REFRIGERATION FOR SUPERCONDUCTING AND CRYOGENIC SYSTEMS[*]

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For many years an ability to achieve and work at low temperatures has been useful to experimentalists performing certain types of high energy physics research. In fact, the demands of physics have been largely responsible for cryogenic technology as it stands today. Ten years ago or so, the increase in size of bubble chambers beyond capacities of a few liters of liquid was a significant event. The larger liquid hydrogen chambers being commissioned today depend not only on liquid hydrogen technology, but in another significant step, on liquid helium technology for successful operation of the superconducting magnets surrounding the detectors. The effort required to conceive, design, start up and operate these auxiliary low temperature devices has been enormous and there have been many problems, eventually solved, which at one time or another have hampered operation. The term "auxiliary devices" is emphasized because never before has the high energy particle production of the accelerator proper been dependent upon a continuous low temperature environment. The character of some of the next generation of accelerators which are being conceived and discussed now, shifts the burden of planning for the cryogenic environment from the detector experts to those responsible for particle production. The dimension added to accelerator design by low temperature elements must be accounted for from the time of earliest planning. Assurance of reliable operation is critical to the physics experiments and the provision of redundant components should be carefully considered. Cryogenic safety should be planned simultaneously so that it can actually be built into the system rather than be added as an afterthought. The difficult logistics problem of distributing refrigeration to widely separated consumption sites will probably require a different solution for each experimental area or accelerator geometry considered. To a large extent, the method chosen will determine the capital and operating costs, affect the reliability and influence the design of the low temperature enclosures. Among other things, the entire system design must consider the advantage of rapid cooldown time against the amount of excess refrigeration capacity that must be acquired; the expense of unit versus modular construction which will allow quick replacement of defective accelerator components; and the flexibility of the cooling system to efficiently handle a wide range of requirements from standby to cooldown.

Enough experience has been accumulated in the design and operation of low temperature refrigerators and liquefiers to safely assume that almost any cooling requirement can be met. However, the refrigerator (liquefier) will be an integral part of the accelerator and it is conceivable that the cooling capacity needed will exceed the capacity of existing units. The demand for reliability and possible increase in capacity will require the best of cryogenic technology. The prospect of low temperature accelerators and other devices, coupled with increasing superconductor transition temperatures, prompted this updating of an earlier paper[1] and extension of the temperature range to span 1.8 to 90 K. These data (efficiency, mass, volume, and cost) are of interest to those who are anticipating the use of a refrigerator or liquefier. Although there is considerable scatter in the data collected for more than 95 units, significant trends can be identified that yield values useful for estimating purposes. The efficiency data show the amount of input power required by a refrigerator and thus give one part of the operating expense. The mass of a unit may not be of concern to an accelerator designer interested in large units, but it can be important in the applications calling for low cooling capacity. Space occupied by the refrigerator can be important, especially in the premium areas near accelerators or in experimental halls. The interest in capital cost is obvious since this type of machinery is not inexpensive. In all of the charts which follow, lines have been drawn through the data which represent the author's judgment of an average and are thus subject to arbitration. Open symbols indicate units under development or proposed; these data were not used to establish the average. The general shape of the curves can be predicted from a knowledge of the characteristics of low temperature refrigerators, but since there is wide variation in the data any quantitative interpretation must be approached with caution.

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Efficiency

Through the second law of thermodynamics, the minimum power required to produce a unit of refrigeration under ideal conditions is given by

$$\left.\frac{W_c}{Q}\right)_{\text{Carnot}} = \frac{T_o - T}{T} \qquad (1)$$

where W_c is the net input power required (power for compression minus the power produced by expanders if any), Q is the refrigeration produced, T_o is the temperature of the surroundings, nominally 300 K, and T is the desired refrigeration temperature. As T becomes smaller, the specific power requirement increases rapidly as seen in Table I which also gives the ideal power requirement for liquefaction. T is taken to be normal boiling temperature of the fluids.

The difference in input power required to cool an object with liquid produced by a liquefier or with a continuously operating refrigerator is evident. More power is required by a liquefier because when the liquid is evaporated at another location, the cold effluent vapor cannot be used in the liquefaction process to help cool the feed gas stream. An ideal helium liquefier would require a power input of 236 W to produce liquid at the rate of 1 liter per hour. The heat of vaporization of helium is low and 1 W will evaporate 1.38 liters per hour. Therefore, 326 W would be required to power a liquefier whose liquid product were used to absorb a 1 W heat load at 4.2 K. An ideal refrigerator would require 70.4 W input power to produce 1 W of refrigeration at the same temperature level. This difference in power requirement does not mean that a refrigerator should be chosen over a liquefier for all cooling applications; there are conceivable circumstances in which a liquefier would be the better choice.

When comparing the efficiencies of low temperature refrigerators, it is informative to examine the ratio

$$\text{Percent Carnot} = \frac{\left.\frac{W_c}{Q}\right)_{\text{Carnot}}}{\left.\frac{W_c}{Q}\right)_{\text{Actual}}} \times 100 \qquad (2)$$

This ratio indicates the extent to which the actual refrigerator deviates from ideal performance. The same ratio is formed for liquefiers using the values from Table I and the actual power consumption per liter per hour. The capacity of the liquefiers included in the data has been converted to equivalent refrigeration capacity by determining the percent of Carnot performance that they achieve as liquefiers and then calculating the refrigeration output of a refrigerator operating at the same efficiency with the same input power. In some instances equivalent refrigeration capacity was given by the manufacturers and was used directly. In all instances, the input power was taken as the installed drive power, not the power measured at the input to the drive motor.

In figure 1, the percent of Carnot given by equation (2) is plotted as a function of the refrigeration capacity in watts. The largest of the units in the 1.8 to 9 K temperature range is a proposed refrigerator and the next two smaller units, between two and three thousand watts capacity, are large liquefiers whose capacity has been converted to refrigeration power.

TABLE I

REVERSIBLE POWER REQUIREMENTS

FLUID	T (K)	REFRIGERATION (W/W)	LIQUEFACTION (W hr/liter)	EVAPORATING LIQUID REFRIGERATION* (W/W)
Helium	4.2	70.4	236	326
Hydrogen	20.4	13.7	278	31.7
Nitrogen	77.4	2.88	173	3.87

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*Obtained by dividing the ideal liquefaction power requirement by the heat of vaporization of the fluid.

Historically the contention has been that higher temperature refrigerators (or liquefiers) are more efficient. The data for refrigeration temperatures between 10 and 30 K (and 30 to 90 K) refüte that notion at least when presented on this common basis. To be sure, less input power is required to produce the same number of watts of cooling at higher temperatures, but the losses relative to ideal are proportionally the same. For many of the refrigerators of less than 10 kW capacity, liquid nitrogen precooling consumption rates are available, but the equivalent power that would be consumed if the precooling were provided by a closed cycle refrigerator on site has not been included in the efficiency computation. Therefore, the efficiencies of a number of the units would be slightly lower than shown if this factor were included. The largest of the units shown are high capacity hydrogen liquefiers. Here nitrogen temperature precooling is commonly provided by closed cycle nitrogen refrigerators and the input power requirements are known and have been included. This means that the values are more nearly true and are not slightly biased as are some of those at lower capacities.

Performance data for higher temperature plants, in the 30 - 90 K range, are not as numerous but the trend is obvious. In the 10 to 1000 W range, indeed efficiencies are higher, but the estimate given by a supplier of large facilities (shown at the right as off scale) is comparable to lower temperature plants. At lower capacities, the deviation in performance is an entire decade. It must be noted that these are units of very low input power and it is not surprising to find such variation.

In spite of the scatter in the data, it is clear that smaller low temperature refrigerators are subject to proportionally higher losses than the larger units. The major contributor is heat leak from the surroundings since the geometry of the cold components becomes progressively unfavorable as the size decreases, i. e., the surface area to volume ratio increases rapidly.

Volume

The decrease in size of the proposed small capacity units (1. 8 to 9 K) is seen at the lower left of figure 2 in the upper section, and the developers have been reasonably successful in actually achieving compact packages. Data for higher temperature units show the same trends and the lines are a fair representation. High capacity refrigerators and liquefiers are comparable to chemical process plants and require sites measured in acres. Except in the compact low capacity units, volume reductions could be realized by better packaging. However, fabrication costs might rise and certainly maintenance and repair would be more difficult.

Mass

As in the volume representation, the proposed low capacity units (1. 8 to 9 K) are grouped at the lower left of the upper section in figure 3. Low mass is important for military and satellite use but may also influence the cryostat design if, for example, a small refrigerator is to be mounted directly on a magnet enclosure. There is a potential for reducing the weight of most units if it is necessary.

Cost

Some time ago the line shown in figure 4 was established for 4 K refrigerators with only a few points. Notice that the abscissa is now input power, not refrigeration capacity. The input power at any refrigeration capacity can be determined from the efficiency data. The cost of many classes of machinery is proportional to the 0. 7 power of the installed input power. Hydrogen temperature units and even higher temperature refrigerators and liquefiers follow the trend quite well. These data indicate that to a first approximation for refrigerators and liquefiers operating in the range 1. 8 to 90 K,

$$C = 6000\ P^{0.7} \tag{3}$$

where C is the cost in dollars and P is the installed input power in kilowatts. The several million dollar units in the upper right are typical of large hydrogen liquefiers; here the costs are hard to define because in some instances, the equipment for producing hydrogen feed gas is included in the cost figures. Again it is emphasized that the charts are intended for estimating purposes only.

Reliability

Well designed and operated low temperature facilities can be as reliable as any other type of dynamic machinery. Bubble chamber refrigerators have run for long periods of time and the large liquefaction facilities are on stream for months. Smaller 4 K refrigerator runs of over 13, 000 hours have been recorded. However, the problem is that information about minor interruptions in service or even major breakdowns is difficult to acquire. Definition of the problem is also difficult because a one-hour interruption of cooling may not affect one application but may be critical in another. Reliability in operation should not be confused with start-up and break-in periods. Quite likely problems will be encountered during that period of time.

Conclusions

The successful long term operation of any low temperature facility will require careful long range planning and much attention to detail. Existing low temperature refrigerators cover a wide range of capacity and temperatures and the performance (input power) can be fairly well predicted. It does not appear that any significant increases in efficiency have been achieved for the entire class of devices in the past few years although in certain instances good performance has been realized. The more efficient facilities are in the large sizes and are the product of complex thermodynamic cycles. Perhaps the same performance potential exists in smaller units, but costs might be prohibitive and the savings in electrical power would not justify the greater capital outlay. Another item to consider is that in principle at least, the simpler cycles have fewer dynamic structures, fewer seals and are easier to maintain. The trends are identifiable in the mass and volume characteristics and there is the potential for reducing both, perhaps with an increase in price. Capital cost should be predictable for standard types of refrigerators at least. Experience shows that special requirements are expensive but the field is quite competitive as indicated by the ten European prices which are included. Redundancy should be carefully considered in situations where reliability is essential.

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Reference

[1] Strobridge, T. R., and D. B. Chelton, Size and power requirements of 4.2 K refrigerators, Advances in Cryogenic Engineering, (ed. K. D. Timmerhaus, Plenum Press, New York, N. Y., 1967) Vol. 12, 276.

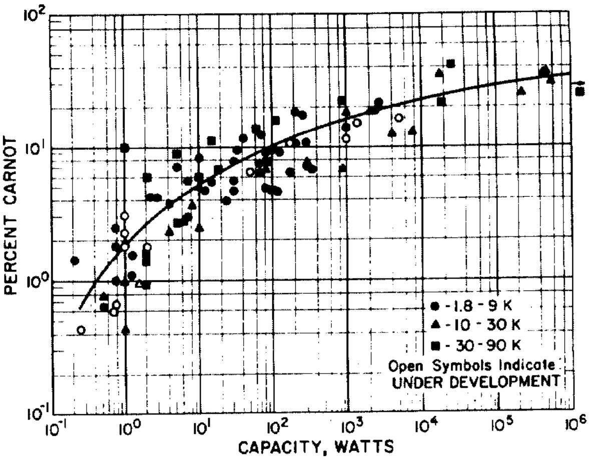

Figure 1. Efficiency of low temperature refrigerators and liquefiers as a function of refrigeration capacity.

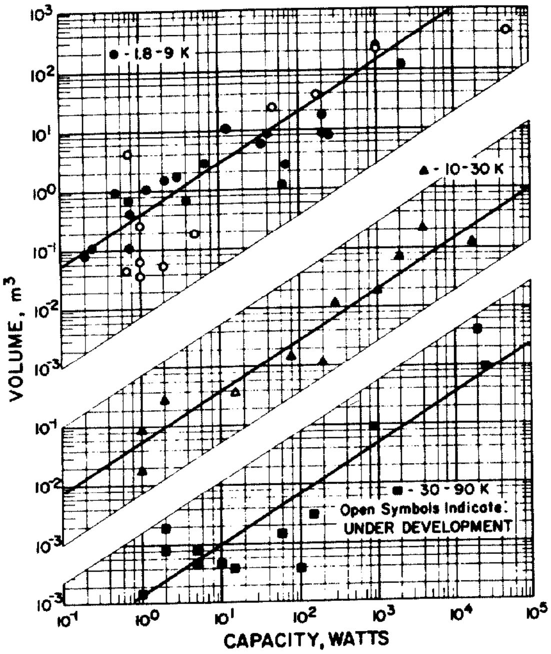

Figure 2. Volume of low temperature refrigerators and liquefiers as a function of refrigeration capacity.

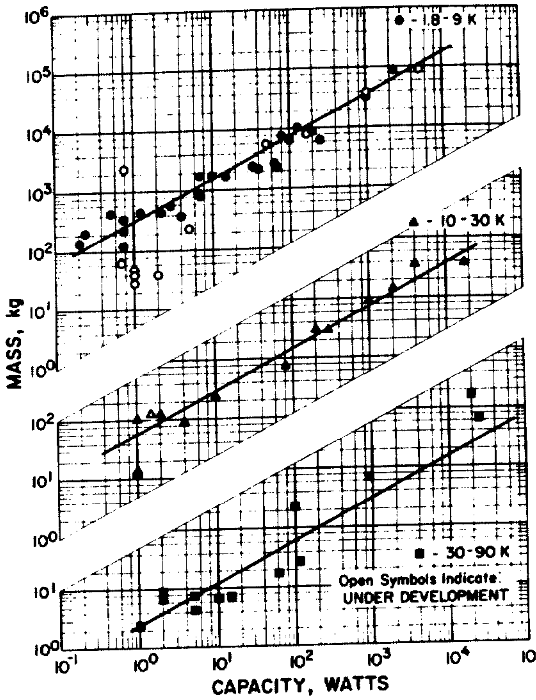

Figure 3. Mass of low temperature refrigerators and liquefiers as a function of refrigeration capacity.

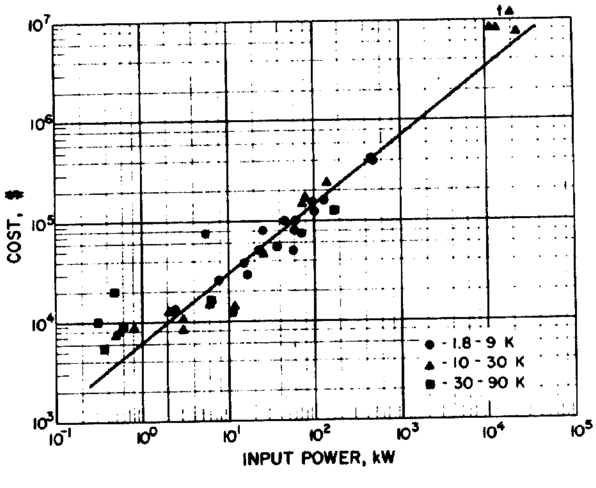

Figure 4. Cost of low temperature refrigerators and liquefiers as a function of installed input power.