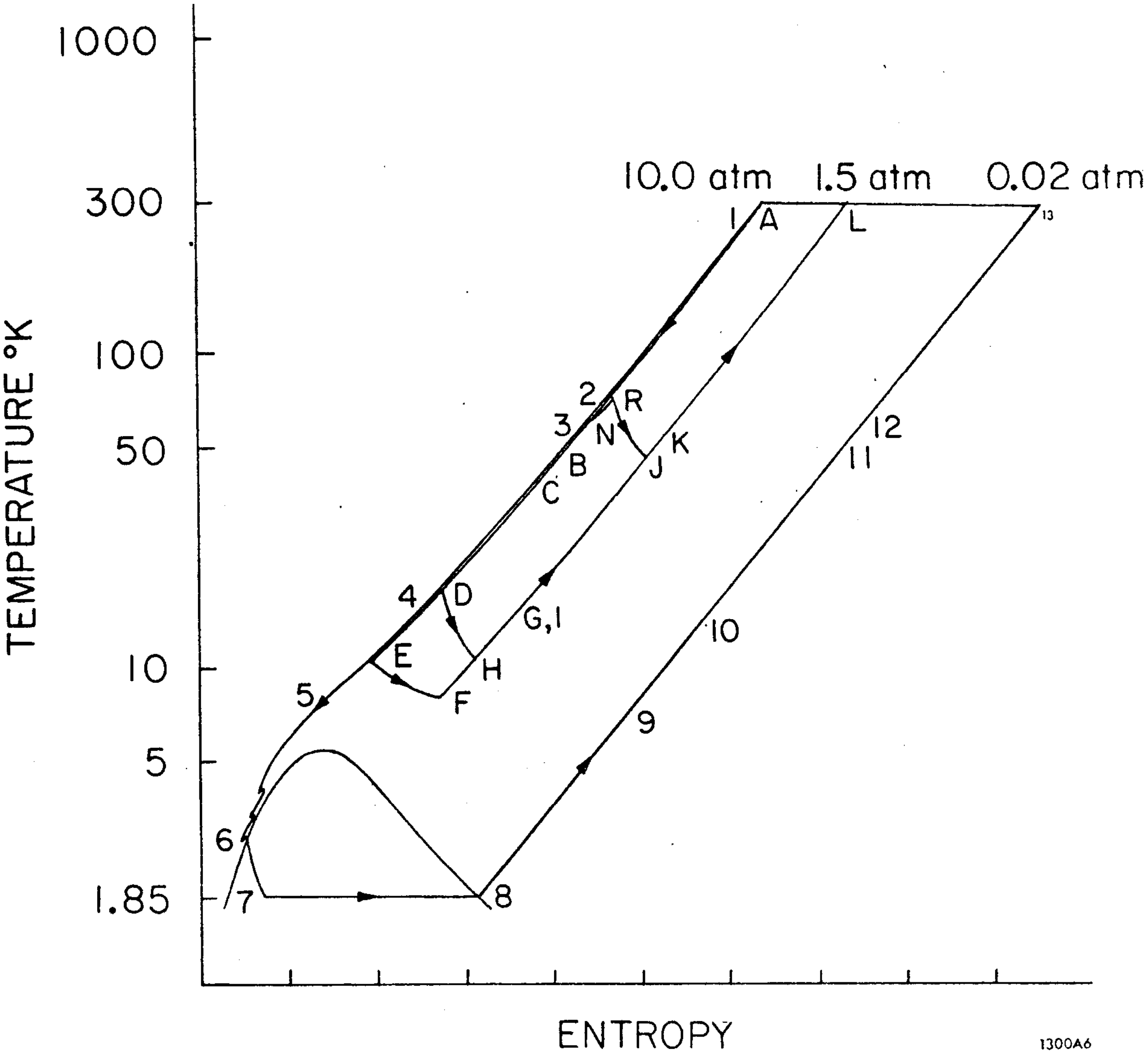

FIG. 2--1.85 K refrigerator schematic helium temperature entropy diagram.

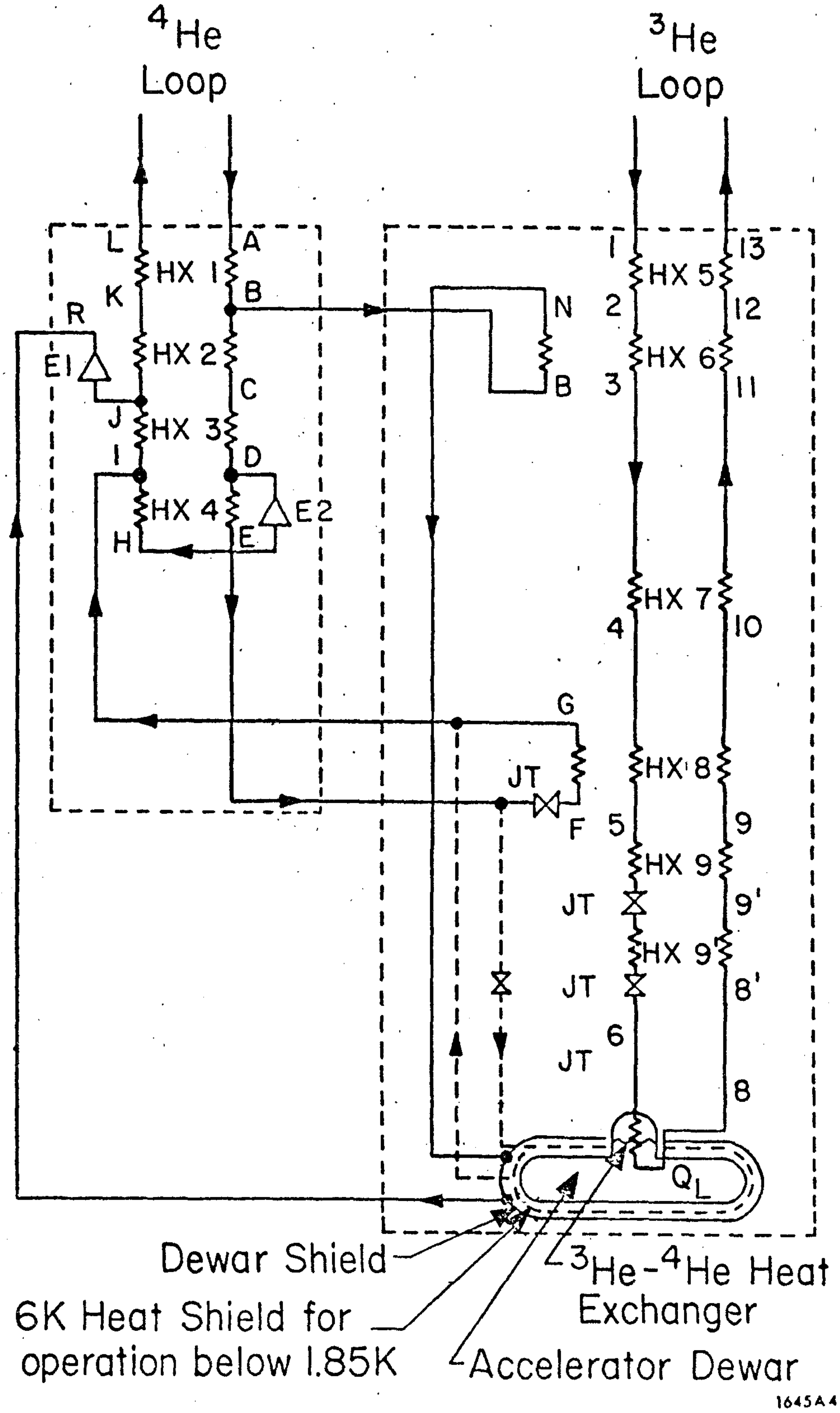

FIG. 3--1.85 K hybrid ^{3}He-^{4}He refrigerator schematic flow diagram.

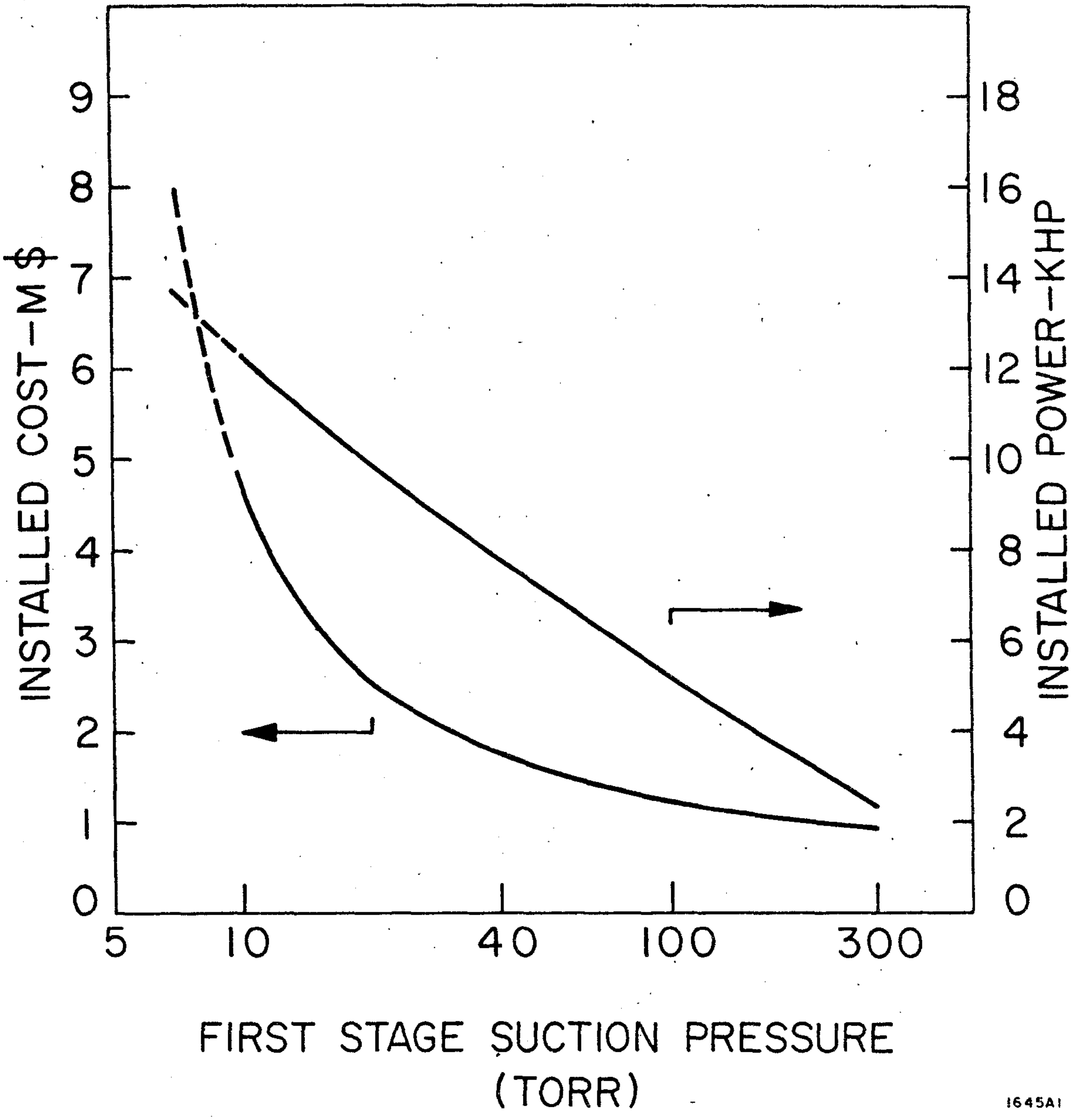

FIG. 4--First stage vacuum pump suction pressure as a function of installed cost and horsepower for the 1.85 K refrigerator.