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THE COST OF HELIUM REFRIGERATORS AND COOLERS FOR SUPERCONDUCTING DEVICES AS A FUNCTION OF COOLING AT 4 K

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ABSTRACT

This paper is an update of papers written in 1991 and in 1997 by Rod Byrns and this author concerning estimating the cost of refrigeration for superconducting magnets and cavities. The actual costs of helium refrigerators and coolers (escalated to 2007 dollars) are plotted and compared to a correlation function. A correlation function between cost and refrigeration at 4.5 K is given. The capital cost of larger refrigerators (greater than 10 W at 4.5 K) is plotted as a function of 4.5-K cooling. The cost of small coolers is plotted as a function of refrigeration available at 4.2 K. A correlation function for estimating efficiency (percent of Carnot) of both types of refrigerators is also given.

KEYWORDS: Cryogenic Refrigeration, Small Coolers, Refrigeration Cost.

INTRODUCTION

This paper was written in memory of Rod Byrns of the Lawrence Berkeley National Laboratory, who passed away two years ago. This report updates costs given in a 1991 and 1997 paper concerning the cost of helium refrigeration [1, 2]. This report is restricted to the estimating of cost for helium refrigeration only.

In 1966, Strobridge, Mann and Chelton [3] developed a technique for estimating the cost of helium refrigerators based on a limited number of cost data points available at the time. In 1969, Strobridge [4] updated his study to include cryogenic refrigerators of all types. The cost of refrigeration was estimated based on the input power to the compressor. The 1969 Strobridge study was expanded in 1974 [5] to include a number of newer refrigerators being built at that time. From 1966 to 1974, the cost of helium refrigeration did not change appreciably. From 1974 until 2000, the capital cost of refrigeration appears to have escalated at the nominal rate of inflation.

This report includes a number of small coolers that have appeared on the market during the last fifteen years. The trend of using small coolers to cool superconducting magnets continues. Projects that would have been cooled using small Claude cycle refrigerators ten years ago now used small coolers because they are less expensive to install and operate. The small coolers also provide cooling at 40 to 60 K.

One of the difficulties of estimating the cost of helium refrigeration is the choice of the appropriate parameter from which to calculate cost. For most of the helium refrigeration systems in this report, the refrigeration capacity at 4.5 K is used as a scaling factor. Thus the cost of small coolers is based on the refrigeration generated at 4.5 K. Helium refrigeration at other temperatures is scaled to 4.5 K using the Carnot ratio. Liquefaction is converted to refrigeration at 4.5 K by the use of the refrigeration to liquefaction coefficient. (This coefficient is between 75 to 125 J g^{-1} depending on how the cycle has been optimized. Recent experiments with pulse tube coolers show that the helium refrigeration to liquefaction coefficient can be as low a 40 J g^{-1} [6].)

THE THERMODYNAMIC EFFICIENCY OF HELIUM REFRIGERATORS

Strobridge in his papers [3] to [5] discussed the efficiency of various kinds of refrigerators. Efficiency was defined as the input power of a perfect Carnot cycle refrigerator over the actual compressor power that goes into the refrigerator. FIGURE 1 is an efficiency plot that contains both the Strobridge data and newer data. The refrigeration at 4.5 K is the equivalent refrigeration produced at all temperatures from the cold box. None of the refrigerators shown in FIGURE 1 use liquid nitrogen pre-cooling. There is an apparent efficiency increase of 1.2 to 2.0, when liquid nitrogen pre-cooling is used (depending on the machine design). Large refrigerators tend to use less liquid nitrogen per unit refrigeration produced than do small refrigerators. When one considers the power needed to produce liquid nitrogen, the efficiency advantage of liquid nitrogen pre-cooled machines disappears. The capital cost of machines using nitrogen pre-cooling is often lower. The use of wet expanders in place of a J-T valve will result in increased machine efficiency, but none of the machine in FIGURE 1 use wet expanders [7].

The effects of plant size on efficiency can be seen in FIGURE 1. Efficiencies range from less than 4 percent of Carnot for 10-watt plants to about 30 percent of Carnot for larger plants. Increased plant size requires larger pistons or rotors with fixed clearances. The leakage is reduced with respect to total flow through the expander or compressor. Smaller cold boxes may only have one or two expanders, whereas the large machines may have many expanders [7]. As the size of the plant grows, the turbines can have efficiencies that are competitive with piston expanders. In 2007, for plant sizes >100 W, a turbine expansion system is often the best choice. Since a major part of the plant inefficiency is in the compressors, the larger plants will often have staged compressors with inter-cooling between stages.

The newer data points shown in FIGURE 1 show that on average the overall efficiency of helium refrigerators has increased since the mid 1990s. The reasons for this are: 1) Newer machines often have no nitrogen pre-cooling, so the cycle is better optimized for no pre-cooling. 2) Turbine expanders in small machines have become more efficient. Refrigeration plants that are more efficient often have a higher capital cost, but not always, because increased expander efficiency can lead to smaller heat exchangers and compressors. If one considers cost of the energy needed to run the plant over its lifetime, buying an efficient plant is the right thing to do.

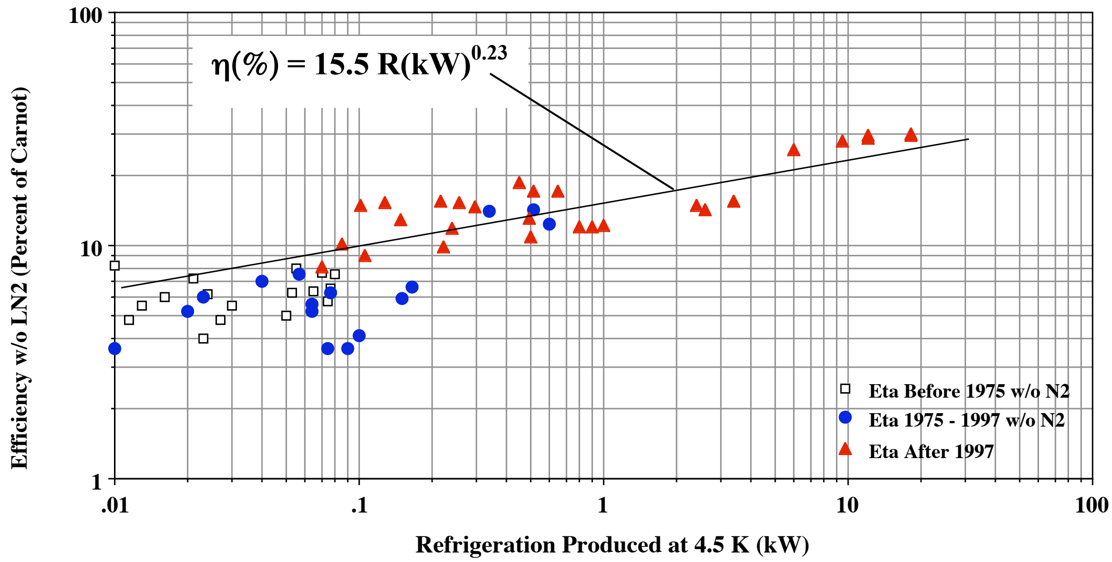

FIGURE 1. Helium Refrigerators Efficiency (percent of Carnot) as a Function of 4.5 K Refrigeration (kW). In all cases, there is no liquid nitrogen pre-cooling in the machines. The open squares are for machines made before 1975; closed circles are machines from 1975 to 1997, and closed triangles are for machines after 1997.

LARGE 4.5 K HELIUM REFRIGERATOR CAPITAL COST

FIGURE 2 shows the cost of various 4.5-K refrigerators (compressors, heat exchangers, expanders and a minimal amount of piping connecting them together) escalated into 2007 dollars as a function of design refrigeration at 4.5 K. The costs included in FIGURE 2 do not include the conventional facilities (power lines, cooling towers and other such things) needed to support the helium refrigerator. Large amounts helium purification and storage are not included. Liquefaction was converted to refrigeration using the refrigeration-liquefaction coefficient for the machine. (When the refrigeration-to-liquefaction coefficient is not given, a refrigeration-to-liquefaction coefficient of 100 J g^{-1} was used.) Refrigeration at temperatures different from 4.5 K was converted to 4.5 K refrigeration by using the Carnot ratio. The cost of foreign made machines was converted to dollars at the average exchange rate during the year of manufacture. The dollars were then escalated from the year of manufacture to 2007 dollars (See the escalation factors in Ref [8] and multiply by 1.34).

In FIGURE 2 there is a line plotted with the cost points. This line represents the average capital cost in 2007 dollars for newer 4.5 K helium refrigerators that produce refrigeration in the range from 0.01 to 30 kW. The equation for this line is:

$$C(M\$) = 2.6\,[R(kW)]^{0.63} \qquad (1)$$

where C is the refrigerator capital cost is given in millions of 2007 US dollars and R is given in kilowatts of refrigeration normalized to a temperature of 4.5 K. The line in FIGURE 2 is flatter than in the earlier studies [1, 2]. This agrees with cost equations that came from studies at the CERN-LHC in 1999 [9, 10].

The largest plants shown in FIGURE 2 are quite complex. Some plants have several cold boxes and heat exchanger units tied together. Other plants may include helium pump systems to circulate sub-cooled helium. Liquid helium storage and distribution systems can cost almost as much as the basic cold box and compressor system. When large plants were fabricated from smaller components, the size and cost of the smaller plants was used.

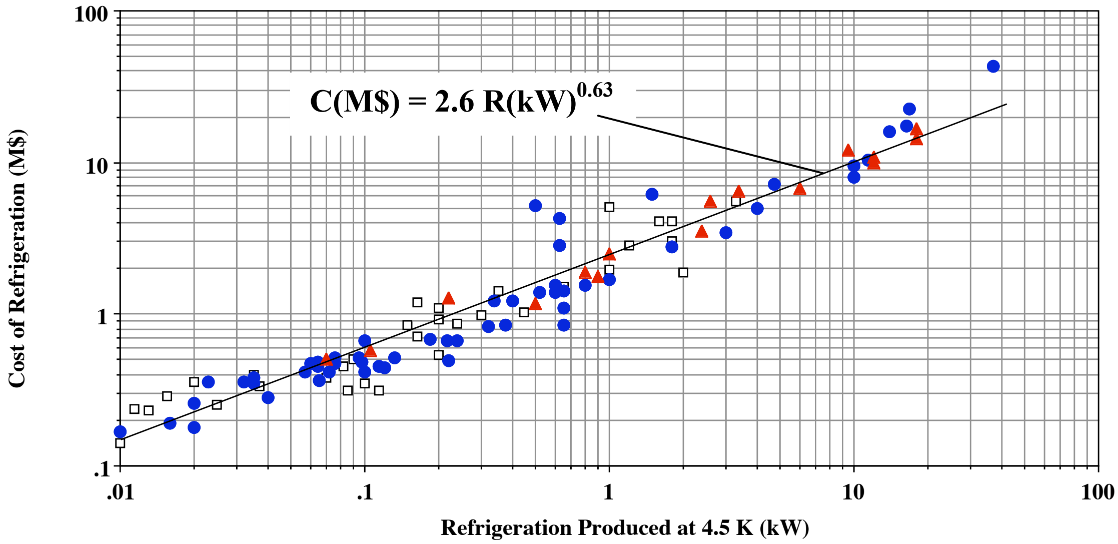

FIGURE 2. The Cost of Helium Refrigerators (cold boxes and compressors) versus Refrigeration at 4.5 K

On the room temperature side of the plant, helium gas storage, recovery, purification and distribution can add significantly to the cost of the plant. In many areas of the world, the costs of installing the machines are more than the cost of the machines. In some instances the cost of the safety review and the costs associated with the delay caused by the safety review become a factor. The refrigerator vendors have responded by producing turn-key systems that cost more than the non-turn-key systems that were produced a decade or two earlier. Other factors that increase the cost of refrigeration include: computer control systems (in small machines computer controls are often not needed), extra purification within the cold box and the extra documentation that may be required by military type specifications. In some systems, the computer control system can cost up to one third of the cost of the cold box and compressor. The costs of computer software and the debugging of that software are often grossly underestimated. If one is seriously interested in minimizing refrigerator capital cost, one should seriously consider whether a computer control system is needed.

Since 1997, the cost of larger refrigerators (>200 W at 4.5 K) has increased over a factor of two. There are several factors for the apparent increase. The first factor is that the material used to fabricate the heat exchanger for large units has escalated a factor of two or more. The demand for basic raw materials such as copper and aluminum is driven by the growth rates of the economies of countries such as China and India. The second factor is the fact that the production of machines in the range from 20 to 250 W (at 4.5 K) may have gone down. In the US, the workhorse laboratory machines (20 W to 100 W) are now being replaced with small coolers. This may not be true in all countries. Third machines in the range from 20 to 250 W now have computer controls; fifteen years ago they did not. (It is not clear that the added cost for the computer controls has resulted in an overall savings in the cost of a W hour of refrigeration at 4.5 K.) Fourth, energy efficiency is far more important today than it was ten years ago. Fifth, the companies that produce the world's largest helium refrigerators are European companies. As a result, there is little competition and the value of the Euro against most currencies has increased fifty percent in the last five years. The entry of companies from China or India could change the capital cost of refrigerators of all types during the next decade.

SMALL 4.2 K HELIUM REFRIGERATOR (CRYOCOOLER) CAPITAL COST

Small coolers are being used to cool superconducting magnets. The coolers are rated by the cooling delivered at 4.2 K. The cooling of MRI magnets is most commonly done with a 1.0-W cooler. MRI magnet leads and the leads of magnets that run in persistent mode are either retracted or they are low-loss leads using HTS conductors. Increasingly, magnets are being operated on small coolers with the leads connected and carrying current. The leads in this case are combined HTS leads (from 60 K to 4 K) and copper leads (from 300 K to 60 K). Small coolers are not designed to produce cold gas for lead cooling. As a result, the leads are cooled by conduction to the first stage of the cooler.

Conventional wisdom says that small coolers can't be used to produce liquid helium, unless there is a separate J-T circuit. Even with a separate J-T circuit, the refrigeration-to-liquefaction coefficient is quite high (>150 $J\text{-}g^{-1}$). As a result, small coolers have not been used to supply gas to electrical leads or gas-cooled shields. Recent advances with some of these machines, suggests that conventional wisdom is not always correct. There are pulse-tube coolers that are commercially available that will liquefy helium with a refrigeration to liquefaction coefficient as low as 40 $J\text{-}g^{-1}$ [6]. Machines of this type are currently being used in remote locations to re-liquefy helium. A 1-W cooler can liquefy helium at a rate greater than 0.7 liters per hour [6]. The liquefaction efficiency of GM coolers can be improved, but as liquefiers these machines appear to be less reliable than a properly designed liquefier built around a pulse-tube cooler.

Small 4-K coolers can be operated very well at 20 K. A 1.5-W cooler (at 4.2 K) will produce over 20 W of cooling at 20 K without sacrificing performance at 60 K. Both GM and pulse tube coolers can be used to liquefy hydrogen, but in general the liquefaction performance for a pulse-tube cooler will be better. A pulse-tube cooler can have refrigeration-to-liquefaction coefficients as low as 700 $J\text{-}g^{-1}$. A conventional hydrogen liquefier will have a refrigeration-to-liquefaction coefficient above 1200 $J\text{-}g^{-1}$. A 1.5-W (at 4.2 K) pulse-tube cooler can potentially liquefy more than 1.3 liters per hour of hydrogen depending on how the cooler first stage is utilized in the liquefaction process.

Small refrigerators (less than 40 W) will cost more than is given by equation (1) (see FIGURE 2). These machines do not have liquid-nitrogen pre-cooling. Even if they did have nitrogen pre-cooling, they would be inherently less efficient. Therefore, these machines require larger compressors with respect to their refrigeration output at 4.2 K. It can be argued that small plant cost should be plotted separately and that this type of plant should have a separate cost equation. FIGURE 3 shows a plot of the cost of various small helium refrigerators (given in thousands of 2007 US dollars) versus the maximum refrigeration available at 4.2 K (given in watts). 4.2-K coolers that exist for the military and space applications are not included in FIGURE 3. They would be off the graph.

From FIGURE 3, one can see that escalated cost of small refrigerators fits a different cost equation than is given by equation (1). In FIGURE 3 there is a line plotted with the cost points. This line represents the average cost in 2007 dollars of modern 4.2-K coolers (built after 1997), which produce refrigeration from 0.1 W to 10 W. The cost equation for this line is:

$$C(k\$) = 37\,[R(W)]^{0.38} \qquad (2)$$

where the capital cost C is given in thousands of 2007 US dollars and R is refrigeration at 4.5 K (given in watts). The price of small commercial 4.2-K GM and pulse coolers produced in 2007 has hardly changed in the last eight years. In some cases, the prices have gone down even though the coolers have become more reliable.

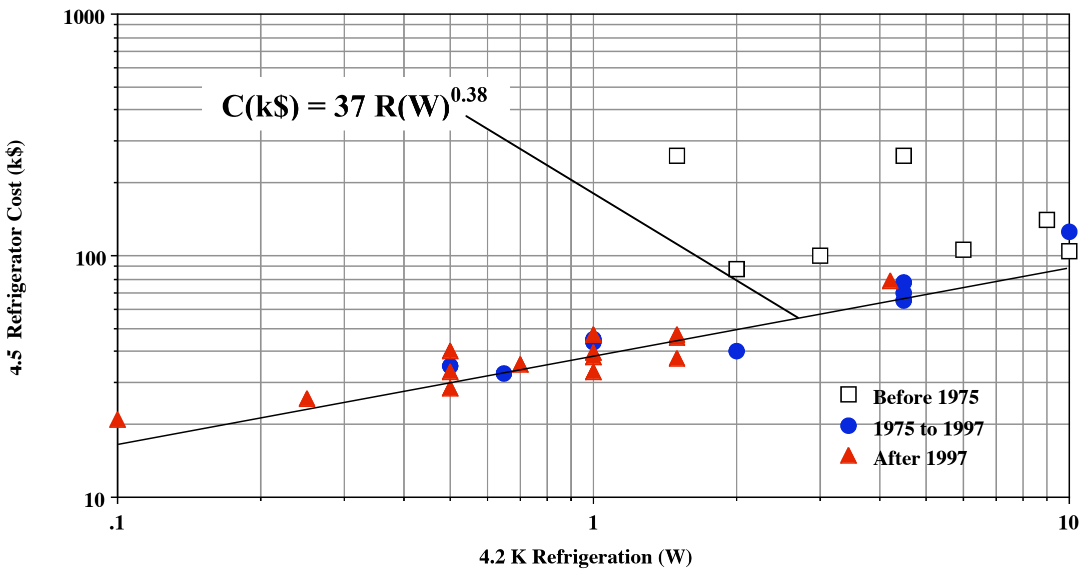

FIGURE 3. The Capital Cost of Small Helium Coolers (k$) versus the Design Refrigeration at 4.2 K (W)

THE EFFICIENCY OF SMALL 4.2 K COOLERS

Small refrigerator efficiency shown in FIGURE 1 is lower than the line that fits the efficiency data above 40 W. Conventional machines can provide cooling on the upper stages as well as the 4.5-K stage. If the cooling on the upper stage is normalized to 4.5 K, the efficiency will be higher. Some of the machines in FIGURE 1 provide cooling at other temperatures besides 4.5 K. This cooling was considered in the machine efficiency calculation. FIGURE 4 shows the efficiency of small coolers with only the 4.2-K cooling considered (the lower line) and the efficiency when the cooling on all stages is considered (the upper line). If the line shown in FIGURE 1 were extended to 1 W at 4.5 K, it would lie close to the upper line shown in FIGURE 4. The efficiency of the 4.2-K end a small cooler is generally limited by the performance of the low-temperature regenerator.

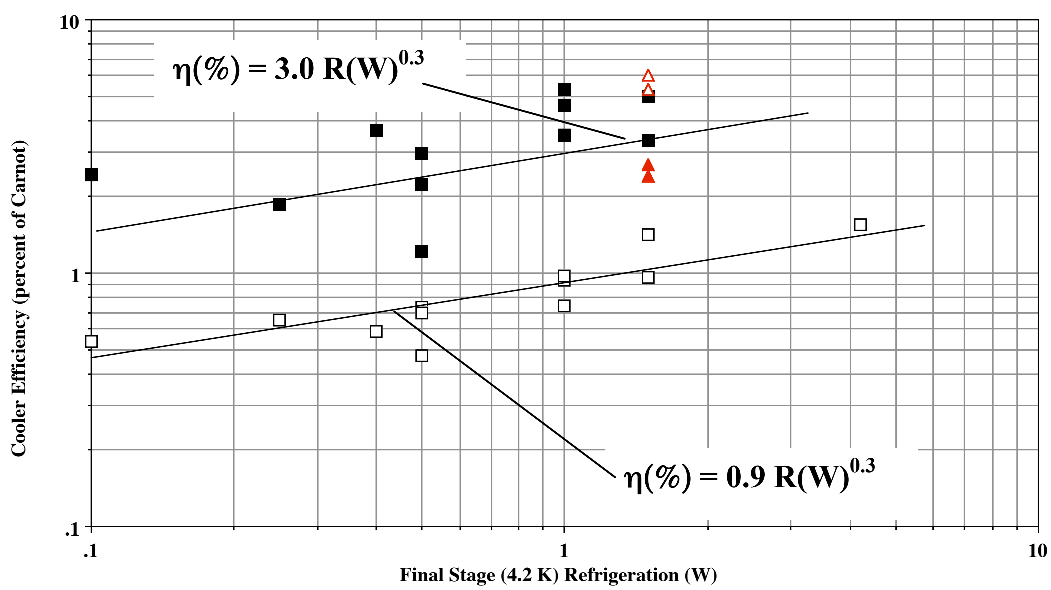

FIGURE 4. The Efficiency of Small Coolers versus the Design Refrigeration at 4.2 K. (The open squares are for efficiency calculated using the 4.2-K cooling alone. The closed squares are for the efficiency when to cooling on all stages is considered. The closed triangles show the efficiency of a 1.5-W cooler at 20 K using only the cooling at 20 K. The open triangles show the 20-K efficiency when all stages are considered.)

DISCUSSION

The helium refrigeration cost expressed by equations (1) and (2) represent the average cost for the compressors, minimal piping between the compressors and the cold box, the cold box and the expansion engines. Water-cooling for the compressors, helium dewars, external helium distribution, and computer controls usually cost extra. The price for any given helium refrigerator depends on the level of competition at the time the order is placed. The price of a refrigerator or cooler in US dollars also depends on the exchange rate at the time of the order. The trend toward electronic monitoring and control is part of the reason that the cost of refrigerators manufactured after 1990 are more expensive.

In the last five years the price of large refrigerators has escalated faster than the overall rate of inflation. The reasons for this have to do with the costs of material and the part of the world these machines are being manufactured.

Small coolers have become an important part of the 4-K refrigeration market. The advent of reliable coolers has reduced the cost of cooling individual magnets. Reliable small coolers make magnets fabricated from low Tc superconductors competitive in many applications.

The efficiency of 4.5-K machines with capacities above 100 W has improved in the last ten years. The primary reason for this is the improvement in expander technology.

ACKNOWLEDGEMENTS

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