Particle Accelerators, 1970, Vol. 1, pp. 213–221

REFRIGERATION OF SUPERCONDUCTING MAGNETS†

MICHAEL A. GREEN

Lawrence Radiation Laboratory, University of California, Berkeley, California, USA

This paper describes the Lawrence Radiation Laboratory helium refrigeration system and its use on superconducting magnets. A discussion of our operational techniques includes reliability and maintenance of components, cold transfer line techniques, and large magnet cooldown and operation. The validity of assumption used in previous studies of large refrigeration systems for accelerator experimental areas is discussed. As a result of operational experience a revised set of recommendations for large experimental area refrigeration systems is made. The interrelationship of cryostat design on the refrigeration is briefly discussed.

1. INTRODUCTION

This paper describes what has been learned from one year of operation of the LRL helium refrigeration system. Refrigeration for superconducting magnets in a large accelerator experimental area is looked at again in light of new knowledge gained by operational experience. New input, engineering, and cost data will allow us to revise previous estimates of cost of an experimental-area refrigeration system.

The discussion of LRL operational techniques centers around (a) reliability and maintenance of system components, (b) cold transfer line techniques, (c) magnet cooldown and operation. The above topics include a brief description of LRL operating techniques for various modes of refrigerator operation.

The validity of assumptions used in previous studies of large refrigeration systems is discussed. As an example, we will find the concept of a central compressor house to be particularly valid; the small-unit concept also is still valid for spread-out loads. The refrigeration requirement per magnet has been, in general, underestimated by a factor of 2 or more. We also find the refrigeration and cryostat design parameters are strongly interrelated.

2. LRL OPERATIONAL EXPERIENCE

The LRL machine was made in 1968 by 500 Incorporated (now Cryogenic Technology Incorporated). The machine is a 9-liter-per-hour liquefier with two compressors and nitrogen precooling. When operated as a refrigerator it is capable of delivering 30 to 35 W at 4.5 °K. Our system consists of two primary subsystems which are in two separate buildings 200 feet apart. The compressors, recovery system, and helium supply system are in Building 63A (formerly a liquid hydrogen storage shed); the machine cold box, nitrogen system, and control system are located in the LRL Superconductivity Laboratory at the north end of Building 64. Figures 1 and 2 show the major components of the LRL machine. Detailed construction and operational data may be found in several LRL internal reports,(1–3) which are available upon request.

Our system has been operating for just over 1 year.(4) During the first year of operation our machine has operated 6060 hours or 70 per cent of the time. Our machine has produced and delivered more than 14 000 liters of liquid helium to various customers around the Hill. In addition, the machine has provided more than 1200 hours of refrigeration to various LRL superconducting-magnet experiments. Our machine has been operated totally unattended for as long as 5 days, and is consistently run overnight and over the weekend.

During the first year the LRL machine has had several serious maintenance problems. We feel that most of these problems can be corrected by proper design of components and by proper operating techniques.

2.1. *Reliability and maintenance of system components*

The compressors have been the least reliable component of the LRL system. We have two kinds of compressors, and one is clearly superior to the other.(5) The better compressor is a converted heavy-duty industrial type 500-psig air compressor that has water-cooled jackets and heads. This compressor has given more than 10 000 hours' service without any major repairs. (This is equivalent

---

† Work performed under the auspices of the U.S. Atomic Energy Commission.

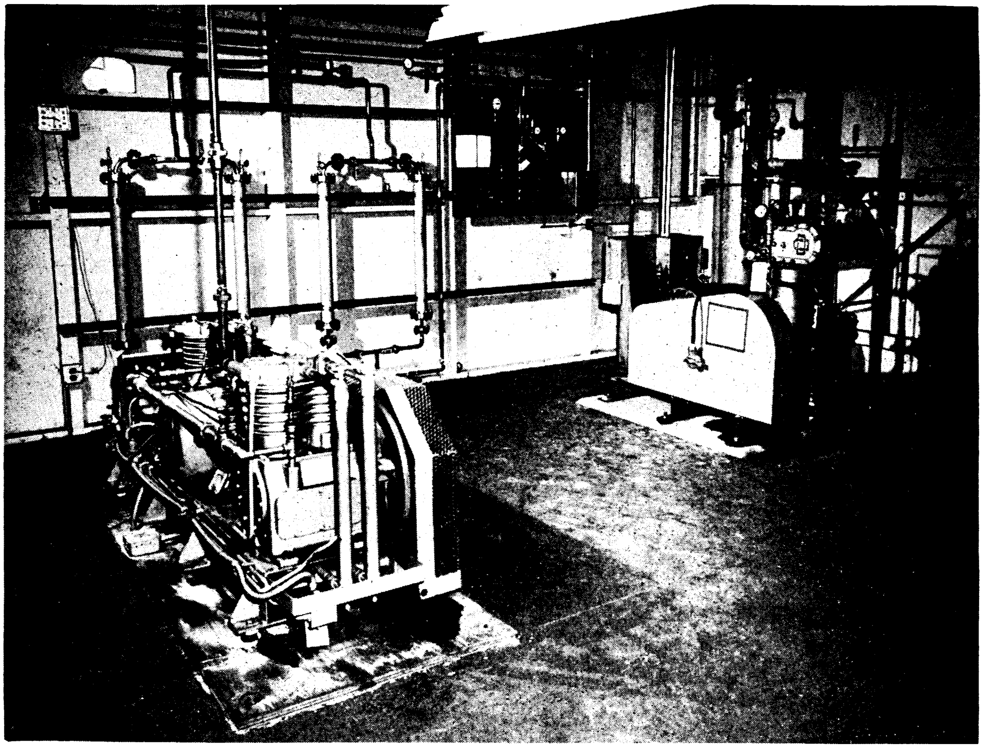

FIG. 1. Compressor house for the Lawrence Radiation Laboratory refrigerator showing the compressors, oil absorbers, and recovery system.

to driving your car 250 000 miles without an overhaul.) It is currently running better than when it was first installed. The conversion from air to helium was successful because the compressor was derated in the process. Helium is a harder gas to pump than air, but with proper precautions helium compressors can be run for many hours with a minimal amount of routine maintenance.

Contamination has been the cause of most of the system shut-downs. Contamination in the machine generally is in the form of frozen air, although some contamination has been caused by water vapor and hydrogen. Contamination has come from the following sources:

(a) Hydrogen and neon from the helium tube trailer that is not removed by the cryogenic adsorbers. We have observed this only during long liquefaction runs.

(b) Leaks (air gases) into the system when helium leaks out of the system—air is counter-diffused into the system. This type of contamination has been observed only when the machine had a bad leak.

(c) The cooldown of dirty cryostats. This form of contamination has resulted in the bulk of the LRL system problems.

We can decontaminate our machine and put it back in operation in less than 4 hours—as a result, contamination has not had the bad effects on our operation that compressor failure has. Contamination can be minimized if the following precautions are taken: (a) the gas entering the system from bottles or recovery tanks is repurified, (b) system leaks are minimized, (c) the machine cold box has a repurifier on it, (d) magnet cryostats are cleaned properly prior to cooldown, (e) the machine is run as a refrigerator instead of a liquefier.

The refrigerator cold box has a pair of reciprocating engines. The engines have been very reliable and nearly maintenance free. Our reciprocating cross head has fewer than 20 moving parts, and most of the time it runs at speeds lower than 150 rpm. We have had only one repair in our cross head: the machine ran more than 2500 hours on a faulty bearing before we replaced it. The cold box and heat exchangers have been very reliable. There has been one leak in one of the remote delivery tubes

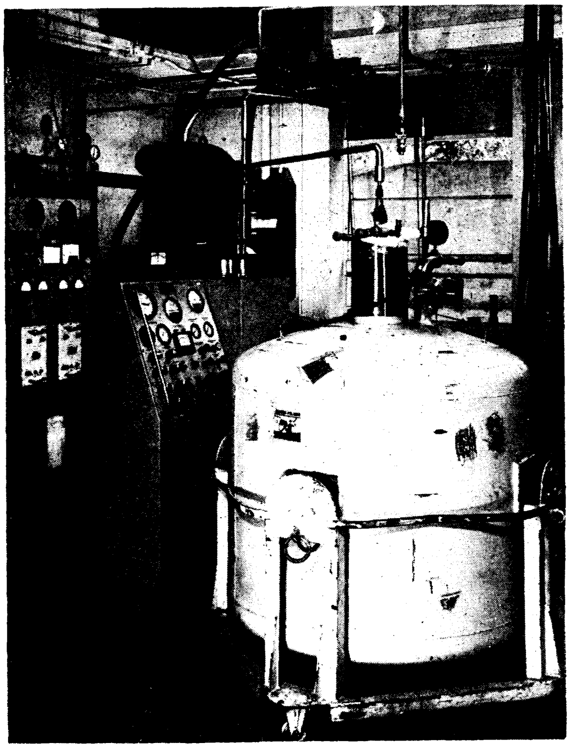

FIG. 2. The LRL refrigerator cold box, two remote delivery tubes, liquid level control system, and 500-liter storage Dewar.

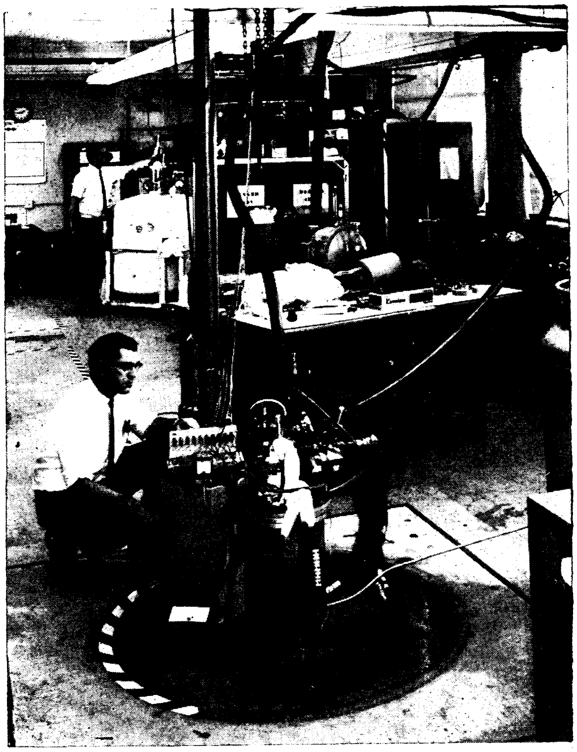

FIG. 3. A one-meter long dipole cryostat (foreground) being run from the LRL refrigerator (background) through a 50-foot long coaxial transfer line (black hose entering the cryostat from the top of the picture).

which required less than 8 hours to repair. We ran the refrigerator for more than a week before fixing this leak.

Automatic controls of gas and liquid nitrogen supplies pay for themselves very quickly. Handling of liquid nitrogen and helium gas in bulk has resulted in considerable labor savings. Our liquid nitrogen control system$^{(3)}$ paid for itself in less than 2 weeks by reducing our nitrogen consumption from 22 000 liters per month to 13 000.

Our experience indicates that low maintenance–low manpower operation is both feasible and practical. We have been very successful at operating our machine for long periods of time without an attendant. A maintenance machinist checks compressor lubrication and cryogenic adsorber traps once a day while the machine is running unattended. We typically run in this fashion over weekends and holiday periods. We average about half a man-month of labor per month to perform routine maintenance, operate the machine, and fill helium Dewars for other Laboratory users.

2.2. *The cold helium transfer line*

We have successfully refrigerated moderate-sized superconducting magnets (weighing up to 300 lb) at the end of a 50-ft semiflexible transfer line (an extension of the refrigerator remote delivery tube). The transfer line is of simple construction and can be built for a cost that is lower than the cheapest commercially available transfer lines by at least a factor of 5.$^{(6)}$

The transfer line consists of two concentric tubes which carry helium. The inner one carries the liquid-gas mixture which has been expanded through the Joule-Thomson (J-T) valve; the outer one carries the return cold gas back to the refrigerator. The concentric lines have an aluminized Mylar-nylon netting superinsulation system rolled around the outer line. The superinsulated inner lines are slipped into a rubber vacuum hose outer jacket. A second line now under development has a smooth-wall aluminum tube outer jacket. The second line will have an expansion valve at the magnet end of the line. The transfer line has a

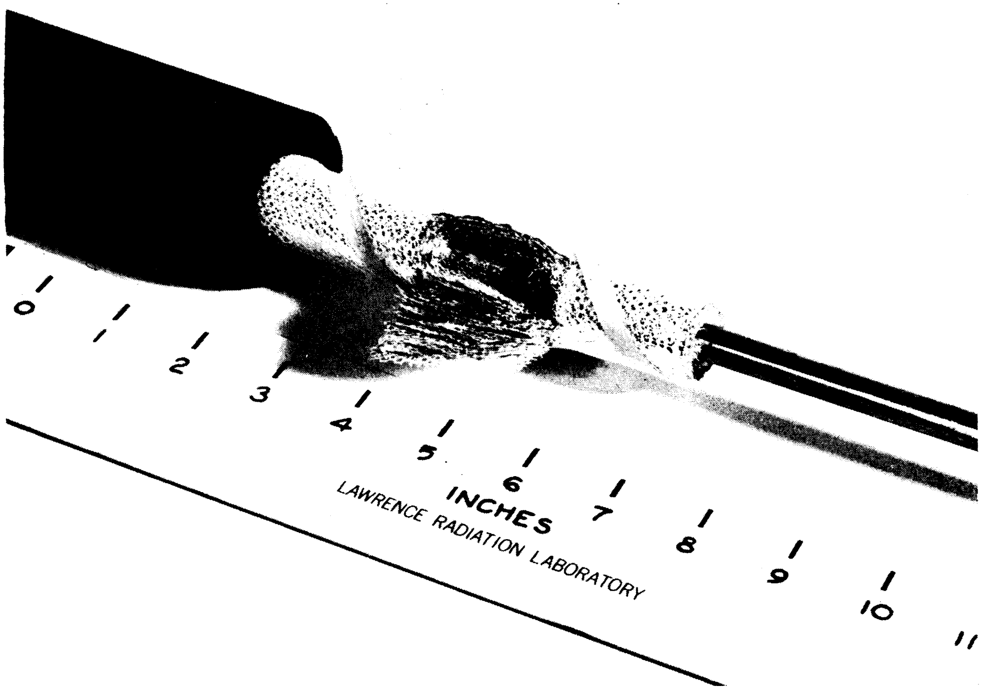

FIG. 4. Cutaway view of the LRL transfer line, showing the vacuum jacket (black hose), the superinsulation system, and the outer tube of the transfer line.

2-ft bayonet joint which slips over the end of the refrigerator remote delivery tube, permitting easy connection with the refrigerator.

The line can be produced in 50- to 100-ft lengths at a cost of less than $10 per foot. The construction is simple enough that the inner portion of the line can be built in the shop and installed in the vacuum jacket that has already been installed in the shielding of an accelerator experiment.

The line that was built by William Chamberlain and used on superconducting magnet experiments had some vacuum problems during initial tests. These vacuum problems have been considerably lessened during subsequent operation. The second version of this line will be much more reliable in this respect.

3. COOLDOWN AND OPERATION OF SUPERCONDUCTING MAGNETS ON THE REFRIGERATOR

The cooldown of large Dewars and superconducting magnets has been generally successful. LRL now cools nearly all its superconducting magnets, large and small, with the refrigerator because of the savings in cost in both helium and labor. We have become so dependent on the refrigerator that we have found it difficult to cool our largest magnets without it.

Proper design of the magnet and its cooldown apparatus is required if the cooldown of large magnets with the refrigerator is to be successful. Large magnets can be cooled only if the cold gas is forced through the magnet itself. We have been able to cool 300 lb of magnet from room temperature to 10 °K in less than 6 hours by use of our refrigerator.

Operation of superconducting magnets on the refrigerator was more difficult than first expected. The lead losses at first were much higher than predicted from our liquid pot experience. After some experimentation and improvement in lead design we were able to reduce lead-refrigeration requirement to an acceptable level, which is still almost a factor of 2 above previous predictions. Our operating experience indicates that 10 to 12 W of refrigeration is required per pair of 1000-A leads, and that this load is not linear with lead current.

We have found that leads must be gas cooled. However, bleeding gas through the lead, hence not returning the cold gas through the refrigerator, takes away from the refrigeration capacity (about 4 W per 25 ft^3/hr passing through the leads, which is the equivalent of 1 liter/hr liquefaction). Adjusting gas flow through the lead is important. It should be noted that the liquid level seems to affect lead performance.

Several other things that we have learned may be useful.

(a) It makes little difference whether the magnet Dewar has an intermediate temperature shield or not, because in all but the lowest-current magnets lead losses dominate.

(b) Operation of the refrigerator changes the cryostat design problem: cryostats that are to be refrigerated only (not designed for liquid pot operation) can be made much simpler, hence much cheaper.

(c) The space required for the J-T valve is generally larger when the magnet is refrigerated than when gas is being liquefied into a Dewar. Separation of the stream from the J-T valve from the stream returning to the refrigerator is important.

(d) Dual J-T valve operation (two cryostats) has been moderately successful, but further experimental work is required. In order to run more than two J-T valves from the same refrigerator, a slight change in design of the cold box is required; this is discussed in the next section.

4. RECOMMENDATIONS FOR A LARGE EXPERIMENTAL AREA REFRIGERATION SYSTEM

Refrigeration systems for the 200-GeV NAL machine experimental area have been discussed in reports by Strobridge[7,8] and Green *et al.*[9,10] The latter reports suggest that the most flexible and least expensive refrigeration system for the NAL experimental area would be one that consists of many small refrigerators supplied with warm helium gas from a couple of large central compressor stations. In general, I feel that the same conclusions still hold except that larger units supplying as many as five or six magnets would be used in areas where the magnet density is high. In areas where magnets are widely spaced, the small-unit concept still holds. Making the units capable of being moved and changed quickly is still very important for reliable operation.

The desirability of supplying gas from a central compressor station has been reinforced by our experience. The compressor houses should be automatically controlled so that operational manpower can be minimized. The piping from the compressor house to the machines can be made of any of a number of materials and should present no large engineering problems. The concept of using no nitrogen in either the refrigerator or intermediate temperature shields in the magnet cryostat is probably still valid, even when improved methods of handling liquid nitrogen are considered.

4.1. *The central compressor house*

The general functions that a central compressor house must serve are as follows: (a) supply high-pressure gaseous helium at room temperature at a constant pressure over a wide range of flow rates; (b) keep the helium gas free of water vapor, hydrocarbon vapors, air gases, and other impurities; (3) perform most of its operations automatically. Helium fill and recovery must be fully automatic; helium repurification and the shutdown of defective units should also be fully automatic.

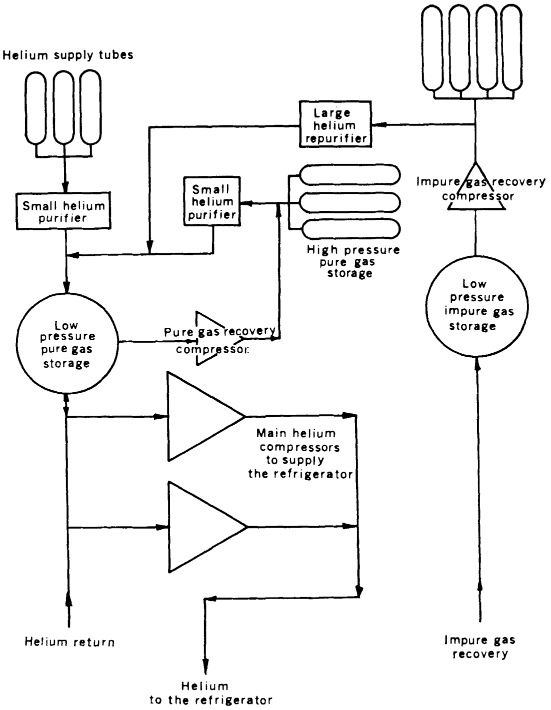

FIG. 5. A simplified schematic diagram for a large central compressor house to supply helium to a number of refrigerators.

Our experience indicates that heavy-duty industrial compressors with water-cooled heads and intercoolers will work reliably for long periods of time in a helium system. Helium is a much more difficult gas than air to pump because of its low molecular weight and its higher ratio of specific heats. Air compressors can be made to pump helium if the following steps are taken: (a) compression ratios should be limited to 5 or 6 to 1 for oil lubricated compressor and 3 to 3.5 to 1 for teflon ring compressors, (b) two stage air compressor will work well at rated continuous service if the heads and cylinders are well cooled, (c) water cooled intercoolers are required because the gas leaving the cylinders will be at temperatures as high as 350 °C, (d) the crankcase should be gas tight and operated at positive pressure, and (e) a gas tight unloader system should be used.

A well-designed compressor should operate more than 10 000 hours without any major maintenance. The nonlubricated compressor appears attractive, but it should not be used at the expense of reliability or excessive cost. Molecular-sieve oil absorbers must be included on all oil-lubricated compressors, and since they also absorb water, their use is recommended on any compressor that is water cooled or has water-cooled intercoolers. Small refrigerators (25 to 100 W) with reciprocating engines require 2 to 3 scfm at 250 psig per watt refrigerator capacity (turbine machines, which run at 150 psig, will require three to four times this gas flow).

The compressors (300 to 600 scfm capcity) should be capable of starting and stopping themselves. The number of compressors running at a given time should depend on the flow needed to operate the refrigerators. Spare compressors to replace defective units, of course, should be provided. Unlike our present system, the excess gas should be recovered by a separate compressor. The LRL machine uses a gasholder (similar to natural gas gasholders) to control helium supply and recovery operations. This method works very well, but it is more expensive than other methods that can be used.

Cryogenic purifiers are needed on the pure-helium supply and the recovered-helium supply. The recovered-helium supply should be split into two parts, one for pure gas, the other for impure gas. The contaminated-gas recovery system should be separated from the refrigerator-compressed gas circuit. Automatic recharging of the cryogenic purifiers should be provided. Either activated charcoal or molecular sieve may be used as an absorption medium for the purifiers.

The helium compressor stations require cooling water. We use tower water with corrosion and algae inhibitors in it. Inlet water temperatures of 40 °C are acceptable. A temperature rise of 30 °C across the compressors is also acceptable. Proper flow switches are necessary to shut down the compressor in the event of cooling-water failure.

The electrical requirements for the compressor house are the same as for any system that uses large motors. In general, for refrigerators in the 100-W size range, 500 to 750 W of electric power will be required per watt of refrigeration at 4 °K (turbine machines require more) when nitrogen precooling is not used.

4.2. *Helium piping system*

Helium gas can be distributed through any pipe that is not permeable to helium and does not contaminate the helium. Cheap steel or aluminum pipes can be used as long as they are leaktight. Copper pipe with soldered joints serves very well, but is expensive. Plastic pipe should work as long as it can stand the pressure. Greased O-ring seals or rubber seals have performed well in our system. Ball valves with Teflon seats have proven very successful in our system, even when they are used at liquid nitrogen temperatures.

Flexible hoses should be selected with care. Some hoses are permeable to helium, others contaminate the stream. Anaconda all-metal hoses are very good but expensive. LRL uses heavy rubber vacuum hoses for low-pressure use.

4.3. *Refrigerator cold box*

The refrigerator cold box should consist of the following components: (a) helium purifier; (b) counterflow heat exchangers with a liquid nitrogen precooling loop: (c) expansion engine system to cool gas down to 10 to 15 °K; (d) Joule-Thomson circuits to liquefy helium and provide 4.5 °K refrigeration; (e) automatic controls to control the refrigeration in each magnet cryostat; (f) cold-helium transfer lines to transfer helium to and from the magnet cryostat.

Each refrigerator cold box should have a small helium repurification unit which recharges itself automatically. Such repurifiers are commercially available today as standard units on helium refrigerators that are being sold by at least two manufacturers. The refrigerator should be designed to run efficiently without liquid nitrogen precooling. However, a precooling loop should be provided in the event that additional capacity is

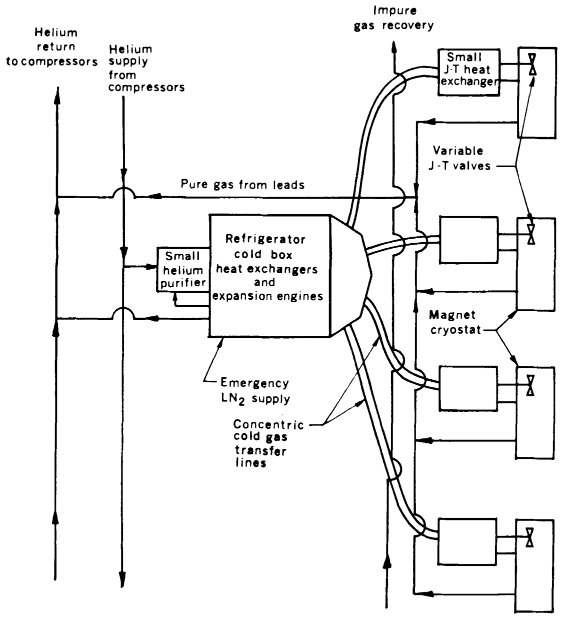

FIG. 6. A simplified schematic diagram of a helium refrigerator which is refrigerating four superconducting magnet cryostats.

needed, or to bolster an ailing refrigerator until the next regular maintenance period. Our machine doesn't have sufficient upper heat exchanger for efficient operation without precooling. Newer Cryogenic Technology Incorporated machines have at least partially remedied this situation.

The expansion engine system is the heart of the helium refrigerator. All the energy removal in the gas takes place in the expansion engines. Two expansion engine systems are in use today, the reciprocating piston engine and the turbine expander. The choice of which should be used will be based on economics. The turbine expander's biggest advantage is that it will expand large volumes of gas in a relatively small physical volume. Its biggest disadvantage is that the efficiency of the machine is lower and it operates at lower pressures. Both these factors affect the sizing of pipes, heat exchangers, and compressors. These components make up a significant portion of the cost of an experimental-area refrigeration system. Both the turbine and reciprocating engine systems can be made reliable. The single-moving-part argument often advanced by turbine proponents doesn't mean very much when you consider that the one moving part runs at speeds up to 250 000 rpm, compared with less than 550 rpm for the reciprocating engine, which has 20 or so moving parts. It is my opinion that the turbine machine will find its greatest use in large units, and the reciprocating expander will continue to be economical when used in small units.

The J-T circuit provides the low temperatures needed to run superconducting magnet systems. In order to deliver controlled refrigeration to each magnet cryostat, constant-temperature constant-pressure gas must be provided at each J-T valve. Constant pressure is maintained by regulating the compressed-gas system. The temperature is regulated by controlling the rate of expansion through the expansion engine. The constant-temperature (8 to 12 °K) gas should be fed to the J-T valves through a J-T heat exchanger, which could be located at the magnet cryostat. The refrigeration fed to the magnet is controlled by regulating the flow of cold gas through the high-pressure side of the J-T valve.

Supercritical helium refrigeration (the helium gas pressure is above the critical pressure) appears to be very attractive when applied in the following ways: (1) in large superconducting magnets where high current densities are not needed and where hollow superconductor can be used without difficulty, (2) in special magnets, such as thin septa$^{(11)}$ and beam splitting magnets, where thin conductors and moderate fields (10–20 kG) are needed. Supercritical helium cooling may become attractive in general experimental area magnets if the stability and ac loss characteristics of superconducting material continue to improve. Gas cooling tests indicate that fine stranded, twisted material can be made to perform reasonably well.

Two methods can be used to provide super critical cooling: the first method is to provide gas at 4.5 to 6 °K and to circulate the gas with a cold pump.$^{(12)}$ The second method is to let the refrigerator be the source of high pressure gas, allowing the gas to flow through the load, then through a J-T valve and back through the low pressure side of a J-T heat exchanger. The second method appears to be practical if a refrigerator is to be used on magnet system.$^{(13)}$

The advantages of supercritical cooling are obvious; they are: (a) the magnet cool down is quick and positive; (b) a large reservoir of liquid helium is eliminated. (Supercritical helium is a single phase fluid.) The total system volume is reduced; (c) the cryostat construction is simplified by the elimination of necks and other conventional parts. The primary disadvantage of supercritical cooling is that the heat transfer is rather poor unless the flowing supercritical helium is in direct contact with the superconductor. As a result, supercritical cooling becomes impractical in high current density superconducting magnets unless the superconducting material is intrinsically stable and has low ac losses.

The most useful size for a helium cold box is probably in the 100-W range without precooling. Such a unit should be portable enough to be moved around the experimental area by use of lift trucks (just as today's conventional magnet supplies are moved). The cold box should be capable of supplying controlled refrigeration to 4 to 6 magnets simultaneously. It is to be noted that one should not expect a refrigerator to run continuously at its rated load. This is not the practice with most mechanical equipment. The helium refrigerator shouldn't be any different. The experimental-area transfer lines should be made in standard lengths so that standard superinsulated inner lines may be used interchangeably in different custom-shaped outer vacuum lines. Cold helium can be transferred from the refrigerator to the magnet and back by transfer lines similar to ones under development at Berkeley.

4.4. *Magnet cryostat*

The concept of a simplified, low-cost dipole and quadrupole cryostat is discussed in Ref. 14. A summary of the findings follows.

(a) Elimination of intermediate temperature shields and support points should be seriously considered. Much of the refrigeration required in a beam-transport cryostat is needed to cool the leads. The extra refrigeration needed because there is no intermediate temperature shield will in most cases cost less than the intermediate temperature shield itself.

(b) Superinsulation, even as little as five layers, is far superior to other insulation systems.

(c) If the magnet aperture is small, serious consideration should be given to moving the iron into the cryostat.

(d) The support system should be made as simple as possible.

(e) Cold bore magnets should be considered if the magnet is long and the bore is evacuated. In short, simplicity is desirable throughout.

4.5. *Cost of an experimental area system*

The heat load estimated for the Green, Coombs, Perry report(9) was underestimated largely because lead-cooling problems were not well investigated. Because of recent advances in refrigeration technology, the cost of the experimental-area refrigeration system for 252 magnets mentioned in the Green *et al.* reports(9,10) should be even lower despite the fact that projected heat load is doubled over the previous report estimate. The estimated capital cost for refrigerating a superconducting beam transport line is of the order of $15 000 to $20 000 per magnet cryostat (compared with $25 000 per cryostat given in previous estimates). I feel that continued development of refrigeration systems will tend to lower the cost of refrigeration even further, particularly if a standard-size unit can be adopted.

5. SUMMARY

Several conclusions can be drawn from the experience gained at LRL. These are:

1. Refrigeration requirements are generally underestimated; the electrical loads are typically the largest part of the load.
2. Large superconducting magnets can be cooled down in a reasonable amount of time if the proper techniques are employed.
3. Cheap efficient transfer lines can be built and operated on a helium refrigerator.
4. Many laboratory superconducting magnet experiments work very well on the refrigerator, and at lower cost than the conventional open pot system.
5. Many procedures used on open pot superconducting experiments cannot be employed when a refrigerator is used to cool the experiment.
6. Conclusions on operating superconducting magnet experiments on a refrigerator should not be drawn from open pot experiment data.

Several conclusions about large refrigeration systems can be drawn from our operating experience.

1. The large central house is needed for a large system.
2. The smaller unit concept is valid for experimental areas where magnets are widely spaced. In general, the more compact the system of magnets the larger the refrigerators that would be used to supply the magnets with cold gas or liquid.
3. Inexpensive transfer lines can be built in moderate lengths to carry moderate amounts of cold gas. They will not be built by industry if manufacturers continue to charge their present high prices. Small transfer lines can be built in 50- to 100-foot lengths for $10 to $15 per foot.

4. Large refrigeration systems can be built for superconducting synchrotrons. It is my opinion the cost will come down on these as well.

5. There will be a continuing trend toward eliminating liquid nitrogen from the refrigeration process and from cryostats that operate on the refrigeration system. The reasons for this are purely economic.

REFERENCES

1. Michael A. Green, The Dual J-T Valve Test at 500 Incorporated, UCID-3286, Nov. 13, 1968.
2. Michael A. Green, A Description of the LRL Liquefier System, UCID-3389, Sept. 15, 1969.
3. Michael A. Green, Operating Procedure for the LRL Liquefier, UCID-3428, Dec. 23, 1969.
4. Michael A. Green, The First Year of Operation of the LRL Liquefier, UCID-3429 (to be issued).
5. Michael A. Green, Report of the LRL Liquefier System Breakdowns and Progress, UCID-3407, Nov. 13, 1969.
6. William Chamberlain (Lawrence Radiation Laboratory), private communication on helium transfer lines.
7. T. R. Strobridge, D. B. Chelton, and D. B. Main, A Preliminary Analysis of Refrigeration Requirement for Superconducting Magnet in the Experimental Area of the 200 BeV Accelerator, NBS Report 9259, Oct. 31, 1966.
8. T. R. Strobridge, Refrigeration for Superconducting and Cryogenic Systems, *IEEE Trans. Nucl. Sci.*, **NS-16**, No. 3, 1104 (1969).
9. Michael A. Green, Gordon P. Coombs, and James L. Perry, *Refrigeration for Superconducting Magnets in the 200 BeV Accelerator*, *Weston*, *Illinois* (500 Incorporated, Cambridge, Massachusetts, June 1, 1968).
10. M. A. Green, G. P. Coombs, and J. L. Perry, An Examination of a Liquid Helium Refrigeration System Superconducting Magnet in the 200 BeV Experimental Area, in *Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators*, Part I, p. 293, BNL-50155 (C-55).
11. M. A. Green, Heat Deposition and Heat Transfer in a Superconducting Thin Septum Magnet, UCID-3168, April 1968.
12. H. H. Kolm, M. J. Leopold, and R. D. Hay, Heat Transfer by the Circulation of Supercritical Helium, *Advances in Cryogenic Engineering*, Vol. 11, p. 539, 1965.
13. H. Brechna, Materials and Conductor Configurations in Superconducting Magnets, in *Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators*, Part II, p. 478, BNL-50155 (C-55).
14. M. A. Green, Simplified Helium Cryostats for Superconducting Dipole and Quadrupole Magnets, UCRL-19764, May 1970.

Received 17 April 1970