Final version, May 2002

Cryogenics Assessment Report

M. J. Gouge, J. A. Demko and B. W. McConnell, ORNL
J. M. Pfotenhauer, University of Wisconsin

Executive Summary

DOE and the national laboratory, industrial and university teams working on electric system applications of high temperature superconductors (HTS) have long recognized the importance of cryogenics as an enabling technology. Cryogenic workshops were held at the 1998 and 1999 DOE Peer Reviews. These workshops examined the state-of-the-art in cryogenic components and estimated performance requirements when used with HTS electric power systems. The key issues in employment of cryogenic support technology were identified as efficiency, reliability and cost. The participants developed a Cryogenic Roadmap and a companion Implementation Plan. Building on this planning base, the principal objectives of the present effort are:

1) Determination of the characteristics of the cryogenic refrigeration systems for use in HTS electric power applications.
2) Critical appraisal of the state of cryogenic refrigeration technology, comparing how well this technology matches the needs of the HTS power applications.
3) Determination of deficiencies in cryogenic technology that must be mitigated.
4) Identification of the R&D program elements that should be undertaken to fulfill the needs of the HTS power applications, and
5) Development of an appropriate programmatic approach, involving contributions from government, industry and academia, to insure that cryogenic refrigeration technology will be adequately mature to enable practical HTS power applications.

After reviewing the relevant cryogenic technology and the needs of the HTS electric applications, the following recommendations are made:

1) A specific SPI-type program targeted to cryogenic support systems for HTS electric applications is recommended. Cryogenic equipment vendors should lead the effort as this is the center of expertise as well as the future industrial base to support the HTS electric applications. It may be possible to leverage similar efforts in DOD.
2) Standardization across devices is strongly recommended where feasible. This appears possible for motors, generators, transformers, FCLs, HTS coils and perhaps, cables. This approach will enable the focused R&D resources to benefit the most applications.
3) The Stirling (valveless) pulse tube shows promise with no moving parts in the cold section of pulse tube and drive units that can be oil-free with non-wearing internal parts. Reliability and efficiency have the potential to approach the Cryogenic Roadmap goals.
4) Single-stage G-M cryocoolers are the workhorses of the present SPIs and their potential needs to be determined relative to that of pulse tube cryocoolers.
5) For HTS cables, the availability of cryocoolers that can provide 1-2 kW at 70-80 K with performance near Cryogenic Roadmap goals would be an attractive solution relative to the physically larger Brayton and Claude Cycles with helium or nitrogen as the cycle fluid.
6) Consider a parallel program, especially for cables, on lowering cryostat heat losses (i.e. lower the system heat load-W/m) and improving cryostat reliability (solve the problem of high vacuum degradation). The initial effort led by NASA-Kennedy Space Center shows promising results for flexible cryostats.

Cryogenics Assessment Report

M. J. Gouge, J. A. Demko and B. W. McConnell, ORNL
J. M. Pfotenhauer, University of Wisconsin

Introduction and background

DOE and the national laboratory, industrial and university teams working on electric system applications of high temperature superconductors have long recognized the importance of cryogenics as an enabling technology. A workshop was held at the 1998 DOE Peer Review entitled *Cryogenic Needs of Future HTS Electric Power Equipment.* This workshop examined the state-of-the-art in cryogenic components and estimated performance requirements when used with HTS electric power systems. A second, follow-up workshop was held at the 1999 DOE Peer Review, which identified the key issues in employment of cryogenic support technology as efficiency, reliability and cost. The participants formed a steering committee to develop a Cryogenic Roadmap. Various versions of the Roadmap were drafted in 2000-2001, with the latest version dated June 2001 and available on the internet at the ORNL HTS website (see reference 1). Tom Sheahen presented the final version of the Cryogenic Roadmap at the January 2000 Wire Development Workshop. The Cryogenic Roadmap articulated performance goals for cryogenic support systems. An *Implementation Plan for Cryogenic R&D in Support of HTS Program* was issued in May 2001. This document, edited by Tom Sheahen and Ben McConnell, is also on the ORNL HTS website (see reference 2).

Objectives of the present effort

The principal objectives of this effort are:

1) Determination of the characteristics (performance, cost, reliability) of the cryogenic refrigeration systems that are expected to be required for use in HTS power applications in the near future (2 years), in the medium future (5-10 years), and in the far future (> 20 years).
2) Critical appraisal of the state of cryogenic refrigeration technology at the present time, comparing how well this technology matches the expected needs of the HTS power applications.
3) Determination of obvious deficiencies in cryogenic technology that must be mitigated if the technology is to satisfy the needs of the HTS power applications.
4) Identification of the areas of research and development that must be undertaken to fulfill the needs of the HTS power applications, and
5) Presentation of appropriate programmatic approaches, involving contributions from government, industry and academia, to insure that the cryogenic refrigeration technology will be adequately mature to meet the needs of the HTS power applications in the next ten to twenty years.

The present assessment involved interviews (during the period October 2001-January 2002) with individuals from cryogenic industry, the Superconducting Partnership Initiative (SPI) teams, electric utilities, national laboratories and universities active in cryogenics. A presentation of status and initial recommendations was made at the 2002 Wire Development Workshop in January 2002. This report was drafted in February 2002 and issued in March for comment. A final report to DOE with recommendations will be issued in late March 2002. A competitive DOE cryogenic R&D initiative is proposed in early FY 2003, depending on the availability of funds.

Broad goals from the Cryogenic Roadmap

The Cryogenic Roadmap presents three broad goals for cryogenic support systems for electric applications:

1. Increase reliability to allow availability of 99.8%

This is the availability of the cryogenic subsystem including controls. Recent feedback from industry indicates that the HTS power component itself requires 99.8-99.9 % availability: this means the cryogenic subsystem needs 99.9% and higher reliability; this is about one 8-hour shift of unavailability per year.

2. Increase efficiency to achieve 30 % of Carnot

Some ways to increase efficiency may lower reliability: for example going from 1 to 2 expanders in a Brayton Cycle. The reliability can be increased through redundancy but this impacts front-end cost.

3. Decrease cost from $100 to $25/W at ~ 65-80 K

The least painful way to do this is to increase the production base and use standardized components.

Technical Background

A block diagram of a typical cryogenic refrigerator is shown in Figure 1 below. There is a heat load at the cold temperature (T_c) the HTS device wants to operate at. This heat load can be from the environment, typically radiation, solid/gas conduction and fluid convection from adjacent regions or structures at higher temperatures (for example, a liquid nitrogen heat shield at 77 K or the warm end of a current lead at 300 K). The heat load can also be internally generated in the component from sources such as ac losses and eddy currents in conductors. The heat from the load is transferred to the cold region of the refrigerator (for example, the cold head of a GM cryocooler) by solid conduction or fluid convection. Therefore, there has to be a small temperature difference (typically a few degrees Kelvin or less) between the cold region of the refrigerator and the slightly warmer HTS load. The working fluid (typically but not exclusively helium gas) in the cold section of the refrigerator absorbs this heat and flows next to a heat exchanger where this fluid is further heated by exchange with a counterflow gas stream. From there it enters a compressor where external work is done on the fluid compressing it to high pressures and further increasing the fluid temperature. After this the fluid flows to an ambient heat exchanger where the heat of compression is rejected near room temperature (at T_h). Next the fluid goes to the heat exchanger discussed above where it is further cooled by rejecting heat to the counterflow gas stream or regenerative matrix. From here the cold fluid can go to the load or be further cooled by expansion of the fluid to remove energy. If the working fluid temperature is below the inversion temperature (~45 K for helium), a Joule-Thompson expansion can reduce the temperature an additional amount. For an ideal process it can be shown that the efficiency (more precisely, this is called the coefficient of performance since it can be >1) of such a refrigerator is:

$$\eta_{Carnot} = \frac{T_c}{T_h - T_c}$$

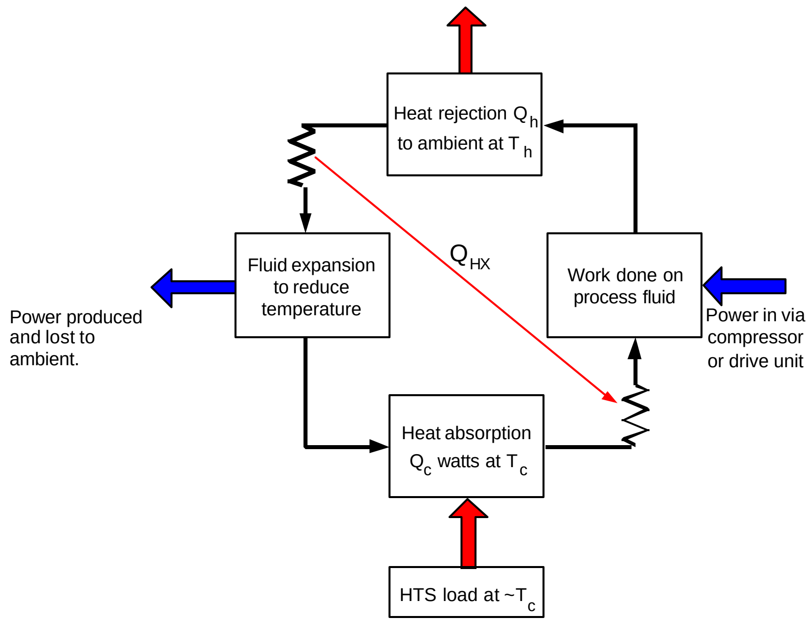

Figure 1. A typical cryogenic refrigerator

Several observations can be made. To begin with, part of the attraction of HTS electric applications is the fact that T_c is in the range 25-80 K compared to 4-10 K typical of low temperature superconductors; this results in higher Carnot efficiencies and means that the cryogenic refrigerators for HTS can be smaller. Also heat should be rejected at as low a temperature as practical; usually this is room or ambient temperature. Real refrigerators typically run at a fraction (less than 10 % and up to 30%) of Carnot efficiency due to losses in compressors, heat exchanger effectiveness, etc. The inverse of the Carnot efficiency is called the Carnot specific power and is the number of watts required at ambient to provide 1 watt of refrigeration at the lower operating temperature T_c.

Operating Temperature (assume heat rejection temperature is 303 K)	Carnot specific power (W input per W lifted)	Typical specific power for >100 W heat loads (W input at 303 K per W lifted at T_{op})
273 K	0.11	~ 0.4
200 K	0.52	~ 2
150 K	1.01	~ 4
100 K	2.03	~ 8-10
77 K	2.94	~ 12-20
50 K	5.06	~ 25-35
40 K	6.58	~ 35-50
30 K	9.10	~ 50-90
20 K	14.15	~100-200

Table 1. Carnot (ideal) and typical specific power for operating temperatures from 20-273 K

In Table 1, the Carnot (ideal) specific power and a more realistic specific power accounting for the typical performance at 10-30 % or less of Carnot efficiency is shown for operating temperatures from 20-273 K. The heat rejection temperature is assumed to be 303 K.

SPI overview

Table 2 below lists cryogenic technology used to date and planned for the future in DOE Superconducting Partnership Initiative (SPI) project devices listed in the first column. In some cases for past SPIs, the cooling system is not necessarily the optimum for the eventual long lifetime utility or industrial application but could have been chosen based on available equipment or minimal cost. Note that almost all the SPI projects plan to move to cryocoolers.

SPI	**Cryogenic technology used to date**	**Cryogenic technology planned**
HTS industrial motor	Reverse Brayton, G-M single-stage cryocoolers	G-M single-stage cryocoolers, pulse tube cryocooler
HTS generator	N/A	G-M single-stage cryocoolers, pulse tube cryocooler
HTS transformer	G-M 2-stage cryocooler(s), LN with sub-cooling	G-M single-stage and pulse tube cryocoolers, LN with sub-cooling
HTS cable	Open-cycle LN with sub-cooling, Reverse Brayton	Reverse Brayton, Claude, large capacity cryocooler
FCL	G-M single-stage cryocoolers (3+6)	TBD
SMES, magnetic separation, MRI, flywheel bearings	G-M 2-stage cryocooler	G-M single-stage cryocoolers, pulse tube cryocooler

Table 2. Cryogenic technology used in SPI projects

Summary of heat loads

Table 3 below summarizes the order of magnitude of the heat load of HTS electric components at their operating temperature. There is a column for both 1st generation tape (BSCCO) and second generation tape (YBCO) which will operate at different temperatures if the application has to function in significant magnetic fields.

HTS Component	**BSCCO Heat load, T_{op}**	**YBCO Heat load, T_{op}**
Cable (per phase)	3-5 kW/km at 65-80 K	3-5 kW/km at 65-80 K
Transformer (5-100 MVA)	50-100's W at 25-45 or 65-80 K	50-100's W at 60-80 K
Motors (1000-10000 HP)	50-200 W at 25-40 K	50-200 W at 50-65 K
Generators (10-500+ MWe)	100-500 W at 25-40 K	100-500 W at 50-65 K
FCLs	30 W at 30 K, 750 W at 80 K	~ kW at 50-80 K
SMES, magnetic separation, MRI, etc.	10's of watts at 20-30 K	10-100 W at 50-65 K

Table 3. Typical or anticipated heat loads at T_{op} for HTS components

Cryogenic System Considerations for Electric Systems

In each section below cryogenic systems for major HTS applications (synchronous machines, transformers, cables) are discussed. These sections were initially developed as stand-alone documents so there may be some overlap of content.

Cryogenic System Considerations for HTS Synchronous Machines

Potential applications of HTS conductors in the rotating dc field windings of synchronous machines include:

- Industrial motors at 1-10 MW, ~1800 rpm
- Propulsion motors at 5 MW-30 MW, 100's of rpm
- Electrical generators at 100's of MW, 3600 rpm
- Propulsion and distributed generation at few-30 MW, 3600 or higher rpm

For BSCCO HTS conductor, the typical operating temperature (T_{op}) is 25-40 K. For the 2nd generation YBCO conductor the expected operating temperature is higher, perhaps 50-65 K[1], but likely lower than 77 K in order to achieve desired performance at the higher magnetic fields needed in rotating machines. The refrigeration load at the operating temperature is a small fraction of the machine's electrical rating. Motors or generators rated at 10's of MWe typically have thermal loads of a few hundred watts or less at T_{op}. When the machine output is increased to 100's MWe, the thermal load increases but at a slower rate than the linear increase in machine rating, still being less than 500 W at T_{op} for the largest generator electrical outputs. This is because the cryogenic loads are a combination of terms that include current leads (which increase linearly with field coil current) and other terms such as torque tube conduction, transfer coupling losses and radiation from ambient surfaces which increase less than linearly with machine output power. This is in contrast to cables where the thermal and ac losses increase directly with the cable length and transformers where there is an additional ac loss term as well as the heat load from current leads. For synchronous machines with dc field windings, there is no direct ac loss term, but rather an additional heating term in transients and faults that has to be accommodated in cryogenic system capacity or by thermal inertia.

One can crudely subdivide the cooling system for the rotating HTS field windings into two sub-systems: 1) a cryocooler or refrigeration cycle providing a solid mass near T_{op} or a cryogenic fluid near T_{op} and 2) a heat transfer system that links this point with the rotating HTS field coil via piping, transfer couplings, solid conductors, etc. The second system is more tightly coupled to the specific machine design and will not be considered further except to note that it has to be simple in concept and highly reliable as it is captured inside the synchronous machine and subject to a variety of static and dynamic loads. The first system is of direct interest as it is a product that the cryogenic industry will have to develop as part of the enabling technology for HTS electrical applications.

The cryogenic system requirement for the HTS synchronous machines in utility or transportation applications can therefore be broadly stated at 100-500 W at 25-40 K for BSCCO and 50-65 K for YBCO (see Table 3 above). As noted above, the Cryogenic Roadmap has three broad goals for cryogenic support systems:

1. \$25 per W of cooling at T_{op} (T_{op} is about 65-80 K; the intent is to reduce the normalized cost about a factor of four from today's values).
2. efficiencies about 30% of Carnot
3. availability > 99.8% (i.e. on-line for > 364 days/year)

For HTS synchronous machines, the overriding factor is goal 3, the cryogenic system availability. Since the refrigeration loads are modest for synchronous machines relative to the device's electric rating, the cryogenic cost and efficiency goals are desirable but not technology drivers. For example, if a 1000 MWe HTS generator had a heat load of say 500 W at T_{op} , the cryogenic system cost using today's figure of merit of \$100/W, would be \$50K. It would be desirable to reduce this by 2-4 but the incremental savings in purchase price would be less than 1% of the overall generator cost. On the efficiency issue, a doubling of the efficiency from 15% to 30% of Carnot (T_{op} = 30K) would decrease the room temperature power requirement from 30 kW to 15 kW. This is beneficial but the 15 kW savings is a very small fraction of the generator rating of 1000 MWe. The availability goal, however, is crucial to this technology especially for the larger machine ratings typical of base generation for utilities and ship propulsion for motors. In fact, even higher targets of 99.9% are desirable[2]. This is downtime of a fraction of a day per year and reflects the value of the base generation asset to the electric utility.

The refrigeration technology to provide on the order of 100-500 W at T_c has in the past been typically met by reverse Brayton cycles or, more recently, G-M cryocoolers. A new generation of single-stage G-M cryocoolers has been developed with capabilities of 100+ W at T_{op}[3]. This capability fits well with the cryogenic heat loads of synchronous motors and generators at ratings from a few-1000 MWe. Development in the G-M cryocooler line that would benefit the next generation of synchronous machines would include increases in unit performance from about 100 W at T_{op} to several hundred watts and increases in reliability and required maintenance intervals. A related technology with potential for increases in reliability is pulse tube cryocoolers[4] as they have no moving parts at the cold section. Pulse tube cryocoolers have been designed with a goal of order 1 kW at 77 K[5]. The unit would have about 350 W capacity at 50 K; the capacity at lower temperatures required for BSCCO tapes is not stated.

For HTS synchronous machines, the following areas are recommended for targeted development:

1. Capacity, reliability and maintenance interval improvements to single-stage G-M cryocoolers.
2. Development of pulse tube cryocoolers with capacities of order 100 W at 30K to several hundred watts at 50-65 K and improved reliability and reduced maintenance compared to state-of-the-art G-M cryocoolers.
3. Standardization of cryocoolers should be considered.

Cryogenic System Considerations for HTS Transformers

High temperature superconducting transformers have potential advantages over conventional units of similar capacity. First, they are expected to be smaller and lighter in weight. Second, the life of a conventional transformer is shortened when running the unit near full capacity. HTS transformers do not suffer from the insulation degradation when run at full capacity and, if so designed, can even tolerate being operated at up to twice rated capacity without loss of life, provided that sufficient incremental cooling is available to maintain the HTS materials in a superconducting state. Finally, oil and its potential fire hazard is eliminated in the transformer unit.

There are two basic approaches for cooling HTS transformer coils. One approach involves a bath cooling of the transformer coils in liquid nitrogen (LN). A second approach, using closed cycle cryocooling, allows the coils to be cooled to as low as about 25K. The LN systems can in principal be operated in a closed cycle with cryocooling or in an open cycle with replenishment of the stored LN. The second approach using cryocoolers can support lower operating temperatures, thereby providing improved current capacity in any of several candidate HTS conductor types in order to allow an optimization of the combination of conductor cost and refrigeration cost. This applies for both first and second generation HTS conductor and can include MgB_2. A disadvantage of the lower temperature operation is that any ac losses must be removed at that temperature.

Temperatures are maintained by thermally isolating the transformer from the surroundings and external heat loads by a cryostat. The thermal loads that determine the required refrigeration capacity can be broken down into static loads that come from having to maintain the HTS transformer system cold in a warm ambient environment, and dynamic loads that depend on the ac losses associated mainly with the electrical loading of the HTS transformer system. The static loads are present at all times and are a significant but smaller fraction of the total thermal load on the HTS transformer system under normal operation. Dynamic loads normally exceed the static loads at rated operation and can greatly increase under overload conditions.

Specially designed leads make the transition from the conventional grid at ambient conditions to the superconducting transformer coils at temperatures below 80 K. The refrigeration load at the operating temperature is a modest fraction of the machine's electrical rating, even when multiplied by a refrigeration coefficient of performance that determines the amount of compressor power required for a given loss at any particular temperature. HTS transformers rated at 10's of MVA are expected to have thermal loads of a few hundred watts or less at T_{op}. When the transformer rating is ~ 100 MVA, the thermal load will be larger but less than would be expected from a linear increase in machine rating.

As in synchronous machines, one can crudely subdivide the cooling system for the HTS transformers into two sub-systems: 1) refrigerator and 2) means for conveying heat to the refrigerator. The second system is more closely coupled to the specific system design and will not be considered further. Refrigerator compressor power tends to be continuous and is comparable to the substantial no-load losses of the transformer. Reliable continuous operation with a minimum of maintenance is paramount and for HTS transformers, the dominant factor is also goal 3 from the Roadmap.

For example, if a 30 MVA HTS transformer had a heat load of say 200 W at T_{op}, the cryogenic system cost using today's figure of merit of \$100/W, would be \$20K. It would be desirable to reduce this by factors of 2-4. Medium to large conventional power transformers operate in the 99.7% to 99.9% efficiency range. A doubling of the cryocooler efficiency from 15% to 30% of Carnot (T_{op} = 30K) may decrease the room temperature input power from 12 kW to 6 kW, which is small relative to the 30 MVA rating, but is still significant relative to the total losses of order 30-90 kVA. The availability goal is crucial to this technology especially for the larger device ratings. This downtime of a fraction of less than a day every year reflects the value of the continuous operation of the medium power transformer in the electric utility.

The refrigeration technology to provide of order 100-500 W at T_c meshes well with a new generation of single-stage G-M cryocoolers with capabilities of 100+ W at T_{op}[3]. This capability fits well with the cryogenic heat loads of transformers at ratings from 10-100 MVA. Development in the G-M cryocooler line that would benefit the next generation of transformers would include increases in unit performance from about 100 W at T_{op} to several hundred watts and increases in reliability and required maintenance intervals. A related technology with potential for increases in reliability is pulse tube cryocoolers[4] as they have no moving parts in the cold section. Thus pulse tube cryocoolers could be relevant to both HTS synchronous machines and transformers.

A load following capability is desired in the cryogenic refrigerator system. When the transformer is operating at a reduced load, existing cryocooler technology that operates at a single compressor setting will tend to cause the HTS transformer to operate at lower temperatures, due to decreased ac losses. If the cryogenic refrigerator can be turned down to match a lower load on the transformer, and reduce the energy consumed by the refrigerator, an additional energy savings is achieved. With present cryocooler technology, refrigerators and compressors are sized for the peak load and run with a near constant compressor power even when the heat load is much reduced. As much as a factor of four savings in compressor power for refrigeration of the dynamic, (major) heat load is possible if the compressor operation could be adjusted to run in proportion to the load through the diurnal and seasonal load cycles of the transformer.

RECOMMENDATIONS

For HTS transformers, the following areas are recommended for targeted development:

1. Capacity, reliability and maintenance interval improvements to single-stage G-M cryocoolers.
2. Development of pulse tube cryocoolers with capacities of order 100 W at 30K to several hundred watts at 60-80 K and improved reliability and reduced maintenance compared to state-of-the-art G-M cryocoolers.
4. Development of a load-following capability.
5. A method of removing a cryocooler without warming up the transformer for cryocooler maintenance or replacement.

Standardization is a key factor in reducing costs and providing reliability. Standard parts, "one size fits all" would be better approach than individual design for each HTS transformer system.

Utilities continue to move toward unmanned operation. Thus a key component is instrumentation and needed experience with unattended operation. Lower cost cryogenic instrumentation is a must if costs are to be reduced. Desired features for any power application are modular units, low maintenance and high reliability.

In addition, research that reduces system heat loads should be an objective. The sources of heat load to the HTS transformer system are the static load from the vessel containing the superconducting components, followed by reductions in the dynamic load from ac losses.

Cryogenic System Considerations for HTS Power Cables

HTS CABLE REFRIGERATION OVERVIEW

To deploy an HTS power cable, it must be maintained at operating temperatures typically below 80 K. This is accomplished by thermally isolating the cable from the surroundings and external heat loads by a cryostat. The HTS cable is electrically connected at the ends to an electrical supply and load using a termination. The termination also provides for ambient temperature electrical connections to the HTS cable. For dc operation below the critical current of the HTS cable, there would be minimal internal heat generation. Under ac operation, heat generation from the ac losses and dielectric losses are present which contribute to the refrigeration load of the HTS cable system.

COST

The cost target of $25/W for a HTS cable cryogenic system was mentioned in the Cryogenics Roadmap. The engineering costs of designing the system and the specialized fabrication procedures required are important cost factors. The engineering costs could be reduced by standardizing the systems to basic building block refrigeration capacities. Standardization of the refrigeration systems could be done in terms of length of the HTS power cable as discussed in the section regarding thermal loads. It is difficult to estimate how much the cost of cryogenic refrigeration systems will drop. If it is assumed that the engineering costs are eliminated by standardizing the cryogenic refrigeration system design, one could expect that the cost should drop to around 80% of present day cost. There may be some other reductions that arise from mass production of some system components. Others system components, such as the compressors, may already be in mass production and would realize smaller price reductions as the number of units produced increases.

THERMAL LOADS

The thermal loads that determine the refrigeration capacity required come from the termination and the cable. They can be further broken down into static loads that come from having to maintain the HTS cable system cold in a warm environment, and dynamic loads that depend on the electrical loading of the HTS cable system. The static loads are present at all times and are a large fraction of the total thermal load on the HTS cable system.

The terminations located at each end of the HTS power transmission cable must provide a room temperature connection to the electrical network as well as the cryogenic liquid couplings that provide supply and return locations for the liquid nitrogen coolant to the cable. For a high-current connection, McFee (reference 3) demonstrates that the minimum heat load between 300 K and 77 K is around 45 W/kA for a conduction-cooled, copper conductor in a vacuum at full current. In a shielded (co-axial) HTS cable, two current connections are required at each end. If for example 2 kA is the desired rating, this results in at least 180 W per termination from the current leads alone. A standard bayonet connection to the HTS cable end contributes about 20 W (depending on the size). Other heat loads are present because of the finite size of the termination. Previously measured heat loads on a typical termination were around 300 W (reference 4). The heat load (in watts) for a termination on one end of the HTS cable system can be estimated by equation [1] with N_e electrical connections, I_e the capacity of the connection in kilo-amperes, and an additional heat load from the environment of $Q_{env.}$

$$Q_{end} = 45 \times N_e \times I_e + Q_{env} \qquad [1]$$

The environment heat load depends on the physical size of the termination and could be as much as 200 W. The physical size of the termination is determined by several factors including the number of cable phases contained in the termination and the voltage rating.

The HTS cable thermal loads are determined on a unit length basis so the total refrigeration load depends on the length of the cable. The static load from the environmental heating depends on the thermal performance of the cryostat used in the system. At least two configuration options are available. In one configuration, the three phases are contained in three separate cryostats, and the second configuration all three phases are in a single larger cryostat. The HTS cable cryostat typically is a flexible double-wall construction with vacuum multi-layer insulation (MLI). The ambient sink temperature, $T_{¥}$, could range from 245 K to 320 K depending on the HTS cable location and time of the year. The performance of several thermal insulation systems for both rigid and flexible piping, or cryostats, for use with HTS is addressed in two papers by Fesmire et al. (references 5, 6). The first paper compares the thermal performance of rigid and flexible cryostats with different insulation systems. Fesmire indicates that the flexible cryostat will generally have higher heat loads than a rigid cryostat due in part to the corrugated geometry of the tube walls. In the second paper, Fesmire investigates the additional heat load from simulated spacers and bending of a cryostat. The degradation in overall thermal performance was reported to be typically greater than 50 percent at high vacuum conditions. Typical commercially available vacuum-insulated flexible cryostats have an effective or actual field-installation thermal conductivity, k_{oafi}, of 0.001 W/m-K. The local heat transfer through the cryostat per unit length can be calculated using Eq. (2) and depends on the local liquid nitrogen temperature, T_v, and the cryostat inner and outer tube diameters, D_{ci} and D_{co}. The temperature difference driving this heat-transfer term is typically more than 220 K for the outer cryostat.

$$Q = \frac{2p k_{eff} L (T_\infty - T_v)}{\ln\left(D_{co}/D_{ci}\right)} \qquad (2)$$

The dynamic loads are the AC and dielectric losses. The sum of the ac loss and dielectric loss are around 1W/m-phase. The dielectric losses are typically modest at distribution level voltages, of order 0.05 W/m-phase. They must be accounted for at higher transmission-level voltages.

Applying these principles to a 1000-meter long HTS cable system results in a thermal load of around 8 kW of refrigeration for a single cryostat, two-termination HTS cable system or 12 kW of refrigeration for a HTS cable system using three separate cryostats and six terminations. These loads are significantly larger and are at somewhat higher temperatures (65 K – 80 K) than the heat loads on HTS synchronous machines and transformers.

CRYOGENIC REFRIGERATION

The refrigeration of an HTS power cable is the price that must be paid to run the cable. The typical operating temperature range is expected to be between 65 K and 80 K. The ideal amount of work required for each unit of refrigeration is determined from a Carnot refrigeration cycle. The specific power figure-of-merit is around 3.2 W/W for an ideal, or Carnot cycle operating at 70 K. A Carnot efficiency of 30% that corresponds to a refrigeration penalty of 10 W/W or less could help increase the use of HTS power applications. This level of performance is not yet available, but is being approached. For practical applications, a balance between complexity of the cycle, reliability, and efficiency must be achieved. The field demonstration project at Detroit Edison will utilize a dual-expander, reverse Brayton cycle refrigerator (reference 7). Saji et al. (reference 8) have proposed a cycle that uses two expanders and a mixture of helium and neon as the working fluid that has a specific power of 12.1 for conventional cable applications.

An excellent study of refrigeration cycles for HTS cable applications has been done by Fleck et al. (reference 9). In this paper, Fleck describes different cooling cycle options including reversed Brayton cycles using gas mixtures, and Claude cycles based on nitrogen. One significant conclusion of this work is that the efficiency of the refrigeration cycles proposed for HTS applications is limited mostly by the compressor system performance.

INDUSTRY FEEDBACK

Some informal discussions were conducted with different individuals from companies interested in HTS cable manufacturing, electric utilities, and refrigerator manufacturing. The various individuals involved offered their best insights at this time to the research and development needs for cryogenic refrigerators needed in HTS cable applications. In general the utility position comes down to the following key points:

- Minimize footprint
- Increase reliability
- Consistent with the footprint, minimize size
- Keep cost competitive in terms of benefits
- Stored LN backup may not be practical.

These five key points are top-level objectives that are thought to be important for the widespread commercial application of HTS cable systems by the electric power utility companies. Some of the technical issues and some potential research paths to achieve these objectives that were identified are briefly discussed below.

Standardization was described as a key factor in reducing costs and providing reliability. Standard parts, "one size fits all" would be better approach than individual design for each HTS cable system. Standardize components or use standard components (compressors, pumps, cold box). Redundant systems are required for higher system availabilities. For example, the utility replaces a single component, the cable, with two components, the cable and refrigerator or cryocooler. The net result is that both must be more reliable than the conventional copper cable.

There was input from several sources on the attractiveness of kW-level Stirling single-stage pulse tube cryocoolers (discussed above for synchronous machines and transformers) even for cables, particularly if efficiencies 20-30% of Carnot can be achieved. One could use a cryocooler on each end for the 3-phase terminations and use a cryocooler periodically spaced (every few 100 m) along the length of the cable to take out the heat input from cryostat thermal and internal ac losses. With such a concept, an extra cryocooler could be implemented for redundancy. It was felt this relatively simple and compact cooling concept would be more attractive to utilities than a large refrigeration plant. The use of compact cryocoolers distributed along the length of the cable could reduce reliability unless temporary operation at somewhat higher temperatures can be maintained in a "gapped" position due to the loss of a single cryocooler. This distributed approach would require additional space in manholes as well as power and cooling water for the cryocoolers.

Utilities continue to move toward unmanned operation. Thus a key component is instrumentation and needed experience with unattended operation. Lower cost cryogenic instrumentation is a must if overall costs are to be reduced. What minimum instrumentation is needed or required for safe operation? This question is not always considered part of a traditional research project.

The operating conditions for equipment are very stringent. Installations must operate between 245 K to 320 K. As an example, the Detroit Edison/Pirelli/DOE project had to install compressor oil heaters because of cold weather conditions.

A back-up refrigeration system using LN is being implemented by the Detroit Edison/Pirelli project for up to 3 days of HTS cable operation. A minimum of 2 days is considered a must. The utilities do not like having to rely on trucks delivering LN to sites.

Pirelli is planning to use a nitrogen cycle refrigerator for their HTS cable project with EDF in France. The refrigeration system compressors are conventional units; therefore, it is easier to prevent leaks. Nitrogen is also much easier to work with and much less expensive than helium. Of course, the HTS cable conductor must provide adequate performance at temperatures above 65 K.

Per the roadmap discussion, DOE could look into field testing of refrigeration systems. One idea would be to replace the refrigeration systems at HTS cable sites with improved commercial systems (perhaps a nitrogen-based refrigeration cycle).

The Detroit Edison/Pirelli project suggested that the nitrogen subcooler system should consider a cold compressor for pumping on the subcooled bath as opposed to warm vacuum pumps. One advantage is that the cold compressors could reduce the system footprint.

Cryostat development for HTS cables is another significant technical issue to be addressed. High thermal efficiency at moderate vacuum (1 W/m-phase at 0.1 torr) in a flexible cryostat is a very desirable goal. Since standby and heat influx losses are the largest losses, improved performance would reduce cryogenic load and thereby reduce both operating losses and capital costs of the cooling system.

The HTS cable is a system, cable and cryogenics. Cryogenics research is needed else the system may not meet desired performance goals. Cryogenics is a critical issue for commercialization and needs attention. Refrigeration systems should be pre-commercial or commercial or else the custom nature will raise front-end costs.

What is desirable: modular units, low maintenance and high reliability. DOE should survey to develop some global requirements or specifications to be used in developing cryogenic refrigeration etc. (MJG note: this is actually one of the goals of the effort summarized in this document).

From a cryogenic refrigerator manufacturers viewpoint, much of the needed technology is available in cryogenic refrigeration, but there are no off-the-shelf systems because there has been little demand. Refrigerator manufacturers have built cryogenic refrigeration systems that operate unmanned for large-scale helium systems at high-energy physics laboratories. Other industrial process plants run automated routinely. One issue is that the systems are costly, far from the $25/W target used in the Cryogenics Roadmap.

RECOMMENDATIONS

There are several thrusts for research efforts to support the commercial application of HTS power cables. Research and development is needed to improve existing technology in order that the target efficiency of 30% Carnot can be attained. A primary focus for achieving the higher efficiencies is to reduce the input work, i.e. significantly raise the compressor performance. The performance of other system components is high and although small gains in performance may be achieved, the largest amount of lost work or irreversibility is in the compressor system of a cryogenic refrigerator.

There are difficulties associated with applying refrigerators using helium as the working fluid. Refrigeration cycles based on gas mixtures or gases other than helium (e.g. nitrogen) show some promise. Process simulation is needed to study the different refrigerator system configurations.

Development of kW-level, Stirling single-stage pulse tube cryocoolers at efficiencies around 20-30% of Carnot could provide an attractive alternative to large refrigeration cycle equipment for HTS cables if long maintenance intervals can be demonstrated.

In addition, research that reduces system heat loads should be an objective. The largest source of heat load in a long HTS cable system is the static heat load in the flexible cryostat, followed by the dynamic heat load from ac losses in the HTS tapes.

Cryogenic Systems

There are a number of options for cryogenic systems (see references 10 and 11) in electric system applications. Reference 9 has analyzed several classical refrigeration cycles including Brayton and Claude with 1-2 expanders and different cycle fluids. A helium Brayton cycle is being used for the Detroit-Edison/Pirelli cable system demonstration and this cycle has been used in the past on HTS motors. Given the stringent availability goals in the Cryogenic Roadmap, it is prudent to look at liquid cryogens as well as emerging cryocooler technology which is inherently simpler than a standard refrigeration cycle with expanders and compressors.

Liquid nitrogen open cycle systems

An analysis of the use of liquid nitrogen as a consumable (once-through cooling) in lieu of an electric refrigerator is given in Appendix 1 to the Cryogenic Implementation Plan (reference 2). The variables include the cost of nitrogen (which depends on the demand, the cost of electricity, transportation and handling costs), the cost of electricity, the efficiency and purchase price of the cryocooler and the component lifetime. There are scenarios where either approach could be attractive; one study indicates that once-through cooling is the most economical approach for all but larger HTS transformers. There are also factors which could favor refrigerators such as the limited ability of utilities to provide periodic access for filling or concerns on cryogen availability at an attractive price over a 30-50 year component life. Another concern is intrinsic impurity buildup from the supplied nitrogen over time in small diameter sensor or cooling lines. Factors which could favor stored liquid cryogens include ability to handle load variations by variable boil-off rate with little change in system efficiency as well as intentional overloads. A reliability comparison of the two approaches may also influence the decision; the stored cryogen approach needs a cryogenic pump to circulate the cryogen and vacuum pumps for subcooling but does not require a compressor if the supplied cryogen is viewed as a commodity. An interesting system design approach is a hybrid system where stored cryogens are used for back-up cooling capacity and/or incremental capacity so the electrically-powered refrigerator can be chosen with a rating closer to the average rather than peak thermal load. This also enhances the cooling system reliability. For the purposes of this assessment, it is assumed that the use of liquid nitrogen is a mature technology with known cost and reliability.

Cryocoolers

The workhorse of the present SPIs is the G-M cryocooler as shown in Table 2 above. Table 4 below is a summary of cryocooler technology, courtesy of Marty Nisenoff.

SPECIFICATIONS FOR SELECTED LARGE CRYOCOOLERS

PRODUCT	TYPE	INPUT POWER	WEIGHT	COOLING CAPACITY	COP
CRYOMECH 330	G-M	7.4 KW	-	300 W @ 77 K	12%
CTI M 1050	I STAGE GM	5.5 KW	126 kg	100 W @ 80 K	5%
APD DE-108	G-M	4.5 KW	100 kg	100 W @ 77 K	6%
CRYOMECH AL-200	G-M	5 KW	160 KG	180 W @ 80 K 120 W @ 60 K	10 % 9.6 %
STIRLING C&R LPC-01	STIRLING	12 KW	850 KG	500 W @ 65 K	15%
STIRLING C&R LPC-02	STIRLING	25 KW	1500 KG	1300 W @65 K	18%
STIRLING C&R LPC-04	STIRLING	60 KW	3750 KG	2800 W @ 65 K	17%
STIRLING C&R LPC-08	STIRLING	135 KW	7500 KG	5800 W @ 65 K	16%
STIRLING C&R SPC-01	STIRLING	11 KW 7.6 KW 5 KW	600 KG	1050 W @ 80 K 2,250 W @ 150 K 3,450 W @ 250 K	26 % 29 % 13 %
STIRLING C&R SPC-04	STIRLING	45 KW 31 KW 20 KW	1255 KG	4,500 W @ 80 K 9,500 W @ 150 K 14,500 W @ 250 K	27 % 31 % 15 %
PRAXAIR (Under Development)	LINEAR STIRLING	20 KW	450 KG	1,500 W @ 80 K 2,100 W @ 100 K 3,400 W @ 130 K	20 % 21 % 21%
GEA (Germany)	LINEAR STIRLING	2.6 KW	70 KG	150 W @ 77 K 235 W @ 109 K	17 % 16 %
AISIN SEKI Model SC	LINEAR STIRLING	14 KW	-	1000 W @ 77 K	20%
AISIN SEKI Model SS	LINEAR STIRLING	6 KW	-	400 W @ 77 K	20%

Table 4. Cryocooler state-of-the-art

The last column that is labeled COP is the percent of Carnot efficiency at the specified temperature. As can be seen, there is a wide variation in efficiency relative to Carnot with the larger capacity units running closer to ideal performance. The cryocooler unit shown in the first row is a popular cryocooler in the DOE SPI projects as well as several DOD R&D projects. More complete data for this unit is provided at the internet address given in footnote 3. This single-stage G-M cryocooler provides about 100 W at 30 K, values close to the operating temperature and heat load of several synchronous machines and transformers using BSCCO tape (more recent vendor information indicates the compressor power has been reduced to 7 kW). Note that the fraction of Carnot efficiency at 30 K is also about 12 %. Most G-M cryocoolers use water- or air-cooled compressors with oil lubrication. Two-stage G-M cryocoolers are used to achieve temperatures below 20 K. Routine maintenance is recommended every year to replace the displacer seals and every 15,000 hours to replace the compressor oil absorber. These preventive maintenance actions can be done in less than 1 day.

Stirling (valveless) pulse tube cryocooler concept

The cryogenic industry and superconducting applications staff interviewed were generally enthusiastic about the potential of pulse tube cryocooler technology. Because of this and other assessments of prospects for this cryocooler concept, a short discussion of the technology is provided below. Pulse tubes have been designed and tested in a wide variety of configurations. However, one of the more simple configurations would most likely be attractive for HTS applications. A sketch of this simple, Stirling-type orifice pulse tube is shown in Figure 2 below. Unlike G-M cryocoolers, there are no moving parts in the cold section, a feature that should result in lower scheduled maintenance and higher reliability. The cycle is implemented by an effective gas piston in the pulse tube section.

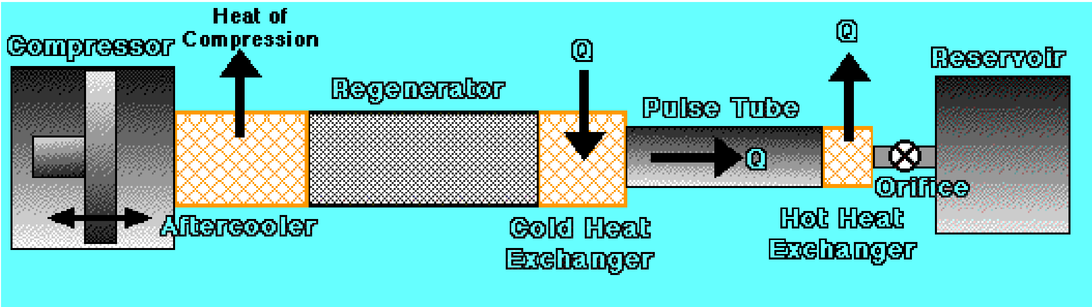

Figure 2. Pulse tube cryocooler components

The ideal efficiency of a Stirling pulse tube is given the simple equation below (reference 12):

$$h_{\mathrm{ideal}} = \frac{T_c}{T_h}$$

Note this is somewhat less than the ideal efficiency of a G-M cryocooler. For cryocoolers operating between 300 K and 30 K, the G-M ideal efficiency would be 1/9 while the pulse tube ideal efficiency would be 1/10. Thus, to achieve equal or better efficiencies than G-M cryocoolers, pulse tube cryocoolers have to minimize the non-ideal losses in the compressor or drive unit and regenerator beyond what has been achieved in GM cryocoolers. In one compilation of performance results at 80 K, Radebaugh shows that Stirling-type pulse tubes are in fact demonstrating higher efficiencies than both GM and Stirling cryocoolers. The world record for efficiency to date is 25% of Carnot at 80 K. This was achieved by TRW in a Stirling-type pulse tube of approximately 7 W capacity. A drive unit currently used on a prototype pulse tube under development is shown in Figure 3.

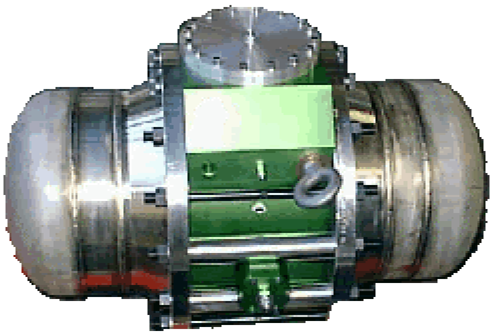

Figure 3. Drive unit (courtesy of CFIC, Inc.)

This is a valve-less, electroacoustic device that produces alternating pressure and volume flow in a pressurized gas. It is oil free, has non-wearing surfaces and produces low noise and vibration. The unit shown has 20 kW input power, weighs 1000 lb with all ASME code required structure, and has dimensions of 24" x 24" x 38". Pulse tube cryocoolers (Stirling or acoustic type), driven by linear resonant motors also offer modulation capability mentioned above as desirable on transformers and cables. This has been demonstrated on machines from 200 to 20,000 watts electrical input, turning down the cooling (rated 10 to 1300 watts @ 77 K) by more than 80 %.

Recommendations

GENERAL RECOMMENDATION

A specific SPI-type program targeted to cryogenic support systems for HTS electric applications is recommended. Cryogenic equipment vendors should lead the effort as this is the center of expertise as well as the future industrial base to support the HTS electric applications. Partnering with national labs/university staff where it makes sense to accelerate R&D and provide analytical support is also recommended. Involvement of HTS electric equipment vendors and utilities in an advisory role is encouraged to ensure technology is relevant. It may be possible to leverage similar efforts in DOD and NASA.

SPECIFIC RECOMMENDATIONS

1. Standardization across electric power devices is strongly recommended where feasible. This appears possible for motors, generators, transformers, FCLs and HTS coils. For cables, especially > km lengths, the heat loads are substantially larger but it may be possible to use kW-level cryocoolers on the end terminations and periodically along the cable. This approach will enable the focused R&D resources to benefit the most applications. It will also result in more units produced per year which can lower cost and increase reliability. In Appendix II, we provide a draft specification that could be used in a statement of work.
2. The Stirling (valveless) pulse tube shows promise with no moving parts in the cold section of pulse tube and drive units that can be oil-free with non-wearing internal parts. Reliability and efficiency have potential to approach the Cryogenic Roadmap goals.
3. Single-stage G-M cryocoolers are the workhorses of the present SPIs and their potential needs to be determined relative to that of pulse tube cryocoolers.
4. For HTS cables, the availability of 1-2 kW at 70-80 K cryocoolers with performance near Cryogenic Roadmap goals would be an attractive solution relative to Brayton and Claude Cycles with helium or nitrogen.
5. Consider a parallel program, especially for cables, on lowering cryostat heat losses (i.e. lower the system heat load-W/m) and improving cryostat reliability (solve the problem of high vacuum degradation). The initial effort led by NASA-Kennedy Space Center shows promising results for flexible cryostats.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the various people listed in Appendix I. These individuals that took the time to offer insight, judgments and opinions that assisted in the preparation of this assessment report. This effort would have very little relevance without the inputs of the various industrial parties.

FOOTNOTES

1. It is often assumed that all electrical devices will run at 70-80 K for the second generation HTS conductor. This is not necessarily the case and depends on the conductor performance at specified temperature and magnetic field. For the field coils of synchronous machines with B ~ 4-5 T at the coil, the operating temperature is lower because the irreversibility field of YBCO at 77 K is only 5-7 T.
2. Private discussion, Jim Bray, GE. Note this higher availability can be achieved through redundancy (with cost penalties) or by more robust/simple components.
3. For example see the Cryomech AL-330 G-M cryocooler specification sheet at http://cryomech.com/Cryorefrigerator%20Specification.html
4. See http://ranier.oact.hq.nasa.gov/Sensors_page/Cryo/CryoPT/CryoPTHist.html for a short history of pulse tube cryocoolers.
5. See for example, http://www.cficinc.com/WebPages/NewsOppsPage/Praxbro.pdf

REFERENCES

1. See http://www.ornl.gov/HTSC/pdf/Cryogenic_Roadmap.pdf
2. See http://www.ornl.gov/HTSC/pdf/Cryo_Implement_Plan_5-17-01.pdf
3. McFee, R., "Optimum Input Leads for Cryogenic Apparatus" *Rev. Sci. Instr.* **30**(2), 98-102 (1959).
4. Demko, J. A. et al., "Cryogenic System for a High Temperature Superconducting Power Transmission Cable," *Adv. Cryo. Engr.*, **45**, Plenum Press, New York, 1411-1418 (2000).
5. Fesmire, J. et al., "Thermal Insulation Performance for Flexible Piping for Use in HTS Power Cables," Paper C-06A-01, Cryogenic Engineering Conference, Madison, Wisconsin, July 17–20, 2001.
6. Fesmire, J. et al., "Overall Thermal Performance of Flexible Piping Under Simulated Bending Conditions," Paper C-06A-02, Cryogenic Engineering Conference, Madison, Wisconsin, July 17–20, 2001.
7. Steve, N. et al. "High Temperature Superconducting Field Demonstration at Detroit Edison," *Physica C* **354**, 49-54 (2001).
8. Saji, N. et al., "Design of Oil-Free Simple Turbo Type 65 K/ 6 kW Helium and Neon Mixture Gas Refrigerator for High Temperature Superconducting Power Cable Cooling," Paper C-11E-10, Cryogenic Engineering Conference, Madison, Wisconsin, July 17–20, 2001.
9. Fleck, U., et al., "Cooling of HTS Applications in the Temperature Range of 66 K to 80 K, Paper C-15C-08, Cryogenic Engineering Conference, Madison, Wisconsin, July 17–20, 2001.
10. Giese, R. F., "Refrigeration Options for HTS Devices Operating between 20 and 80 K for Use in the Electric Power Sector," ANL internal report prepared for the IEA (1994).
11. Van Sciver, Steven W., "Cryogenic Systems for Superconducting Devices," *Physica C* **354**, 129-135 (2001).
12. de Waele, A. T. A. M., "Pulse-tube Refrigerators: Principle, Recent Developments and Prospects," *Physica B* **280**, 479-482 (2000).

APPENDIX I

Participants in informal discussions

Stan Augustynowicz	Dynacs, Inc. at Kennedy Space Center, FL
Massimo Bechis	Pirelli Cables, Italy
Jim Bray	General Electric Corporate R&D
John Corey	CFIC, Inc.
Jim Daley	DOE
Russ Eaton	DOE
James Fesmire	NASA, Kennedy Space Center, FL.
Rick Fitzgerald	Praxair
Peter Gifford	Cryomech
Paul Grant	EPRI
Don Gubser	Naval Research Laboratory
Jon Jipping	Detroit Edison, Detroit, MI
Swarn Kalsi	American Superconductor
Nathan Kelley	Pirelli Cables NA, Lexington NC
Ken Kreinbrink	PHPK Technologies, Inc.
David Lindsay	Southwire Co., Carrollton, GA
Winston Lue	ORNL
Jim Maguire	American Superconductor
Alex Malozemoff	American Superconductor
Jerry Martin	Mesoscopic Devices
Marty Nisenoff	Consultant
Chuck Oberly	Air Force Research Laboratory
Ed Pleva	Waukesha Electric Systems
Ray Radebaugh	NIST
Marshall Reed	DOE
Bill Schwenterly	ORNL
Uday Sinha	Southwire Co., Carrollton, GA
John Urbin	Linde Process Plants, Tulsa, OK
Don Waltman	Consultant
Mike Walker	IGC Superpower
Yu Wang	General Electric Corporate R&D
Phil Winkler	Air Products
Alan Wolsky	ANL
Burt Zhang	Rockwell

APPENDIX II

Draft Specification for Standardized Cryocoolers

Parameter	**HTS-1** (BSCCO motor/generator/ transformer)	**HTS-2** (YBCO motor/generator)	**HTS-3** (YBCO transformer)	**HTS-4** (BSCCO or YBCO cable)
Range of operation (K)	25-40	50-65	60-80	65-80
Capacity (W) at midpoint of temperature range	200	300	300	1500
Capacity (W) at low end of temperature range	140	210	210	1050
Efficiency (% Carnot)	25 min 30 goal	25 min 30 goal	25 min 30 goal	25 min 30 goal
Cryogenic system availability (%)	99.8 min 99.9 goal	99.8 min 99.9 goal	99.8 min 99.9 goal	99.8 min 99.9 goal
MTTR (hours)	4	4	4	4
MTBF (hours)	17,520	17,520	17,520	17,520
Cost per cooling watt at 65 K	$60 max <$40 goal	$60 max <$40 goal	$60 max <$40 goal	$60 max <$40 goal
Compressor/ drive unit	Oil free	Oil free	Oil free	Oil free
System mass Kg/watt at 65 K	0.75 max <0.5 goal	0.75 max <0.5 goal	0.75 max <0.5 goal	0.75 max <0.5 goal