REVIEW OF THE CRYOGENICS SESSION – SECOND WEEK OF THE BROOKHAVEN SUMMER STUDY ON SUPERCONDUCTING DEVICES AND ACCELERATORS*

T.R. Strobridge
Cryogenics Division, Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado

Although low temperature research and industrial installations are becoming more numerous each year, none approach in cooling capacity at 4°K or in complexity of the heat load distribution the requirements of the high energy physics research facilities which were under discussion at these meetings. To some, helium has become an industrial commodity with the advent of the large liquefiers that are operational today. The bulk transportation of helium in the liquid phase is a routine common carrier matter. To others, liquid helium means low temperatures and the benefits that high energy physics can accrue from the superconductivity phenomenon.

From a cryogenics viewpoint, a superconducting accelerator has poor geometry and physical characteristics (high surface-to-volume ratio, large masses that must be cooled down and that require heavy supports which conduct heat to the low temperature space, and small cooling passages). Furthermore, the superconducting devices which require refrigeration may be separated by kilometers. The fact remains that neither a comparable cooling requirement nor a refrigeration system to meet such a requirement exists today. Yet, the cryogenics support has been referred to as (and should fall into the category of) a utility which is economic and which must be reliable.

Therefore, the lecture topics for the cryogenics section were selected, with these problems in mind, to attempt an assessment of the state of the art directly related to the proposed programs, and to see how closely the utility image can be approximated. In the end, the achievement of utility status for superconducting devices would give great impetus for more widespread application of the technology. This review will give the lecture topics, then outline the experts' opinions, and list the areas which most urgently require further research and development.

The lecture topics were:

1) The low temperature mechanical properties of metallic structural materials.
2) Properties of nonmetallic materials at cryogenic temperatures.
3) Cryostat design.
4) Cryopumping.
5) Cryogenic electrical leads.
6) Cryogenic safety.

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7) Superfluid helium as a refrigerant.
8) Heat transfer to helium I.
9) Refrigeration.
10) The European state of the art.
11) Refrigeration for superconducting magnets in the 200 GeV accelerator, Weston, Illinois.

The following is a narrative summary of the lectures.

THE LOW TEMPERATURE MECHANICAL PROPERTIES OF METALLIC STRUCTURAL MATERIALS[1]

Although many common metals and alloys may not be used as load-bearing structural members at low temperatures because they become brittle, there are a number of materials which are suitable for liquid helium temperature service. The result of a transition from ductile to brittle behavior at low temperatures can be the sudden catastrophic failure of a part under conditions that would not be excessive at ordinary temperature. Such fractures usually occur with little or no deformation. A distinction should be made between the terms ductility and toughness. Ductility is the ability to deform plastically without fracturing under stress while toughness is the ability to absorb energy through deformation under stress and the resistance to fracture propagation. Metals may be relatively ductile in a tensile test but brittle when broken in a test to measure toughness — each test conducted at the same temperature. Investigation of the suitability of new materials for low temperature service must include measurements to determine toughness.

In general, larger grain size will result in a higher temperature for the ductile-brittle transition. Therefore, cast structures which tend to have larger grains may have lower toughness. Hot working generally improves the characteristics of cast metals. Welding leads to larger grains in the welded area. The brittleness and crack propagation tendencies in welds can be alleviated by stress relieving and by welding in vacuum or in proper inert atmospheres which preclude adsorption of detrimental gases (atmospheric, including water which may decompose into hydrogen). Selection of the proper welding rod is essential. The importance of the brittle fracture at low temperatures should not be overlooked since it may be desirable to move equipment which is at liquid helium temperature — for example, superconducting beam transport magnets. Fortunately, there are a number of metals and alloys suitable for liquid helium temperature service in complex or welded structures. Representative materials include 300 series austenitic stainless steels (low carbon grades), and certain alloys of aluminum, nickel, and titanium. Copper and many of its alloys are also suitable.

The developments in fracture mechanics, a relatively new field that is attracting considerable attention, should be of value in determining the critical crack length or stress level beyond which rapid failure will occur. Testing techniques are well established and low temperature testing facilities exist both in industry and in government laboratories.

PROPERTIES OF NONMETALLIC MATERIALS AT CRYOGENIC TEMPERATURES[2]

Structures fabricated from nonmetallic materials may be attractive for several reasons especially since significant progress in understanding the mechanical properties

1. A. Hurlich, these Proceedings, p. 311.
2. R.E. Mowers, these Proceedings, p. 326.

of these materials has been made in the recent past. This progress is attributed to standardization of test techniques and sample preparation, development of stress analysis of the composites — a difficult and complex field, and a reduction in the variations of the constituents of these materials. High strength-to-weight ratios, low thermal conductivities, low specific heats, and ease of fabricating complex shapes are characteristic advantages of the reinforced plastic structures. As a class, they tend to have high coefficients of thermal expansion, a tendency towards brittleness at low temperatures and as stated, stress analysis is difficult. Eddy current heating in the presence of changing magnetic fields is, of course, eliminated and the feasibility of constructing liquid hydrogen bubble chamber bodies from filament-wound laminates has been investigated. Ports and piping penetrations and the sealing of the vessel present problems, but the savings in weight and elimination of eddy currents should lead to lower static heat losses. Filament-wound pressure vessels are promising but the key to success is a suitable nonpermeable liner which can be matched to the high thermal contraction and low elastic modulus of the material. Adhesives have been the subject of research since the bonding of low temperature structures could be very useful and tests have shown that satisfactory joints can be made. The low coefficients of friction of some of the fluorocarbons are utilized in dynamic seals and bearings and laminated flat gaskets have been found superior to certain other low temperature seals. The effects of radiation damage must always be taken into account when considering the use of the organic materials.

CRYOSTAT DESIGN[3]

Cryostat design will depend to a large extent on information which must be provided by the physicist about the device to be protected thermally from the surroundings. The support structure will be determined by the size and weight of the cold apparatus, magnetic forces, orientation, need for precise alignment, the space envelope, whether or not there must be a warm bore, and the possible necessity for periodic disassembly. The electrical lead size and how they are to be cooled are important as is the method of refrigerating the entire assembly. There are many subtle interactions between the insulation system, the scheme for electrical lead cooling, the supply of refrigeration and the cooldown requirements (for example, if cold helium gas can be tapped from the process stream, intermediate temperature gas-cooled shields may be used to reduce heat leak). There is a cost trade-off between cryostat sophistication and liquid helium or refrigeration consumption. The forces which are anticipated due to shipping and handling are very important. Ordinary shipping loads are predictable, but problems have been encountered during user handling or in unusual transportation situations. Designs conforming to ASME Code are adequate using ordinary textbook relations. There are several insulations to choose from and that choice is influenced again by the availability of cold gas, liquid nitrogen, lead cooling, and the maximum heat leak that can be tolerated which is directly related to operating expense. The problems which may be encountered are vacuum leaks, lower than expected insulation performance, and inadequate provision for containment of the effluent gas which leads to long cooldown times.

CRYOPUMPING[4]

Space simulation has been responsible for the development of large cryopumping systems, but the features of cryopumping — high pumping speeds, low ultimate pressures

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3. G.E. McIntosh, Cryogenic Engineering Company, presented at this Summer Study (unpublished).

4. C. Barnes, these Proceedings, p. 230.

(below 10^{-8} N/m^2), and noncontamination of the pumped volume — can also be attractive to high energy physics. In fact, the proposal for a heavy particle accelerator, the Omnitron, which requires very low pressures in the beam path, includes cryopumping at liquid helium temperatures. Cryopumping (to be distinguished from cryosorption and cryotrapping) condenses gas molecules striking a low temperature surface. For highest efficiency, the cold surface must have a wide view of the pumped volume. However, this would mean that a large radiation heat exchange would take place with warm surfaces and the heat load on the cryosurface would become excessive. Therefore, it is common to shroud the condensing surfaces with higher temperature shields at about 80°K. The geometry of these shields is important and calculation of the effects of geometries on both heat load and capture coefficient, though complicated, are handled by Monte Carlo techniques or view factor analysis. A number of different geometries have been used in operating systems, so pumping performance and refrigeration needs are well known and can be predicted for other applications.

CRYOGENIC ELECTRICAL LEADS[5]

Electrical leads are planned for most of the superconducting magnets being considered. These electrical connections are used for charging the magnet, and trimming the field since, although in principle persistent dc operation is possible, joint resistance would degrade the current if energy was not supplied. The most compelling reason for using these leads is the large amount of energy in the magnetic field which must be dissipated outside of the cryostat if there is a failure or quench. Some of the conductors are large — carrying up to 7000 A. This means that large thermal conduction paths exist between the superconductor at liquid helium temperatures and the ambient surroundings, causing the liquid helium to evaporate at a rapid rate. In addition, there is joule heating in the conductor which, upon conduction toward the lower temperatures, imposes an additional heat load on the refrigerant. This may not be a significant problem for small magnets with many turns and low currents, but is costly for larger magnets. The objective is to design leads with the smallest heat introduction per ampere of current carried. A survey of the literature shows that, over the years, numerous analyses and designs have evolved to remedy the high heat loads evidenced by rapid helium boiling. The first solution was to use the cold effluent vapor to intercept the energy above the 4°K level through heat exchange with the lead. The next was to attach superconducting material extending from the lowest temperature end some distance toward the warmer end. The object is that in any portion of the conductor that is below the critical temperature of the superconductor the current will switch to the path of zero resistance and the joule heating will be eliminated. The problem still remains that accurate solutions of the relation describing the flow of energy along the lead, the temperature distribution, and the heat transfer, taking into account the temperature variations of the electrical and thermal properties of the lead material and the heat transfer coefficient, are difficult. A simplified relation for lead design has been developed from which lead dimensions for optimum performance can be calculated. Although gas cooling and the alternate superconducting current path have reduced the heat reaching the 4°K level by a factor of thirty, further improvement should be possible. It is suggested that materials of higher electrical conductivity and lower electrical resistivity should be investigated. The Reynolds number in all leads has been so low that the helium flow has been laminar. A higher heat transfer coefficient could be induced by increasing the Reynolds number. Off-optimum operation should be investigated for it may be of benefit during charging or for short duty cycles.

5. C.D. Henning, these Proceedings, p. 304.

CRYOGENIC SAFETY[6]

The safety hazards associated with the usual laboratory amounts of liquid helium are most often minor, but the amounts of liquid which may be required and the stored energy in the superconducting devices may raise the potential for physical and physiological damage following an accident. Hazards are associated with some cryogens because of their potential for chemical activity; for example, hydrogen, oxygen, and fluorine. All of these fluids including the nonreactive elements can cause damage not related to toxicity, burning, or detonation. Frostbite or deep freezing of tissue occurs rapidly on contact with either the liquids, cold vapor or surfaces at low temperatures. A large spill of a cryogen can, because of the approximate 600-fold increase in specific volume upon warming to ambient temperature, displace the surrounding air and deplete the oxygen supply to a fatally low level. This same high change of specific volume from liquid to room temperature gas means that liquid trapped in a vessel or a line between two valves can build destructively high pressures if there is any heat leak to the system. The solutions to these potential hazards are obvious and simple, but must be implemented. The amounts of liquid helium present in a superconducting accelerator and the stored energy in the magnets are a combination which requires careful study. The damage potential can be predicted and the structures designed accordingly.

Prevention is the best design for accidents. Adequate training, the establishment of well-thought-out emergency procedures and an understanding that bad accidents are caused by seemingly improbable cascading of events are essential to a safe operation. In regard to operational procedures, check lists and alternative actions in case of trouble should be planned well in advance and any plant modifications should be subject to review by those responsible for safety.

An accident resulting from a lack of information is regrettable, but an accident caused by willfully ignoring well-known safety procedures for the sake of economy or expediency is inexcusable. Criteria for accident-free operation of cryogenic facilities are well known, and have been established through bitter experience.

SUPERFLUID HELIUM AS A REFRIGERANT[7]

Superfluid helium has attracted the attention of experimental and theoretical physicists for many years and workable models have been developed to explain some of its truly unique properties. These models, commonly used for the design of small experiments, are by and large adequate; perhaps because research of this nature is amenable to trial solutions. The lecture given by the chairman (H.A. Schwettman) of the previous session on superconducting rf devices and linacs was opened by a statement to the effect that there must be cooperation between physicists and engineers if very low temperature technique is to come out of seclusion in the physics laboratory and become at least a specialized technology. This is a heartening attitude for superfluid helium is a liquid whose engineering potential has not been tapped. Very low temperature is necessary to improve the duty cycle of the superconducting linear accelerator and many liters of superfluid will be used. It is anticipated that the very high thermal conductivity of the superfluid will maintain the temperature constant to within $0.020^{\circ}K$ over a 152 m accelerator length. This operation will be watched with great interest not only by physicists interested in the research, but by engineers as well, for the experience gained in this large-scale use of superfluid will be valuable indeed. The cooling arrangement selected for the superconducting cavities calls for heat transfer from the cavities to the liquid-vapor interface where evaporation occurs. The cold vapor will

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6. M.G. Zabetakis, these Proceedings, p. 229.

7. H.A. Schwettman, these Proceedings, p. 1.

then be returned to the refrigerator through subatmospheric insulated piping. It has been suggested that long lines filled with superfluid could be used to conduct energy away from remotely located heat sources to refrigeration stations. This would not require the separate low pressure vapor return lines which introduce further energy into the system and are another potential source of leaks. There may be real advantage to this scheme and it should be investigated. It was noted that the Kapitza resistance between the superfluid and the superconducting surface of the cavities is not known.

HEAT TRANSFER TO HELIUM I[8]

An understanding of the mechanisms of heat transfer to helium I is critical. The operation of a superconducting magnet may typically involve heat transferred to dense gas during cooldown, to liquid during steady state, and to two-phase mixtures of liquid and gas during a quench. The helium may be single phase at super or subcritical pressures or may be saturated as either liquid or vapor. The cooling passages must be designed to transfer the required energy under any of these circumstances at a rate sufficient to assure predictable behavior and to prevent damage to the coil, cryostat, and personnel. Unfortunately, there are regions where the transport properties of helium required to make correlations of experimental heat transfer data have not been measured. Experimental heat transfer coefficients are also lacking. With respect to transport properties, heat transfer studies are more difficult because the properties vary significantly in value from those of conventional fluids and extrapolation of the correlations are not justified without experimental verification. In the gas region, one would expect the conventional correlations to be generally effective although some modification may be required because of the properties behavior previously discussed. In the liquid region, the properties behavior with respect to that of conventional fluids is quite different; however, the conventional correlations should still form the basis by which one may make heat transfer predictions. Heat transfer phenomena in the two-phase region is not well understood for any fluid. This means that almost any extension of the use of conventional expressions to the helium region should be accompanied by a rather complete experimental verification if any substantial reliability is required in the use of the data. In the pseudoliquid or supercritical region near the line of maximum specific heats, a poor understanding exists, at best, for the heat transfer behavior. Here again, a good deal of experimental data will be required for helium if reliable heat transfer predictions are to be achieved. This paper collects together all of the relevant information with respect to helium heat transfer. The data were reviewed for each of the regions for all modes of heat transfer in those regions and recommendations from among the available correlations were given. Further, recommendations for experimental properties and heat transfer studies were made. It should be noted that some of these experimental programs are now under way.

REFRIGERATION[9]

THE EUROPEAN STATE OF THE ART[10]

REFRIGERATION FOR SUPERCONDUCTING MAGNETS IN THE 200 GEV ACCELERATOR, WESTON, ILLINOIS[11]

A general review of $4^{o}K$ refrigeration was given including some of the appropriate thermodynamics, the process cycles that can be used, the types of components available

8. R.V. Smith, these Proceedings, p. 249.
9. T.R. Strobridge, these Proceedings, p. 193.
10. G. Prast, these Proceedings, p. 205.
11. M.A. Green, G.P. Coombs, and J.L. Perry, these Proceedings, p. 293.

and some of the complete units that are on the market. The description of the progress in Europe showed that refrigerators there are distinctly competitive with those manufactured here. Witness to that are some of the coalitions that have been recently formed between U.S. and European manufacturers. Two points may be germane to this meeting — the distinction between a refrigerator and a liquefier and the input power requirements of existing units. First, most if not all $4^{o}K$ refrigerators produce liquid in the process stream. Energy from the heat load evaporates the liquid and the cold gas (which has high refrigeration potential) is returned to the refrigerator where it is used to cool the incoming gas stream. Thus, refrigeration is produced only at one temperature. In a liquefier, part of the process fluid stream is removed as liquid. Therefore, the return stream in the liquefier is depleted and this means that additional refrigeration is required at all temperatures to cool the unbalanced flow in the inlet stream. The result is that a liquefier with a capacity to provide liquid to a device with a specified heat load at a rate just matched to that load will require approximately 5 or 6 times the input power of a refrigerator just matched to the same load. The second point regards the efficiency of $4^{o}K$ refrigerators. Data on existing refrigerators show that at 1 kW capacity about 500 W of input power are required per watt of refrigeration. At 10 W capacity, about 1000 W/W are required and the specific power requirement increases further for smaller units. About 15 to 18 percent of Carnot efficiency is the best performance recorded for contemporary $4^{o}K$ refrigerators. It is entirely possible that improvements can be made but the refrigerators are likely to be more complex and costly. Since the design of contemporary refrigerators took into account economic factors, it may be that increased efficiency and the resulting reduction in input power may not be justified when the increased purchase price is considered.

It is clear that a reliable supply of cooling is absolutely necessary because the proposed accelerators will be inoperable at higher temperatures. Refrigerators and liquefiers are mechanical devices which are subject to failure. Redundant components and/or reserve liquid supplies are a necessity. A study of how to best refrigerate superconducting beam transport magnets in the experimental area of the 200 GeV machine was made some time ago. The results of another more recent effort were presented to this meeting. Both studies made allowance for failure of the regular cooling supply, but more important, serve to show the logistical problems inherent with such an installation. It is a far different matter to construct a large helium liquefier in the Midwest to fill transportation Dewars than it is to design a $4^{o}K$ refrigeration system for hundreds of small distributed heat loads. The cooling can be done by oversized, crude systems, but the reason for utilizing low temperature phenomena is primarily economic and a system which causes downtime and requires many man-hours will not be economic. The problem posed is certainly not insurmountable, but the solution will require careful study in the selection of the system, and good design with an emphasis on reliability.

CONCLUSIONS

In summary then, although there is the brittle fracture problem with metals, there are a number which may be safely used for structural load bearing members. Testing and evaluation techniques are well established to investigate new metals and alloys. Nonmetallic materials of various kinds are coming of age for use in cryogenic environments. Some of their properties may be very useful and here also testing and evaluation criteria are becoming better defined. Cryostat design is an established field with many choices in approach available. Cryopumping techniques should present no problems. Safety practices in the use of large quantities of liquid helium are well known.

There still seem to be some questions concerning electrical leads and their rôle in large systems. Further work here seems appropriate since lead design will affect cryostat design and refrigeration requirements. If superfluid helium is to play a larger role in high energy physics research, then engineering data are desperately needed and the design practices should be established at an early date. The need for helium heat transfer data is serious and an experimental program is in the first stages of equipment design. The logistics problem of supplying refrigeration to widespread superconducting devices needs serious consideration. The decision on one method or another is virtually irreversible and is important. The choice of cooling method will affect many aspects of the system — including cryostat design and refrigeration capacity.

The conclusion to be drawn is that cryogenic technology is far enough advanced to provide support for almost any superconducting facility. Experience in all aspects of cryogenic engineering is well documented and competent personnel are active in the field. The key to success is to realize and accept the fact that there must be co-operation between the disciplines and that the cryogenics will be an integral part of the system and therefore must be considered in the planning from the very beginning. Just as in superconducting technology, there is research to be done in cryogenic technology. However, there is reason to believe that by careful, long-term planning, the utility concept of cryogenics support can be realized. A poorly thought-out system will lead to enormous waste and refitting.