Cryogenic Roadmap

U.S. Department of Energy
Superconductivity Program for Electric Systems

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This document, originating within the national laboratories and their industrial collaborators, presents a series of suggestions for research and development pertaining to cryogenics. Appendix A is a tabulation of the steering committee members who participated in the development of this document. The editors have primarily used the materials and discussions provided by the steering committee and the 1997 and 1998 cryogenic workshop findings. However, there are added clarifications and suggested outcomes that were not presented in the workshop summaries.

Cryogenic systems providing 100-1000 watts of cooling at 65-80 K are required if devices utilizing high-temperature superconductors are to become a part of the national electric power delivery and utilization system. These systems must have lower capital costs and operate more efficiently and reliably then current off the shelf cryogenic systems. In addition, the physical size, maintainability, and operation must not constrain the expected benefits of high temperature superconducting power equipment. This document addresses the various pathways for the development of cryogenic systems that will enable cryogenic systems to advance from the present state-of-the-art to systems meeting these desired characterisitics. Consequently, it is called a “roadmap”. The roadmap provides goals and objectives along with the desired outcomes that may result if these goals and objectives are completed.

Introduction & Background

The new technology of High Temperature Superconductivity (HTS) offers the promise of many applications, especially that of improving the efficiency of electric power generation, transmission, distribution and use (in electric motors) by means of curtailing the i^2R loss that inevitably occurs in conventional technology used today. Besides improving efficiency, HTS technology also offers the prospect of increasing *capacity per unit volume (higher power density)* in comparison to conventional electrical equipment. This would allow more efficient use of utility rights-of-way and other easements.

The U.S. Department of Energy (DOE), through its *Superconductivity Partnership Initiatives* (SPI) program, is sponsoring teams of collaborators made up of national laboratories, industry and utilities who are building and testing prototype devices for use in the electric power system. The array of projects includes: transformer, motor, cable, fault-current limiter, and flywheel energy storage.

In most of these initial SPI projects, cryogenic support has not been a key focus for the project; that is, cooling to operating temperature has been achieved via refrigeration equipment sufficient to get the job done, usually disregarding questions of the cooling system efficiency, reliability or cost. (The ABB HTS transformer project is exceptional in that it is evaluating the refrigeration needs as an integral part of the system.) Everyone recognizes that the actual use of such devices in the real world of electric power will require cooling systems that are indeed an integral part of the system. For this reason, there will be further refinement of cryogenic systems accompanying future programs, perhaps in another round of SPI projects someday. In anticipation of that, it is desirable at the present time to gain an understanding of what needs to be accomplished in the area of cryogenics; hence the need for a roadmap.

There have been two recent workshops held by DOE to take the first steps toward such a roadmap:

The first was held July 22, 1998 in Washington DC; Appendix B presents a brief summary of its outcome. Attendees at that conference examined the present state of the art in cryogenics and outlined the performance-parameters of the equipment that will be needed if HTS devices are to “come true” as part of the national electric power system. The full conference proceedings are entitled *Cryogenics Needs of Future HTS Electrical Power Equipment*, and comprise a key document underlying this roadmap.

The second workshop took place on July 27, 1999. Here the emphasis was on finding out what are the most important considerations of both researchers and users with regard to actually accomplishing the goal of providing cryogenics to meet the needs of the future electric power system, when it includes HTS devices. Appendix C presents a brief summary of that conference.

The three evaluation criteria of cryogenic performance are: efficiency, reliability and cost. In any utility application, *reliability* is absolutely indispensable, and any device that even raises questions of reliability will be rejected out of hand. In general, higher reliability would imply higher costs, especially if reliability is achieved through redundancy (dual systems). Weighing the trade-offs between these three criteria constitutes a key element in the design process of any cryogenic system. The final configuration must optimize these criteria in a way that enables the HTS devices to contribute profitably to the operation of the national electric system.

Present Status

Existing HTS devices need to be maintained at 25K to 77K. (With technological advances in HTS wire, future devices may operate near 80K, which would greatly reduce the cost of cooling.) Cryogenic refrigeration systems can be categorized as two basic types: closed loop systems that use a cryocooler to provide refrigeration, and open loop systems that use once-through cryogens to provide refrigeration. A hybrid system uses both of these.

For small-scale applications, present economics clearly favor vaporization of LN_2 over mechanical refrigerators. Only when temperatures below the operating range of LN_2

(T < 65 K) are required will small-scale mechanical systems be applied. Thus our interest in closed-loop systems is focused on intermediate and large sizes.

A. Closed-Loop Systems – Mechanical Refrigerators

The basic science of cryogenics systems pertinent to HTS applications is adequately presented elsewhere[1,2,3]. The practical engineering of mechanical devices is much more complicated. There are many different types of refrigerators, each of which is best in a certain range.

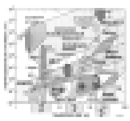

Figure 1 – Refrigeration power requirements and applications.

Figure 1, taken from Radebaugh's presentation[1], displays using variously shaded regions of temperature and refrigeration power where one or another technology works best. Circles indicate where certain of today's SPI devices fall on this graph; (these circles must not be confused with the long term devices that will meet the needs of the utility sector). The problem of selecting the "best" refrigerators for the HTS devices that serve most electric power applications can be understood by scrutinizing the right-central area of figure 1: at 77 K, the desired refrigeration power (100 – 1000 W) is slightly below the *Turbo-Brayton Cycle* range and slightly above the *Gifford McMahon* range. *Pulse Tubes* and *Stirling Cycle* refrigerators cover this range, but only a limited number of such systems have been produced, and their track record in industrial applications is limited. Pulse tube and Stirling cryocoolers developed for space applications have reached this reliability (10 years continuous operation for a few Stirling coolers) but the costs are very high at present. Such reliability is much better than Gifford-McMahon refrigerators. Accordingly, there is a need for improvements in technology that will cover the operating range of greatest interest to us.

The *efficiency* of mechanical cryogenic refrigerators has been improving steadily over many years, but for the devices of greatest interest to HTS applications, their efficiency is typically $\leq$20% of *Carnot efficiency*, defined by:

$$\eta_c = T_c / (T_h - T_c).$$

For an ambient temperature T_h = 300 K and an operating temperature T_c = 77 K, η_c = 0.345; so a typical efficiency is 20% of that, or 6.9%. Another way to represent this is through the *Specific Power* ($\equiv 1/\eta$), which is 14.5 in this case. (Specific Power is expressed in units of watts per watt, i.e. the number of watts of input power required to remove one watt of heat at the cooling temperature.) This means that to remove one watt of heat from the 77 K region, it requires 14.5 watts of input energy. This requirement is known as the *cryogenic penalty*, because it is equivalent to a parasitic loss that diminishes the savings obtained by using HTS wire and eliminating the i^2R loss of the particular electric device.

A variety of calculations have been done to model the behavior of HTS devices operating at various temperatures, including 30 K and 64 K. Obviously the Carnot efficiency is lower at those lower temperatures; e.g., at 30 K, $\eta_c = 1/9$. Hence the actual operating efficiency is lower, the *specific power* of the refrigerator is higher, and the cryogenic penalty is more severe.

Calculations by Mulholland et al[4] suggest that for a 1000 hp electric motor operating at 30 K, the energy savings (i^2R , etc.) are insufficient incentive to compensate for the cryogenic penalty. However, Blaugher[5] has calculated that a 5000 hp motor is large enough to overcome the cryogenic penalty at 30 K, giving a net improvement in efficiency of 1.7%. Transformers and generators save a smaller percentage of the device energy, and hence are even more sensitive to the cryogenic penalty, and to the operating temperature. Consequently, for most electric-power applications, it is an important research goal to develop second-generation HTS conductors that carry high current at temperatures near 77 K.

Therefore, this roadmap confines its attention to refrigerators that will operate above 60 K, with greatest emphasis given to 77 K cryogenic systems. Table 1, provided by American Superconductor Corp., is a tabulation of key parameters of existing cryogenic systems. It will be immediately recognized that the capital cost per watt is very high, and the efficiency (expressed as a percent of Carnot efficiency) is quite low. Clearly there is plenty of room for progress.

Discussion at the first (1998) workshop (see Appendix B) touched in part on the condition characterized by the phrase “If you build it, they will come.” Cryogenic manufacturers have already expressed confidence that it is possible to build excellent refrigerators that will meet the needs of these HTS devices, but without a substantial market, they have no incentive to do so. There is a “chicken & egg” effect going on, whereby the HTS market will always remain small until refrigerators are available, but refrigerators will not become available until the market for HTS devices grows. It is not

	Refrigeration Temperature (K)	Working Fluid	Capacity (Supplier Units)	Approximate Refrigeration (W)	Cycle	Expander	Plant Cost	Capital Cost per Watt $$$	Input Power (KW)	Input Power/ Cooling Pwr (W/W)	% Carnot
Large Scale GM Systems											
Leyblod 120T	65	He	130 W	130	GM	Recip	$20,200	$155.38	6.5	50.0	7.23%
Cryomech AL200	65	He	150 W	150	GM	Recip	$19,600	$130.67	5.5	36.7	9.86%
Helium Gas Systems											
PSI Model 1620	65	He	1200 W	1200	Claude	Recip	$400,000	$333.33	105	87.5	4.13%
Stirling Cycle											
Stirling Cryogenics LPC04	80	He	4200 Watts	4200	Stirling	Recip	$400,000	$95.24	45	10.7	25.67%
Large Scale Recondensing Systems											
PSI	80	??	11,500 Watts	11,500	Brayton	Turbine	$800,000	$69.57	167	14.5	18.94%
Liquid Air Plants											
Cosmodyne GF-1	80	N_2	4 T/Day	8,400	Brayton	Turbine	$700,000	$83.33	372	44.3	6.21%
Cosmodyne Aspen 1000	80	N_2	1000 nM^3/Hr	64,969	Brayton	Turbine	$2,650,000	$40.79	1400	21.5	12.76%
GEECO EDLP-20TN	80	N_2	20 T/Day	42,000	Brayton	Turbine	$1,790,000	$42.62	933	22.2	12.38%
GEECO EDLP-40TN	80	N_2	40 T/Day	84,000	Brayton	Turbine	$2,750,000	$32.74	1773	21.1	13.03%

Table 1 – Present Commercial Cryogenic Systems

at all clear how this problem can be overcome. Certainly government-sponsored R&D is not customarily carried beyond demonstrating one or two devices to establish feasibility; the expansion to a wider market is left to entrepreneurs in the private sector.

Open Loop Systems - Liquid Nitrogen Based

There is a large liquid nitrogen production and supply infrastructure in place throughout the world with literally thousands of tons of available LN_2. This can be utilized in HTS applications with very attractive economics. Such systems would be simple to install and operate with very few complex components. Temperatures in the range of 65K to 77K can be achieved with vacuum pumps.

There are many apparent advantages to an open loop system with LN_2 evaporating in *pool boiling*. The capital costs of such systems are low, and operational reliability is significantly higher since no major machinery is needed and it is a simple system. On the other hand, while LN_2 costs are very competitive and the operating economics look superior to small mechanical refrigeration systems, costs could be higher in some remote locations. Also, geometries of some systems may not favor forced circulation cooling over pool boiling and therefore may need special cryostat designs.

There are several areas for improvement in existing LN_2 open loop cooling systems, and a program that strives toward those improvements could help optimize the HTS refrigeration system

Desired Future Status – Goals, Objectives and Outcomes

A basic goal of any sponsored research is to work the sponsor out of a job. By providing seed money, the sponsor strives to nucleate a commercial developer. Like any good R&D program, the quest for better cryogenic systems is intended to reach a state where manufacturers are competing with one another in a major marketplace, meeting customers' requirements without benefit of any subsidy from a sponsor.

For many other applications of cryogenics, this state has already been reached. However, it appears (based on the workshops of 1998 and 1999) that for the case of HTS devices operating within a utility system, the near-team market outlook is too small and too specialized to attract a fully independent effort by existing cryogenic manufacturers to meet the performance requirements associated with these devices. It is therefore appropriate to discuss the kind of R&D program that could lead to HTS devices being bought and sold on the same business footing as other commercial products.

Direction

The very fundamental question must be asked: What are we trying to do? For cryogenics, the answer is "Remove heat." In any electrical power device or system, the load current varies over time. In general, for those HTS systems in which the superconductor carries varying current, the cooling load that the cryogenics must handle also varies over time. The cryogenic system must be sized to accommodate the highest load, not just the average load. That can become expensive in some instances, requiring large up-front capital outlays for a cooling capability that is fully used only infrequently. Multiple staged cryogenic systems offer one expensive solution to this problem. A variable capacity cryogenic system is a much more attractive oprion.

For systems operating near 77 K, the choice of a liquid nitrogen bath is a convenient way to meet both peak and average loads. (Keeping a LN_2 storage tank filled is a way to deal only with the "average" load.) However, any system operating around 64 – 70 K demands additional cooling equipment (perhaps a vacuum pump; perhaps an electric cryocooler operating from an "ambient" of 77 K, etc.), and that must be sized to handle the maximum load. Moreover, not all applications are able to use a LN_2 bath, for geometric and dielectric reasons.

Recognizing that most HTS devices must operate in a utility setting, which can range from an urban power station to an isolated distribution substation in "desert" condition, the cryogenic system must conform to the parameters of performance placed upon other subsystems within the utility environment. These parameters include very high reliability/availability, low maintenance, and automatic/remote operation. Without these, any HTS device will simply not earn acceptance in the marketplace.

Large electric motors (5000 hp and up are candidates for HTS technology) are commonly used in factories, and have slightly less stringent *performance* requirements than utilities. However, in many industrial applications the shorter payback period forces the *cost* parameter to be more stringent than for utilities. Overall, the demands upon cryogenic systems are very severe.

Goals for Major Parameters

It is easy to say that everyone wants cryogenic refrigerators that are efficient, cheap and reliable relatively small in size and acceptable to utility and industrial markets. The much more demanding task is to turn these adjectives into quantitative measures of performance. Toward that end, we propose the following ***major goals***: **an efficiency of 30% relative to Carnot, a capital cost below $25 per watt of cooling, and an available operating time (or reliability) exceeding 99.8%.** Table 2 below summarizes the goals, objectives and desired outcomes. As discussed below, these goals are reasonable when compared to the present status of cryogenic systems and when weighed against the potential outcomes are highly desirable.

The improvement of efficiency from today's range, 20% of η_c, to 30% appears to be a tractable goal, neither too ambitious nor too conservative. This objective is entirely a technical one.

The distinction between *Availability* and *Reliability* deserves clarification. *Reliability*, in a strict sense, is a measure of the fraction of units operating after a given period of time. The average *lifetime* of a refrigerator deals with the time until replacement. *Availability* is the more important parameter to those who have profitability tied to being able to meet customer specifications. Utilities are generally much more concerned with availability measures than reliability per se. The numerical goal for *availability* may seem stunning by laboratory and factory standards, but not so for utility systems. In fact, the number of 99.8% may be *low* for many applications in real utility systems.

For example, if a HTS cable brings power into certain blocks of a dense central city where there is no alternate delivery path, failure of the cryogenics implies a blackout. Virtually all utilities will insist upon both scheduled maintenance and redundancy for the foreseeable future, until HTS systems are proven beyond any doubt. The achievement of this goal is absolutely indispensable for utility applications.

When building a real cooling system, cost and reliability are strongly coupled. The trade-off of cost for availability that is associated with redundancy is familiar to any utility engineer. For example, one report[6] mentions a case where six standard nitrogen plants had an average of 18 outages per year. However, due to redundancy, this resulted in nitrogen delivery failure only once in 30 years. The history of the utility industry shows that redundancy is the commonest way to assure very high availability.

Redundancy helps to ensure availability, but any instances of multiple outages of a system are unacceptable to the utility. The *breakeven point* between an affordable device (perhaps one risking failure) and a more expensive, more reliable device must be considered – not only from the “maintenance” viewpoint, but also from the perspective of *user confidence* in the system. *Risk* carries a very high cost penalty.

Cryogenic manufacturers have worked hard over many years to improve reliability, by eliminating moving parts at the cold end and reducing mechanical wear through use of flexure bearings and gas bearings. In one representative (pulse-tube) case[7], the top three life-limiting phenomena were helium leakage, gas contamination, and power electronics failure. The first two are controllable through proper design (and perhaps a regularly scheduled helium clean- and fill-up). That leaves the power electronics, the “standard” against which most people judge reliability. To meet utility requirements, manufacturers customarily start with a very reliable design and then try to decrease the cost.

Today’s cryogenic technology is very expensive. Table 1 suggests a ballpark figure of $100/W for sizes of interest to HTS devices. The reduction of cost from here to below $ 25/W is a very aggressive goal, and depends substantially on achieving an

Primary Goals	Objectives	Outcomes
Increased Efficiency (present nominal 20%)	> 30% Carnot by 2005	Reduced operating expenses and market viability
Lower Capital Cost (present nominal $100/watt)	< $25/cooling watt by 2007 with cryogenic components costing < 10% total system	Reduced capital cost and market viability
High reliability (present systems depend heavily on redundancy)	Operating availability > 99.8% by 2007	Mean time between failures of operating cryogenic system > 30 years using redundancy and increased component reliability
Secondary Goals		
Size (present closed cycle systems including auxiliary systems are much too large)	System & cryogenics 50% smaller by 2007	Utilization of full HTS systems increased power density
Variable cooling capacity (present systems might use staged smaller, less reliable, less efficient, more expensive equipment resulting in excess size and cost)	Cryogenics follow load using storage capacity or optimized variable speed drive techniques on HTS system by 2009	Significantly reduced penalty for operating costs (utility cost of base load losses are 2.5-3 x larger than losses which follow load with similar impact on industrial demand charges)
Historic price decline with volume and experience	Reduced costs as HTS systems penetrate market	Commercial units at reasonable cost
Transparency (present MRI systems suggest feasibility)	Customer acceptability by 2007	Low awareness of cryogenic system
Minimal Disruption (present MRI systems suggest feasibility)	Customer acceptability by 2007	No interference of normal operations
Maintainability (present MRI systems suggest feasibility)	Customer acceptability by 2007	Average technicians can operate the system
Soft failure mode (present MRI systems suggest feasibility)	Customer acceptability by 2007	Cryosystem failures allow alternate operational schemes

Table 2. Cryogenic R&D needs expressed as goals, objectives, and desired outcomes.

economy of scale. Looking at the size range below 5 kW cooling capacity, without fundamental breakthroughs in cryogenics it is doubtful that even $ 50/W can be reached until the market size exceeds 10,000 units/year.

As discussed by Mulholland et al[8], there is a consistent relationship across the manufacture of many goods that shows how price falls with increasing volume. On log-log paper, as in figure 2, the exponent - 0.344 recurs again and again in the relationship between price and quantity manufactured. That is,

$$\$ (N_1) / \$ (N_2) = (N_1/N_2)^{-0.344}$$

Trusting in that relationship, it is plausible to expect price to drop from $ 100/W to $25/W if the number of cryogenic units manufactured increases by 2 - 3 orders of magnitude. That condition would correspond to widespread implementation of HTS devices by utilities nationwide.

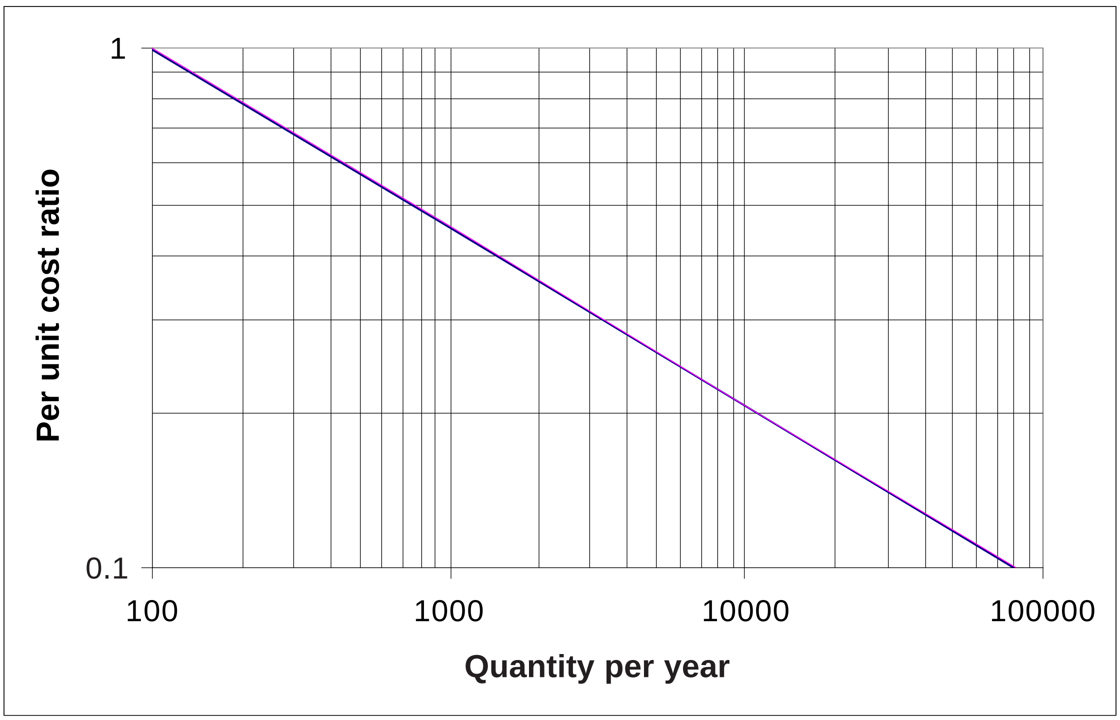

Figure 2 – Estimated relative costs of 60-80 K Cryocoolers vs quantity produced per year

Secondary Parametric Goals

There are additional performance parameters that are still very significant, although not as imperative as reliability, efficiency and cost. These include questions of:

Size – Can the cryogenics fit into a small space without requiring changes in the layout of the components it serves? How large is the refrigerator compared with the equipment it supports? Is the combined HTS apparatus and cryogenic system smaller than a conventional system?
Price History – Is the price declining steadily? Is it reasonable to believe about a certain cryogenic technology that it will be commercially viable within a few years?
Transparency – Can the HTS device, including its cryogenics, be safely ignored (at least for very long periods of time)? Is this device a "turnkey" operation?
Disruption – Does this device interfere with the normal way of doing things?
Maintainability – Can utility employees of limited technical acumen easily carry out the needed maintenance tasks, without extensive training?
Failure Mode – Does this device fail in a "soft" way, giving adequate warning and/or not causing a cascade of other problems? Is there an easy way to work around it?

The latter four fall into the broad category of "acceptability" to utilities.

Elements of the Transition

How will the transition from the present state to a better future state be made? As discussed in a later section, teams will likely carry out the R&D. However, it is crucial to take note of the business conditions faced by any cryogenic manufacturer who tries to carry R&D results forward into commercial success.

There is a commonality associated with the introduction of new technology that deserves emphasis. Dr. Martin Nisenoff[9] of Naval Research Laboratory has observed the way cost declines as military hardware evolves from R&D to large-volume production. Five stages can be identified:

B.

A. <u>*Unit purchase*</u>: This stage is simple: you buy whatever a vendor is selling. For a 200 W class refrigeration system, $ 10^4 is a representative figure. (For a kW cooling-power unit, $ 10^5 would be typical.)

C. <u>*Special Order*</u>: Some modification is involved at this stage. The purchaser goes to a vendor and specifies certain parameters, such as "a 20 Watt cooler" to operate in a certain range with specified efficiency, etc. For a price of the order of $$10^5$ ($30,000 - $300,000), the vendor delivers a device that meets the specifications, but isn't really all that you wanted in the first place. It comes with no guarantee and uncertain reliability.

D. <u>*R&D Project*</u>: At this stage, development is required. The purchaser's specifications are more precise and tailored to the application. The vendor is chosen carefully, based on prior performance. For example, on a spacecraft, you might call for a cryocooler that runs for 5 years with no vibration; accordingly, it will be bought from an aerospace company. The price range has risen by another order of magnitude, perhaps between $300,000 and $3,000,000. This can be funded over a few years, because the units are being purchased one at a time.

E. *Pilot Plant* : At this stage, the price is up to about $\$10^7$. The purchaser demands excellent reliability, so the vendor has to build a prototype manufacturing line to achieve this, and the output will be several cryocoolers. All the non-recurring engineering costs get paid here. But from this point on, the 20-watt cryocoolers only cost $20,000.

It is important to understand that nobody is interested in a $\$10^6$ market, because they can't recover their investment. Also, nobody will commit $\$10^7$ to a pilot plant unless they are guaranteed a $\$10^7$ market; an unproven market doesn't attract investors. Who will build the first $\$10^7$ prototype line? Without it, unit costs won't come down.

Another way of looking at this is to note that the "chicken and egg" problem is often a result of a market with a marginal business case. If the projected profit margin is sufficiently large, businesses will enter. But if you have to commit $\$10^7$ to enter a market with 5% profit margins, it is very difficult to raise capital. Small manufacturers will even go after a $\$10^6$ market, but only if the profit margins are high.

Reliability doesn't come until the vendor builds a *lot* of units. This is basic to the nature of manufacturing processes.

E. *Full Scale Production*: This is the desired end stage for production of cryogenic systems. At this level, cryogenic systems for HTS devices in the national electric power system would be routine. Today, for example, a typical major vendor is CTI in Massachusetts, the world's biggest cryocooler manufacturer. Their business size is around $\$10^8$ per year.

This sequence, drawn from military and aerospace experience, is historically valid for many types of technology. There is probably no way to get around this condition.

List of Issues

Any program of technology development must set its boundary conditions at the outset. For the specific case of cryogenics to support HTS devices, there are an entire series of unique considerations. One list, provided to the July 1999 workshop by Nathan Kelley and Jon Jipping, contains 20 issues that need to be addressed; they are somewhat cable-specific. The list appears here as Chart 1.

Chart 1 - Cryogenic System Issues for Utility Applications

1) HTS technologies are frequently sited for applications in congested regions. Therefore, the size of the refrigeration unit is a critical factor.

2) HTS cables' long length to volume ratio and restricted diameter make the continuous flow of LN_2 critical.

3) A refrigerator should be capable of operating for very long periods of time without external intervention or attention, as most utility locations are unmanned.

4) System should be designed (and guaranteed) for 100% availability.

5) The load on a refrigerator will change depending on the electricity carried from a minimum (equal to the thermal inleak of the system) to a maximum design point. The system must operate efficiently through this entire range and reliably follow the continuously changing load.

6) Owing to their linear geometry, HTS cables have relatively high heat loads, and thus require an efficient refrigerator, not only at design load, but at all operating points. This is particularly significant for cables with daily and/or seasonal dips in loading. The overall system efficiency must be improved from the generally quoted 20W/W, as the life-cycle cost must be competitive with conventional cables.

7) The system should be able to provide larger refrigeration capacity for a short duration following transient thermal conditions, such as short circuit.

8) A system needs to be "low profile". This means that the refrigerator be as compact as possible. And, growing vertically is not always a solution.

9) Most utilities would not permit a third party (i.e. a LN_2 vendor) to make deliveries without their personnel being present. And, it is not feasible for a substation operator to be available every three days for the LN_2 refill. Subsequently, evaporative bath coolers are typically not an option as primary refrigerators.

10) Automatic circuit breakers and reconnects require some cycles to operate. The refrigerator cannot go through a complete shut-down/start-up cycle every time that the power "flickers".

11) The power requirements for different installations could be very different. Despite the capacity differences, it is important that there be standardization of spare parts and repair techniques.

12) Other HTS technologies are operating below LN_2 temperatures, and so will use He based systems. Different cycles or refrigerator types for cables, transformers, etc. would require large parts inventory and diverse training.

13) Major components and long-lead items will need to be stocked, because a system cannot be out-of-service for several months waiting for replacement components.

14) The utility maintenance infrastructure will need training on routine and emergency maintenance.

15) For widespread commercial deployment of refrigeration systems, a skilled field-service force will be required.

16) System availability and reliability should be very high.

17) COST!!! Final system cost must be competitive on first installed and life-cycle basis.

18) Typical utility hardware has a 40-year depreciation. Refrigerator longevity will be compared to this experience.

19) The utilities have little experience with cryogenics and refrigeration. Therefore, they have many questions and doubts. The cryogenics industry must be willing and able to work with system developers to educate the end users.

20) Remote control system capability should be integrated in the refrigeration system. Utilities are spending a lot of money to install remote monitoring and automation on their distribution systems. The refrigeration system must easily integrate with a variety of monitoring systems and protocols.

As mentioned above, this list is oriented toward transmission cables. Comparable lists (with considerable overlap) could be constructed for every other HTS application (generators, motors, transformers, fault-current limiters, etc.). The key point is that for *any* cryogenic system, there will be considerations of this type that have to be addressed.

Various Technology Paths

The available choices of cryogenic technologies can be broadly classed into three categories: recuperative systems, regenerative systems, and hybrid systems. The different refrigerators have various advantages and disadvantages, which trade off against one another in choosing the "best" cryogenic system for a particular application.

The reliability standards of utilities are notoriously stringent. Any cryogenic system that involves moving parts such as reciprocating pistons is immediately suspected as unreliable. The attraction of some newer methods (such as pulse tube technology) is attributable in part to the freedom from moving parts in the cold end.

Recuperative Cycle Cryocoolers

The *Turbo-Brayton* cycle is the foremost unit of this type for reaching temperatures of interest to HTS devices. One major advantage is that the transport fluid can carry cold long distances, and this allows the cryogenics to be placed out of the way in tight configurations. Another advantage is that the operating lifetime is long, because it uses gas bearings. Moreover, the flow is steady, and vibration is not a problem.

The disadvantages of the *Turbo-Brayton* cycle are that it requires a large heat-exchanger, and the unit is expensive to build. Most important, these systems cannot be miniaturized; the cost hits a plateau and doesn't go any lower when the size declines further. In the 77 K temperature range, that plateau comes at about 1000 watts of refrigeration power, too big for most HTS devices. Clearly, should R&D lead to smaller Brayton cycle refrigerators that retain good efficiency while lowering cost, it would be a very welcome improvement.

The *Joule-Thomson* cycle also bears mentioning. It too has steady, vibration-free flow, and can transport cold fluids long distances. The absence of moving parts in the cold end is another advantage. However, it requires high pressure, and that typically means oil-flooded compressors and the possibility of cold-head contamination. Improvements in clean compressor technology and in efficiency (in the 60-80K range) would make these systems more attractive for HTS cooling.

Joule-Thomson systems using mixtures of gases (N_2, H_2, He) are used to reach temperatures well below 77 K. Mixed-gas JT refrigerators are able to achieve temperatures around 77 K using conventional air conditioning compressors, which has been a major advantage of the mixed gases. They also give much higher efficiency. The high pressures are only required for use with pure nitrogen, which has a low efficiency for reaching 77 K. Current technology is limited to > 90K if competitive efficiency is to be obtained.

Regenerative Cycle Cryocoolers

There are three devices[1] (all cousins of one another) that are the leading candidates in this category: *Stirling Cycle*, *Gifford McMahon*, and *Pulse Tube* refrigerators. All three work by having a transport fluid (a gas) pass cyclically through a *regenerator* and a *displacer*. The displacer moves back and forth at low temperatures. These systems operate at frequencies below 60 Hz at 77 K, and as slow as 1 Hz when cooling to below the 4 K range.

The advantage of the *Pulse Tube* device is that the "displacer" is made out of a column of gas, not solid material – it is a gas plug. This eliminates a crucial moving part at low temperatures, and greatly enhances reliability. Most pulse tube cryocoolers built to date have had small cooling capacities (50 W or less), but recent advances have demonstrated the feasibility of systems with up to 1 kW of cooling capacity at 77 K, and much larger capacities are not unreasonable in the future. Pulse tube cold heads have also been used with thermoacoustic engines to build natural-gas-fired industrial gas liquefiers. Such systems offer the possibility of high reliability due to the lack of moving parts in either the driver or the cold head, however the current technology results in a physically large cryocooler with limited efficiency. Rapid advances are being made in the pulse tube and thermoacoustic cooler fields, and the technology shows long-term promise.

The *Stirling Cycle* has several advantages, notably high efficiency, small size and weight, and moderate cost. There is considerable manufacturing experience with such units; over 100,000 have been made already. On the other hand, there is always going to be vibration, owing to the moving displacer. It must be run dry (without lubrication) because of the links (via the coolant gas) between cold and warm regions. Moreover, it is expensive to achieve long lifetimes (3 – 10 years) in these systems.

The *Gifford-McMahon* cryocooler is the most popular of this type. On the one hand, it isolates the compressor from the regenerator and displacer, which allows a modified air-conditioning compressor to be used. This keeps the cost down. About 20,000 units are made per year, so there is plenty of experience, and reliability (assuming regular maintenance) is good. Maintenance *is* required about every one to three years. Lifetime of compressor and valve parts may be about 5 years. Reliability may be good, but not good enough for the utility industry. On the other hand, the efficiency is much lower than in the Stirling cycle, expressly because an external AC compressor is used. There is still inherent vibration from the moving displacer. A Gifford-McMahon unit is large and heavy, but this problem is mitigated somewhat because the compressor can be placed some distance away from the place where cooling must occur.

Hybrid Open Loop Systems

Given that most electric-power applications are expected to operate near 77 K, it is useful to consider systems based on liquid nitrogen, coupled with an auxiliary device to cool slightly further.

The foremost advantage of LN_2 is that it is so cheap. As a byproduct of oxygen-production plants, the available supply of LN_2 so outweighs the demand for it that the price is very low – about six cents per liter in truckload quantities. This implies that someone else has paid the thermodynamic and economic cost of reaching 77 K. The *capital* cost of basing a system on LN_2 must include the cost of a storage tank; the *operating* cost includes the cost of trucking in LN_2 occasionally. The severity of the reliability criterion sets the size (and cost) of the storage tank. These additional cost burdens are small compared to the cost of electric power to reach 77 K in any other way. Wherever other criteria (geometry, location, etc.) do not mandate otherwise, liquid nitrogen is the coolant of choice.

To get to some lower temperature, several avenues are possible:

- First, pumping a vacuum on LN_2 can reduce its temperature from 77 K down to 64 K. Of course, the reliability of the vacuum pump needs to be considered; it may not be as good as most cryocoolers.
- Second, a mechanical cryocooler running from an "ambient" platform of 77 K does not have to work very hard, compared to one running from room temperature.
- Third, helium gas can be used with another refrigeration system to reach much lower temperatures.

Any of these combinations can properly be termed a "hybrid" system.

One variation would be to have a cryocooler maintain a bath of LN_2 at 77 K. That would provide redundancy, and average the load over some time period. If the cooler failed, there would then be a back-up reservoir that would keep things cold for some time, relying on the transport of LN_2.

Trade-offs play a large role in optimizing a hybrid system. For example, suppose it is desirable to have a HTS device operate at 70 K, but it would still be able to function at 77 K, although limited in some way. In the event of 77 K operation, performance would be lessened, but reliability would not be lost. It is plausible that a utility might find that acceptable, and the system designer could save the cost of redundancy. Issues of this type need to be considered when designing a hybrid system.

Candidate Technologies

The question "which class of cryogenic refrigerator is most likely to be used with each application?" needs to be addressed; obviously the actual choice lies with the team pursuing the development of a cooler. However, it is relatively easy to identify certain technologies that initially appear more appropriate to one or another HTS device. (For example, regarding transmission lines, one may ask whether to employ a refrigerator or simply use liquid nitrogen from a dewar.) Table 3 below presents some suggested refrigeration cycles for each of the leading HTS applications. To determine the "best" technology for each case, it is useful to examine obstacles from the point of view of a problem statement and a proposed action. Appendix D offers one type of form[10] that can be used to facilitate the identification and resolution of a problem.

Table 3: Candidate refrigeration cycles for HTS applications

HTS Application	Proposed cycle	Alternate Cycle
Transmission Lines	Reversed-Brayton	Hybrid
Transformers	Gifford-McMahon	Pulse Tube
Motors	Reversed Brayton	Hybrid
Fault current limiters	Gifford-McMahon	Pulse Tube
Superconducting Magnetic Energy Storage	Gifford-McMahon	Pulse Tube
Flywheel Energy Storage	Gifford-McMahon	Pulse Tube
Magnetic Separators	Gifford-McMahon	Pulse Tube

Along the various technical pathways, some of the questions that will be asked of each candidate technology are these:

- Which components of the cryogenic refrigeration system are behind in development for achieving capacity targets?
- Which components of the cryogenic refrigeration system are behind in development for achieving efficiency goals?
- What is the reliability for existing components of the cryogenic refrigeration system?

Moreover, it will be important to develop realistic refrigerator models, using data from real-world components, in order to design systems that achieve the desired capacities.

Research Avenues

The *Superconducting Partnership Initiative* (SPI) approach has proved very successful in bringing HTS out of the laboratory and applying it in actual devices for the electric power industry. It is plausible to think that this method will likewise work well for cryogenic systems associated with these devices. The strongest feature of SPI projects is that they are *industry-driven*. Here the government sponsor pays only half the cost (industry must raise the rest), and industry keeps the patent protection on new inventions. As a result, it is guaranteed that industry remains interested in and attentive to the progress of the work throughout the entire duration of the project. This stands in sharp contrast to an older way of doing R&D, in which government does it all on the front end, and then industry gets into the act only much later – by which time the large government effort may no longer be particularly applicable to the commercial marketplace.

Therefore, this Roadmap strongly recommends that development of cryogenic systems for HTS devices be conducted via programming analogous to the *Superconducting Partnership Initiative.*

Roles of the Participants

In a true collaboration, each partner participates at all stages, although one or another may assume dominant responsibilities in different phases. To assemble a winning team, it is necessary for all the different specialists to work together as a team, dedicated to reaching the goal together. Just as for the HTS devices now being constructed within the SPI program, similarly any successful venture toward better cryogenic systems must contain a collection of very capable individual players:

F.

G. Industry

The economic history of America shows that things don't get done unless somebody makes a profit. At the outset, this roadmap defines the goal as "commercial success", and recognizes that profitability drives business decisions. If there is ever to be commercial success for this program, it will be because industry leads the effort. The focus on business goals – profitability – leads to keeping costs down, to products that are capable of being *manufactured* in quantity (not just laboratory apparatus), and to performance that meets the customers' needs.

When the stockholders are asked to lay their money on the line, there must be an implicit promise that their business goals will be respected, and their decision-making processes given deference in planning an R&D strategy. This is why no realistic roadmap can specify in detail the path to accomplishments. People who have been in the cryogenics business have a strong sense of what works and what doesn't; their leadership is essential to success here.

There is already a very substantial cadre of cryogenic system manufacturers in place nationally. The new requirements of HTS devices to be deployed in utility systems challenges these companies to build systems that are superior in many ways to existing equipment. The companies are also being asked to take a risk that a major market will develop over time for their new products, so that their initial development cost can be recovered. People willing to commit their own capital and take such risks deserve to be the ones who call the shots. Ultimately, industry will choose the manufacturing goals, define a practical timetable, and establish the go/no-go decision points.

H. Utilities

Only in the last few years have utilities begun to participate in energy R&D, through CRADAs and SPI programs. By providing a test-bed where hardware can be installed in real electric power systems, they have very quickly converted research scientists into believers in the very special circumstances under which new devices must function. It is eminently clear that their voice must be listened to carefully, because they are the ones who ultimately must decide whether to commit to installation of HTS devices. There is a go/no-go decision point in the loop that researchers often overlook.

Throughout its 100-year history, the electric utility industry has faced numerous technical and societal challenges. Today, changes in federal and state regulation promise to fundamentally alter the relationship between utilities and their customers. As such, every major utility in the US is engaged in activities to improve productivity and efficiency, thereby lowering costs. At the same time, with rapid advances in and proliferation of personal computers and a host of electronic devices, highly reliable electric service is the single most important feature for customers. Recent events during the summer of 1999 in Chicago and New York illustrate the "zero tolerance" attitude many have toward poor reliability. Utility managers will not commit to install unproven technology on the electric system. This is especially true from a reliability standpoint, but also from a cost perspective.

The foremost role of the utility in an R&D partnership is to keep the focus of all participants on the ultimate goal. Even at the initial design stage, scientists must recognize that their conceptual freedom is limited by very practical requirements. There is no point in starting down a path toward a device that will eventually demand constant attention. By heeding the advice of the utility engineers at early stages, the probability of acceptance later on is greatly enhanced.

When the device is ready to be "rolled out", it is the utility staff, working with the industrial partner, who will test and refine the entire unit within its operating environment. Too often in past R&D programs, this has been treated as an afterthought, but such is not going to be the case in HTS technology. The entire *system*, including the cryogenic system, has to function together, reliably. It is the utility partner who will dominate the decision about how that goal is to be achieved

I. National Laboratories

The highest scientific capabilities in the HTS program reside within the National Laboratories. The Labs have proven over half a century that they have the ability to accomplish very difficult scientific tasks, identifying fundamental obstacles and overcoming them in a scientifically sound manner. In recent years, the labs have demonstrated their ability to work collaboratively with industry through CRADAs. In this roadmap, we envision that the labs will contribute across the board, but especially in fundamental areas such as materials science, properties of gases, and other technologies where industry is unlikely to take a leading role.

For the special case of cryogenics to support HTS devices within utility systems, the present list of obstacles is formidable: we seek an increase in efficiency of 50% above today's level, and we seek to elevate mechanical equipment to a level of reliability heretofore seen only in entirely passive, non-moving components. Even to place these topics on the agenda is to indicate how much confidence we have in the cleverness and resourcefulness of national lab scientists and engineers.

J. Other Government Agencies

The National Institute of Standards and Technology (NIST), as well as NASA and the Department of Defense (especially the Naval Research Laboratory) have had long experience with cryogenic technology. DoD and NASA have taken laboratory devices all the way to reliable satellite systems, and NIST is the leader in most basic areas of refrigeration research[1,11]. It is absolutely essential to the success of this effort that these agencies remain strongly coupled into the program – both because of their expertise in research, and their appreciation of what is required of a cryogenic system operating in the real world.

The very mission-specific nature of most NASA and DoD programs means that they will be complementary to, not overlapping, this work relating to HTS devices for electric utility systems.

Timetable

At this point in time, it is impossible to be either prescriptive or precise in laying out a timetable for cryogenic R&D in support of HTS devices. However, certain general features can be discussed, and the broad scope of the activity delineated:

Fiscal year 2000 is essentially finished. This has been a time of organizing and planning, and this roadmap is part of that process. During this year, continuing discussions among likely participants has to a consensus on the nature of the R&D to be pursued but has also opened other areas for consideration.

In 2001 (fiscal year or calendar year), teams will be assembled, agreements will be reached, and participants will get establish their financial mechanisms. Given the typical time-cycle of government authorizations and appropriations, it would not be credible to think that funding would be available any sooner than the start of FY2002. An incremental appropriation of $10 million as the government's share is about the right size to get several analogous SPI projects (*Cryogenic Partnerships for Superconductivity*) started.

Accordingly, actual work would start in 2002. As discussed above, the utility partners would be only peripherally active in the early stages, while industry and national lab researchers would play a leading role.

This phase of exploring new avenues and trying new technological innovations would last through 2003. The industrial collaborator would certainly be the dominant partner by late 2003. Bench testing and prototype refinements would be the main activity. Some go/no go decision points during 2003 will result in the discontinuation of some projects and greater emphasis on others.

In 2004 and 2005, implementing *real* systems would be the principle theme of the program. Making something work in a utility environment will call for the full cooperation of all partners, from bench scientists to utility engineers, refining the design, the manufacturing process, and the way it is incorporated into the overall system. The government role would be greatly diminished by the conclusion of 2005, and the utilities' role greatly enhanced. Here again, business decisions will be made that further narrow the choices among candidate technologies.

2006 should be a time of final refinements, leading to *proven* hardware that meets the original design goals of reliability, efficiency and cost. The entire program will be almost entirely in the private sector by this time, with national lab scientists playing only an advisory role.

It is an interesting coincidence that in a recent study of the economics of future HTS applications by Mulholland et al[12], the estimated year of first market-entry for many of the HTS devices is 2007.

Obviously, if some of the existing SPI projects prove highly successful in the next couple of years, there will be an incentive to accelerate a cryogenics R&D program. It is plausible to think that an "SPI" for refrigerators could follow upon the present SPI II projects. Imagine a specific example: after the 12-18 month operation of the SPI II HTS Cable demonstration at Detroit Edison, an "SPI III" refrigerator project could install a new and advanced refrigerator at the same site. Much will be learned from the HTS Cable project about the refrigeration system. Subsequently, any SPI II project could be used as a "retrofit" demonstration for an improved refrigeration system.

Summary and Conclusions

This roadmap is offered to the U.S. Department of Energy by the assembly of utility, industry and national lab researchers who believe that now is the right time to develop cryogenic systems that will allow HTS devices to become standard components of electric power systems. Utility equipment is the sum of its parts; in this case, both superconductors *and* cryogenics are required to make the system work. Advances in both the HTS materials and in refrigeration technology (either applied or new) will determine the eventual level of success of these products.

There is widespread agreement that much science is yet to be learned in superconductivity. On the other hand cryogenics has been dismissed as working out a few engineering details to meet the specific needs of the application, and that can be handled mostly by industry. This roadmap opposes that line of thinking. We feel it takes much more than simply providing a few engineering details. To get from where we are now to where we need to be, there is need for much new science in cryogenics to improve the efficiency and reliability and to reduce costs. Understanding how to provide the required refrigeration with fewer and more reliable moving parts and having the process work efficiently requires research.

Because of two previous workshops, this document devotes only a little space to reviewing where we are today. Much more important is where we want to be – where we <u>must</u> get to if commercial success is to be achieved. We establish specific numerical performance goals for cost, efficiency, and reliability. We examine the various possible pathways to reach these performance goals, taking note of both the technologies that can be pursued, as well as the business constraints that must be considered. We also recommend an R&D strategy of forming teams of knowledgeable specialists, in order to improve the probability of achieving success. Finally, we suggest a typical timetable spanning several years over which these activities would take place.

We expect the benefits of this program to be very widespread. Concepts that increase the efficiency, improve reliability, and reduce costs would apply to almost all areas of superconducting power applications, as contrasted to only individual devices developed by SPI projects. This cryogenics R&D would be an "umbrella" program in parallel with other ongoing efforts.

It is too early to specify a detailed research plan, and trying to "pick winners" has always proved futile. Rather, our purpose in this roadmap is to identify the broad scope of collaborative R&D effort involving partners drawn from industry, utilities and the national labs. The details are to be filled in by those (in the private sector) who believe in their potential accomplishments enough to risk their own money in this endeavor. The program described here is definitely an *industry-led* enterprise.

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