Implementation Plan for Cryogenic R&D in Support of the HTS Program

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Summary

In the intervening years since the last 5-year plan[1] was written for this program, it has become clear that major improvements in cryogenics will be necessary if the promise of high temperature superconductivity is ever to be realized in practice. The partnerships that built various HTS devices[2] have demonstrated feasibility, but there is still a long road ahead to commercial success. This *Implementation Plan* attends to the cryogenics that will be part of future R&D efforts.

Drawing upon three previous documents, especially the *Cryogenic Roadmap*, this document reviews the most important factors influencing future collaborations between government and industry in the cryogenic cooling of HTS power apparatus. This document strives to state what must be done for the goals of the *Cryogenic* Roadmap to be reached.

Despite obstacles in the technical, business and institutional categories, the opportunity for public-private cooperation via the SPI mechanism is still open; it invites the participation of people who are original, innovative and entrepreneurial. The technical skills and facilities residing in the National Labs can combine with the practical understanding of engineers from industry who best know their own requirements in the field. The financial incentives and commitment of the private-sector partners contain a very strong guarantee that a project will never become irrelevant.

What we have been careful *not* to do in this plan is to specify project details or otherwise engage in "picking winners". That would be doomed to fail. The most accurate decisions about what works and what doesn't are often made on the factory floor during installation or testing, by an engineer with an understanding of *both* the capabilities of a particular device *and* the dynamic realities of the process being modified. We expect that this will continue to be the pathway to success for HTS devices and their associated cryogenic systems.

Introduction

Throughout the program run by the U.S. Department of Energy (entitled the *Superconducting Program for Electric Systems*[1]), the direction of R&D has been set by industry, not by government. Funds-matching support of projects via the mechanism of *Superconducting Partnership Initiatives* (SPIs) has been used with considerable success[2]. It is the intent of the Department of Energy to continue this practice while going down the path of cryogenics

This is the fourth in a series of documents that deal with the topic of improving cryogenics to support HTS devices used by the electric utility industry. The previous three were:

1. *Cryogenic Needs of Future HTS Electric Power Equipment*, Workshop Proceedings (Washington DC, 22 July 1998).
2. *Cryogenics Vision Workshop for High Temperature Superconducting Electric Power Systems*, Workshop Proceedings (Washington DC, 27 July 1999).
3. *Cryogenic Roadmap*, Submitted by Steering Committee to DOE, January 2000.

The 1998 workshop adequately summarized the existing state of cryogenics. The 1999 workshop examined what would be needed for HTS devices of the future;

particularly valuable is a table showing the parameters of a suitable cooler for each device. The *Cryogenic Roadmap* stated the agreed-upon performance goals for cryogenics, telling *where we want to be* but not *how to get there*; hence, it conforms to the usual definition of a roadmap.

All three of these documents represent the work of a consensus-seeking assembly comprised of: researchers from the national labs, manufacturers of HTS power devices (cables, motors, transformers, generators), manufacturers of cryogenic systems, and utility engineers.

The intent of this *Implementation Plan* is to delineate how private-sector initiatives can mesh with a limited supporting role by government to provide better cryogenic systems for HTS devices. It deserves emphasis that the government role does not include "picking winners" or telling the private sector what to do. The goals set forth in the *Cryogenic Roadmap* will be achieved through a cooperative effort that couples the government contribution (R&D leadership by the National Labs) to the commercially motivated practical direction set by private industry.

A Review and Update of the *Cryogenic Roadmap*

The *Cryogenic Roadmap* included two appendices that are summaries of the workshops of July 1998 and July 1999. The findings of those workshops provided the foundation for the *Cryogenic Roadmap*. The Steering Committee that composed the *Cryogenic Roadmap* reached agreement on its content primarily because a consensus had been reached at the workshops about what needs to be done. After a period of writing, editing and approval in the latter third of 1999, The *Cryogenic Roadmap* was first publicized at the *Wire Development Workshop* for 2000.[3]

The *Cryogenic Roadmap* defined three essential performance goals: **reliability, efficiency, and cost**. These are admittedly much easier to state than to achieve, but their achievement is considered to be necessary if the cryogenics is going to "be there" to allow HTS devices to become regular components of the national electrical grid. The failure to meet any of the three goals would constitute a serious obstacle to the eventual implementation of HTS devices.

<u>Efficiency</u>:

Efficiency is almost always discussed in terms of a fraction of the ideal *Carnot Efficiency*. In the *Cryogenic Roadmap* the stated efficiency goal is 30% of *Carnot Efficiency*. What is implied by this simple numerical goal and why is it important?

First of all, for a system operating between 300 K and 77 K, the Carnot factor is given by

$$\eta_c = T_c / (T_h - T_c) = 0.345.$$

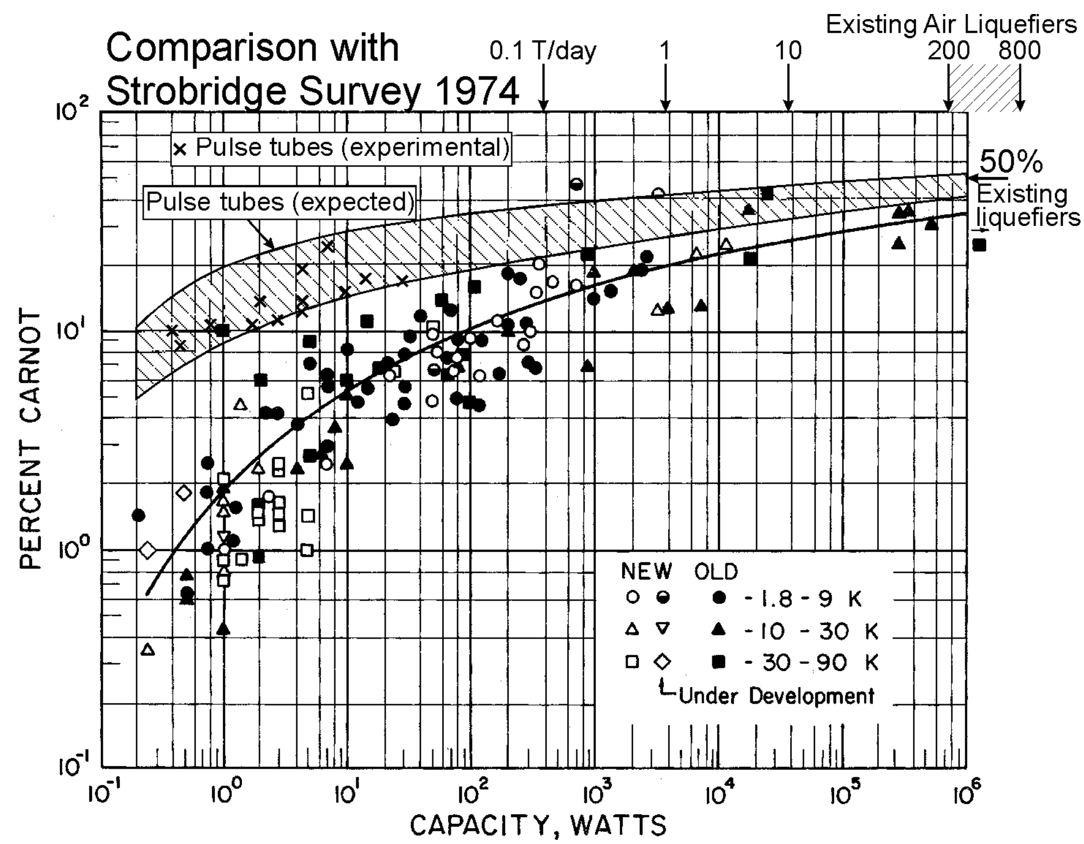
In this case, a cryogenic system with 30% of Carnot efficiency will have an overall efficiency of 0.345 x 0.30 = 0.10, or 10%. It is that latter number which must be inverted to give the *Specific Power*, the number of watts drawn from the power system to remove one watt of heat from the cold end.

In a somewhat different application where the cold end is at 64 K, the Carnot factor would be η_c = 0.27 and (for a system running at 30% of Carnot) the final efficiency = 8.1 %. It is easy to work out the corresponding numbers for colder operating temperatures (e.g., at 30 K, $\eta_c = 1/9$).

Clearly, even when we use the term "30% efficient", we are talking about *Specific Power* ratios exceeding a factor of 10. For more typical systems such as those commonly in use today, 15% efficiency is realistic, and at 77 K the *Specific Power* would be > 19.

The idea of cooling with a bath of LN_2 is always suggested as a way around the concern about efficiency. The cost of LN_2 is remarkably low when purchased in very large quantities, and this makes it very attractive. The price of cooling via LN_2 can be converted to a "per BTU" or "per kWh" basis. This calculation is carried out in Appendix 1. For today's typical price of LN_2 and the cost of a kWh of electricity, it turns out that a cryocooler having 30% of Carnot Efficiency is approximately equivalent to cooling with LN_2. However, the method of accomplishing this cooling may be significantly different. If the efficiency of cooling a HTS device (operating at 77 K) were only 20%, the LN_2 would be a preferred method of cooling unless other constraints, such as electrical insulation performance, presented significant difficulties.

The "Strobridge Plot" has been used since 1974 to display the relationship between efficiency and size of refrigerators[4]; a contemporary version appears here as figure 1. A very wide range of cryogenic devices all are condensed onto this graph; the



T. R. Strobridge, "Cryogenic Refrigerators - an Updated Survey, NBS Tech. Note 655 (1974)

Figure 1. Updated plot of efficiency vs. cryocooling capacity in watts

operating temperature T_{cold} has been taken out of this picture by employing a vertical axis expressed as a % of Carnot efficiency. Evidently the efficiency increases as size increases, but there has been a practical upper limit of about 40% of Carnot efficiency.

At this writing, there is no known refrigeration system of the size needed for HTS devices that functions anywhere near 30% of Carnot efficiency. Figure 1 shows some large cooling systems with nearly 40% efficiency, but those are huge liquid-hydrogen refrigerators used by NASA for providing rocket fuel. For HTS devices, the refrigerator needs to remove between 100 and 1000 W of heat from the cold side, and refrigerators of that size are more likely to have efficiencies around 10 % of Carnot.

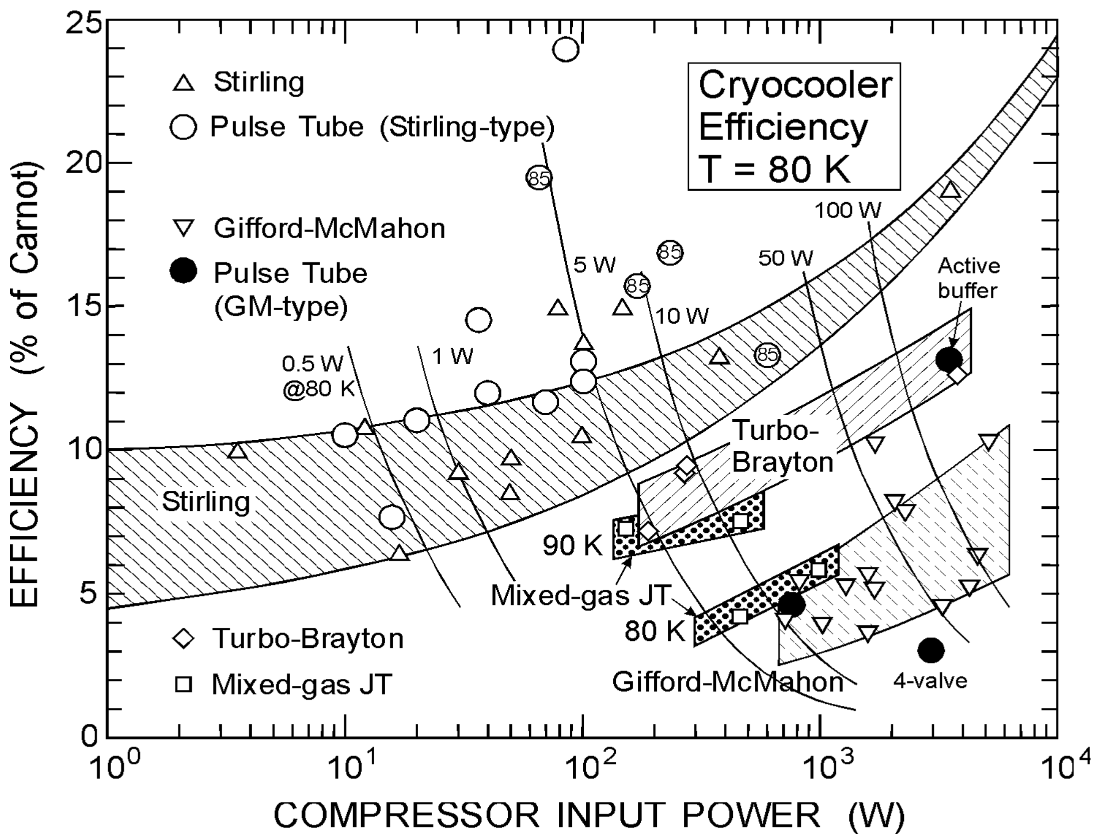


Figure 2. A detailed look at the Strobridge plot region of interest in power applications

In fact, figure 2 is a close-up of the central portion of the Strobridge Plot, and the plotted points are all for devices operating between 80 K and room temperature. The vertical axis is linear in efficiency, and the horizontal axis is logarithmic in the *input power*, which is convertible to the heat removed from the cold end via the *Specific Power*, a number that comes from the efficiency. (Curves of constant *cold-end power* slant across the shaded areas from upper left to lower right.)

The upper right of figure 2 is the area of interest for HTS electric power devices; if a device dissipates about 100 W at the cold end, the input power will be a few kW. The best systems extant (*Stirling* type) have about 20% of Carnot efficiency. Indeed, most are 10-15% of Carnot. **Thus, if we are to reach the goal of 30% efficiency in a practical HTS refrigeration system, major research accomplishments are required**.

What happens if the cryogenic efficiency goal cannot be reached? Calculations by Mulholland and co-workers[5] have considered the trade-off between the price of superconducting wire and the efficiency of cryogenics. For any representative size of some HTS device, such as a transformer or motor, there is a "break even" cost of the device, where the energy savings due to superconductivity just offset the higher cost of expensive component parts, compared to using conventional technology. If it costs more to run the cryogenics, then the HTS wire has to be cheaper in order to still reach break-even. Figure 3 shows one calculated example of the trade-offs: as cryogenic efficiency rises a factor of 3 from 10% to 30%, the acceptable cost of HTS wire rises by a factor of 4 ½. On this graph, each 1% increase in efficiency allows a cost increase in HTS wire of $ 5.45/meter. For other devices or other sizes of a particular device, the exact numbers will shift somewhat, because both the amount of wire and the cooling load are different in each case; but the principle remains the same[6], and the surprisingly high *elasticity* of the tradeoff remains as well.

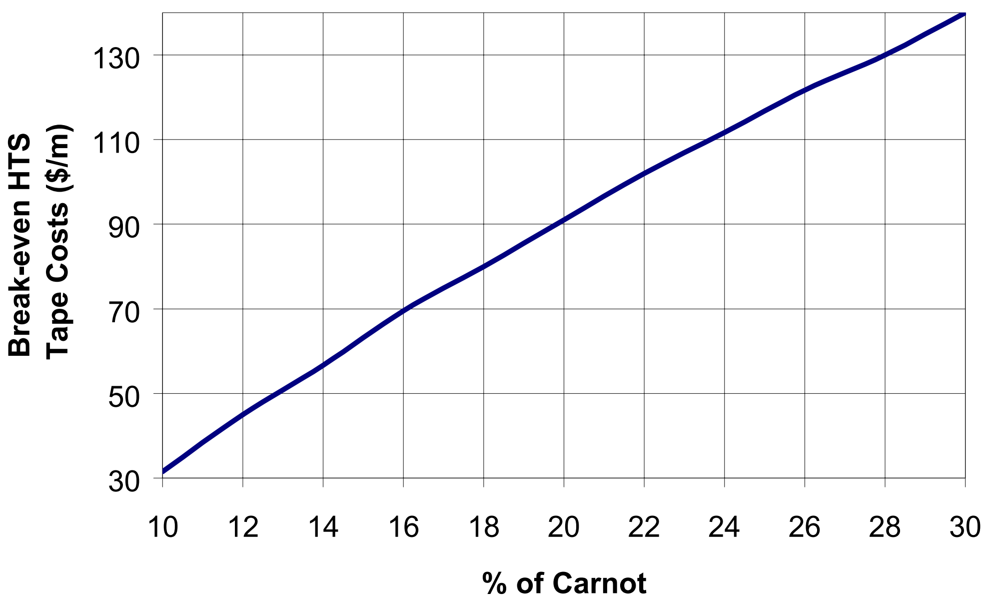


Figure 3. Breakeven cost for high temperature superconducting wire decrease with increasing cryocooler efficiency

Recognizing the ultimate difficulty of reducing first generation HTS wire costs[7], it is well worthwhile to diligently pursue the goal of increasing cryogenic efficiency in parallel with the development of second generation wire. **The strong coupling between needed cryogenic and wire performance cannot be overstated.**

Cost:

The *Cryogenic Roadmap* sets a target of $ 25 per watt of cooling for the capital cost of cryogenic equipment associated with HTS devices. This number is a compromise among many possible values, and roughly represents the idea that the cost of the cryogenics should not be more than about 10% of the cost of the total package. The

Cryogenic Roadmap goes on to discuss the difficulty associated with reducing capital cost from today's \$100/Watt to \$25/watt: an *economy of scale* associated with a large number of units produced is the most likely path. "…without fundamental breakthroughs in cryogenics it is doubtful that even \$ 50/W can be reached until the market size exceeds 10,000 units/year." That corresponds to an increase in market size for cryogenics of two orders of magnitude.

The *Cryogenic Roadmap* does not say *how* so large an increase in market size will come about. It suffices that the *Cryogenic Roadmap* terms this a "very aggressive goal."

There is little reason to expect any "relief" from the stringent upper limit of "10% of total cost" for the cryogenic components. In the deregulated electricity market that is gradually becoming commonplace in most states, the deliverer of electricity (i.e., the utility) has almost no financial motivation to buy energy-saving components that have a higher first cost – the recovery of capital investments over many years is no longer a parameter of interest to utilities.

Just as for the case of efficiency, there is also a trade-off between *capital* cost of cryogenics and the acceptable cost of HTS wire. Figure 4 was derived in a manner similar to figure 3: again the "break even" cost of the device was calculated, where the savings exactly offset the higher cost of HTS components (compared to conventional technology). In figure 4, as the capital cost of cryogenics rises by \$ 1000/kW (= \$ 1/W), the amount that can be spent on HTS wire decreases by \$ 3.44/meter. Again, variations in size or type make a finite numerical difference, but do not overshadow the basic relationship of the trade-off.

Another point about capital costs needs to be recognized. The savings due to HTS devices accrue gradually, and pay back the higher initial costs eventually over time,

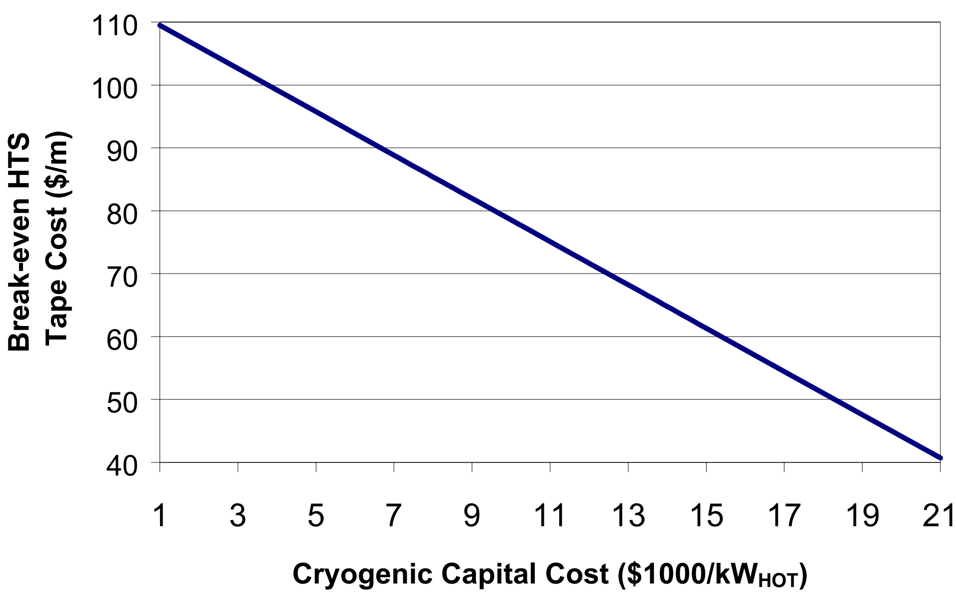


Figure 4. Maximum breakeven cost for high temperature superconducting tape decrease with increasing cryocooler capital cost

spanning the *life-cycle* of the object. Each buyer (factory or utility) will choose its own *discount rate* with which to determine the value of a future stream of income. However, in any case where the buyer is concerned **only** with lowest first cost, then no HTS device could ever appear profitable. With the changes that deregulation is causing in the electric power industry, utilities are finding it harder and harder to justify equipment purchases with substantial payback periods. This condition creates strong downward pressure on the capital costs of a device or its cryogenics.

Reliability:

Utilities are notorious for demanding astonishingly high reliability and their customers have grown to expect it. The *Cryogenic Roadmap* cites an availability requirement of operating 99.8% of the time. About the only way that mechanical equipment (such as refrigerators) can reach the numbers demanded is through *redundancy*, which generally implies a doubling of the amount of capital equipment, and thus a doubling of the cost. Thus, cost and reliability are strongly coupled.

One area that was not explored in detail in the *Cryogenic Roadmap* was the acceptable level of maintenance for various HTS device applications. The initial reaction of every utility to a new idea is "absolutely *no* maintenance!" However, in the exceptional niche case of a cable going under a dense city where there is absolutely no alternative but to use superconducting cable, then maintenance is begrudgingly tolerated. Still, for less draconian situations, the utility is customarily very reluctant to take on any additional requirements to pay attention to equipment. As a rule of thumb, scheduled maintenance at 3 to 5 year intervals is not considered too obtrusive.

The Transition:

The *Cryogenic Roadmap* summarized the historical way that hardware moves from the R&D stage to commercial viability, as the level of manufacturing graduates from single-unit specialty items to mass-production. Each upward step by an order of magnitude represents a major commitment by a private sector firm. There are large infusions of venture capital required at several stages along such a pathway. There is no reason to expect that the growth pathway of cryogenics for HTS devices can evade such a requirement.

A key consequence of this condition, recognized by all members of the *Cryogenic Roadmap* Steering Committee, is that it is absolutely essential that industry not only participates, but also ***leads*** the effort toward better cryogenics. It is simply not plausible for government to call the shots the way it would for a military or NASA procurement. The *Cryogenic Roadmap* called for cooperation between utilities, HTS device manufacturers, and cryogenic manufacturers.

The Technology Paths:

The *Cryogenic Roadmap* reviewed the technology associated with *Recuperative Cycle Cryocoolers*, such as *Turbo-Brayton* and *Joule-Thomson* cycles[8]; and with *Regenerative Cycle Cryocoolers*, especially the *Stirling Cycle*, *Gifford McMahon* and *Pulse Tube* devices[9]. Hybrid open-loop systems (combining LN_2 with vacuum pumping, etc.) were also noted. Optimizing the application of these technologies to specific HTS devices was considered as well, but the *Cryogenic Roadmap* was careful not to "pick winners" at this early stage.

Also noted was the possibility of using *Hybrid Systems*, in which a liquid nitrogen bath is combined with a mechanical refrigerator in some way. The LN_2 bath has the great advantage that it can "ride out" fluctuations in cooling demand, thus allowing the cooling system to be designed and built for the *average* load instead of the *peak* load. Also, reliability is enhanced because the margin of safety goes up when LN_2 is present for enhanced rapid cooling after an interruption.

Two other developing technologies that were not part of the original *Cryogenic Roadmap* and that deserve mention are *Pulse Tube Refrigerators* and *Thermoelectric Coolers*.

- One of the most promising new technologies is that of *Pulse Tube Refrigerators*, which Radebaugh has pioneered[10]. The enormous advantage of such devices is that they have no moving parts at low temperatures[11]. Pulse Tubes of the *Stirling* type have generally had small wattage capacities, but their efficiencies are good (black circles in figure 2). One unit has reached 24% of Carnot efficiency[12]. Pulse Tube Refrigerators of the *Gifford-McMahon* type (white circles in figure 2) are presently less efficient, but have higher capacity. The wish, of course, is that the best of both worlds will be achieved through R&D. If a *large* Pulse Tube Refrigerator can be made, there is good reason[13] to expect that its efficiency can exceed 30%.
- Thermoelectric coolers have received little publicity to date, despite great advances in the past five years. When dissimilar metals are joined[14], an electric field **E** is established by a thermal gradient, and the proportionality constant Q is known as the *thermopower*.[15]

  $$\mathbf{E} = Q\,\mathbf{grad}\,T,$$

  where T denotes the absolute temperature. (The more easily-measured *Peltier Coefficient* is $\Pi = Q\,T$.) This phenomenon can be exploited to carry away heat electrically, wherein lies the principle of a refrigerator. The basic relations governing *thermopower* have been known since the time of Lord Kelvin[16], but *thermopower* has remained mostly a laboratory curiosity (as was superconductivity prior to 1960). Denoting the electrical conductivity by σ and the thermal conductivity by κ, the figure of merit for *thermopower* is $Z\,T = Q^2\,\sigma\,T/\kappa$. With larger Z T, a greater ΔT can be maintained, which in turn means more cooling. Commonly, for most metals, $Z\,T \leq 1$. However, recently Rontani and Sham[17] have proposed on theoretical grounds that a layered structure of metal and rare-earth compound semiconductors (specifically, electronic ferroelectrics[18]) might exhibit much higher Z T values, perhaps > 10 at 77 K.

Since the HTS community is well accustomed to depositing consecutive layers of different materials, it does not seem out of reach to imagine a practical cryocooler someday made from such materials. However, this idea is still in its infancy, having had no experimental data gathered so far. Nevertheless, it serves to remind us that new concepts can come along at any time.

The Research Direction:

An excerpt from the summary of the *Cryogenic Roadmap* succinctly captures its primary conclusion: "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."

The Steering Committee was united in recommending that the research be pursued via the mechanism of *Superconducting Partnership Initiatives* (SPIs). The favorable results achieved so far for HTS devices argues that a similar outcome might be expected for the associated cryogenics. The partners in an SPI typically include industry, utilities, and national laboratories.

The primacy of the industrial partner was characterized as follows: "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. … Ultimately, industry will choose the manufacturing goals, define a practical timetable, and establish the go/no-go decision points."

The Timetable:

The *Cryogenic Roadmap* suggested a series of steps over several years, as follows:

2001: Cryogenic SPI teams form
2002: funds-matching provided and collaborative research work begins
2003: bench testing and prototyping
2004: implementing real systems
2005: field trials
2006: final refinements – *proven* hardware completed
2007: first market entry

Obviously there are many contingencies associated with any real schedule, as contrasted to this very brief sketch. The sustained commitment of the industrial and utility partners is essential to the success of any such development program.

Outlook and Plans

Can the ideas promoted in the *Cryogenic Roadmap* come true? Is the motivation sufficient, and are the resources available, to accomplish the goal stated there: the presence of fully commercial cryogenic refrigerators that serve HTS power devices deployed in the American utility grid? This section focuses on the plans to reach that goal, and the obstacles that stand in the way. A combination of both business conditions and technical parameters will influence the outcome.

Obstacles:

It is convenient to categorize the various obstacles as either "technical" or "business" or "institutional" obstacles.

Technical Obstacles: The foremost technical obstacle is inefficiency. While everyone accepts *Carnot's Principle* as inviolable[19], still it is disappointing that actual devices show efficiencies near 10% of Carnot efficiency. Even the best R&D results don't quite reach 30%, which the *Cryogenic Roadmap* defined as a goal. Many of the calculations in the Mulholland report assumed 30% efficiency, and without that the high cost of cryogenics would prevent most HTS power devices from being profitable. Therefore, increasing efficiency is a primary technical objective. The improvements in heat pump and air conditioning efficiency suggest that industry driven R&D in cryogenic efficiency will be successful.

Within this broad category, there are subordinate technical issues. One important technical obstacle has to do with heat transfer from a "cold head". Several of the relatively efficient types of *regenerative* cryogenic systems conduct heat away from one point that is cold[20]. Stirling systems, Gifford McMahon systems and pulse tube refrigerators all have that in common. The helium gas moving through the regenerator and displacer only collects heat from a small vicinity. If a solid bar of copper is connected to that point, then another nearby point (termed the "cold head") can be equally cold, due to the high efficiency of conductive heat transfer through a copper rod.

The transfer of heat by *convection* from points farther from the cold head is another story. Many potential HTS power applications need to have gases or liquids in motion in order to cool a larger region. When that requirement is added, some form of ancillary heat exchanger is necessary, and that in turn reduces the overall efficiency of the cryogenic system. The Brayton cycle and the Joule-Thomson cycle are *recuperative* systems that transport gases around the apparatus. It has been an elusive goal for some time to construct a recuperative system having the efficiency of a regenerative system[21]. Another elusive goal is to decrease the size of a Brayton device without sacrificing efficiency. The right-central region of figure 2 shows not only that the efficiency of Turbo-Brayton refrigerators decline with size, but also that the lower limit of their size is near 200 W input power.

Other technical obstacles include the well-known condition that any moving part at low temperature is subject to more rapid wear, and risks seizing up when any impurity is present (perhaps tiny amounts of compressor pump-oil). The elimination of all moving parts at the cold end is being pursued mainly via the path of *Pulse Tube Refrigerators*,

These are examples of "generic" issues that cryogenics manufacturers are working on; there is nothing specifically "superconducting" associated with them. In striving for better HTS electrical devices, improvements in these categories are certainly eligible for attention, but there is definitely not any "exclusivity" here by which *only* superconductivity applications care about these issues.

Business Obstacles: The present status of cryogenics for HTS devices can best be characterized by the French word *impasse* (dead end).

At this time, there is no particular reason for a utility to buy HTS devices, because they are so expensive, in part because of cryogenics costs. To meet the huge potential market of electrical utilities, the cryogenics will have to be very cheap, which implies building many units, and selling each at a very low profit margin.

On the other hand, cryogenic manufacturers have no motivation to gear up for major production of specialized cooling units that have an uncertain market. That uncertainty has very deep roots. Essential parameters such as the cooling capacity needed for various HTS devices are unknown. We can't even predict the AC losses reliably, a key element of forecasting cooling requirements. Furthermore, secondary parameters such as tolerable vibration levels are likewise unknown. What's worse, they will **remain unknown** ***even after another round of SPIs*** -- unless a sufficient range of cooling loads is explored to build up a body of data that enables designers to predict the cooling capacity required for all plausible sizes of the various HTS devices --- a very large order.

From the viewpoint of a cryogenic manufacturer, it is much more attractive to follow the terms of a precise contract and sell a few specialized units to NASA or military researchers at a high profit margin. The ratio of risk to reward is very unfavorable for entering the HTS power device open marketplace at this time.

It is not clear that there is a solution to this impasse, short of government purchases of specific cryogenic units for particular projects (i.e., emulating NASA). Given that the philosophical stance of the entire HTS / SPI program is to rely on industry initiative and industry leadership, it would be a major departure from custom to place such a purchase order.

High **cost** is another business obstacle. If the only way to drive down cost is via mass production, then we are at the mercy of a feedback loop that may never start to run at all, because of the "impasse" cited above. There is a need for innovative engineering directed toward reducing the cost of manufacturing cryogenic systems. Ordinarily such cost-reduction engineering is done entirely within the private sector, under company secrecy.

Institutional Obstacles: The two major institutional obstacles are regulated utility structure and the role of government.

Utilities: As entities that provide an essential public service and are therefore regulated, utilities stand in a unique position somewhere between government and business. In serving society, their primary objective is to deliver electricity flawlessly; and in exchange for this the Public Utilities Commission assures them of a fair chance to make a reasonable profit. Accordingly, their foremost thought is about reliability. Deregulation of electric generation would not eliminate this since transmission and distribution systems will remain regulated.

Associated with the matter of ***Reliability*** there is an obstacle that sits astride the technical/business interface**.** When reliability is achieve through redundancy, the capital cost is roughly doubled, but the demands upon the technology are relaxed. That's the simplest solution. However, the associated high cost will decrease the probability of a business decision in favor of buying HTS devices.

Even with superior technology that in fact **is** highly reliable (a no-moving-parts cryocooler comes to mind), still there is reluctance by utilities to risk any downtime caused by new equipment. After all, each of these component replacements only saves 1% or so of the throughput electricity. Consequently, the first two decades of HTS devices serving the national electrical grid will likely be characterized by redundancy, even after it has been proven technically unnecessary. This will slow the entry of HTS technology into the utility marketplace.

Government: The age-old question - "Is there a government role here?" - deserves attention. As in so many areas of technology, there are exceptional capabilities within the National Labs that can be brought to bear on the scientific questions about cryogenics. But having a *capability* does not necessarily imply a *role*. The underlying question asks whether government participation benefits the society at large, and whether participation in this particular R&D is the best use of the government's finite resources.

A prominent new condition is that, with the recent/incipient deregulation of the electric power marketplace, the economics has changed such that utilities (now simply *deliverers* of electricity) can no longer afford R&D for electrical devices. That shifts the locus of the debate about what the proper role of government should be.

Such a question cannot be resolved here. It suffices to note that over the history of the *Superconductivity Program for Electric Power Systems*, the continuing cooperation between public and private sector entities has accomplished a great deal, and so it is reasonable to think that it can continue doing so. Therefore, we might pose the question "What are the various avenues open to the Department of Energy as the future of HTS unfolds?"

Government Program Plans

The Department of Energy, through it's Golden Field Office, has issued a solicitation for a second round of HTS devices. This time the cryogenics will be an integral component of the total system.

There is widespread agreement on the need for integrating the cryogenics. Major superconducting projects of the past (such as the Brookhaven[22] cable project of the 1980s) needed to have integrated refrigeration systems. When cryogenics was an afterthought (one thinks of the SMES at Takoma WA), the problems never went away[23]. It is reasonable that a first round of SPI projects would devote primary attention to getting the basic HTS device to work, but anything that is to lead to a commercial product must behave as a total system, so that the utility can remain oblivious to its details.

One major advantage of using the SPI structure to carry out a project is that the various industrial partners know quite clearly from their utility colleagues just what has to be done to make the device acceptable. The combination of practical experience by working engineers, together with a commitment of stockholder's money, is a powerful motivator to keep a project on track.

We can identify three general scenarios for DOE participation in driving cryogenic systems development for cooling HTS devices:

The "Standard" option:

A major recommendation of the *Cryogenic Roadmap* was to conduct a second round of SPI projects with the cryogenics fully integrated into the HTS devices. Since that is in fact the pathway that the Department of Energy has started down, it is convenient to term this the "standard" option. The timetable for this option is compatible with the projected multi-year, multi-phase scenario envisioned by the *Cryogenic*

Roadmap steering committee. Still, there are other factors beyond the finite boundaries of the *Cryogenic Roadmap.*

One factor that the Department of Energy has had to live with is the policy of single-year funding. It would be better to have this program exempted from that requirement, in order to ensure continuity to the private-sector parties to each SPI. Perhaps the excellent 10-year track record of the *Superconductivity Program for Electric Systems* could be employed to argue for such an exception.

A long-term commitment from government and national lab partners enables private-sector partners to plan coherently for the entire development cycle of a product. The value of such a commitment is very great, and should not be underestimated. Past conflicts between Congress and previous administrations should be relegated to the past in the interest of strengthening the cooperative R&D that makes technological innovations "come true".

The "Aggressive" option:

In this option, we envision a program in which SPI projects are specifically focused upon developing better cryogenics, as contrasted to making the cryogenics an integral part of the HTS electrical device. This would involve an excursion away from past practice by the Department of Energy, which has heretofore left cryogenics R&D to the sponsorship of other agencies, notably the military and NASA.

For such a program to be both comprehensive and fair, it would be necessary to form several SPIs that tackle more than one avenue of R&D. The goal of a "one size fits all" cryogenic system is easy to talk about, but very difficult to achieve in practice. For example, the cooling requirements are quite different between an electric motor and a transformer (movement of fluids, transport of heat, etc.), and that may dictate a fundamentally different choice of refrigeration cycle for each.

Again, the most fundamental principle of any SPI is that it be led by industry, which can better project future markets than can government scientists. Industry signals its confidence in its own ideas with a financial commitment; if the idea turns out poorly, the money is simply lost. No government-run program has so strong an incentive to guide decision-making. It would be an entirely natural outcome of an aggressive multi-SPI program in cryogenics R&D for some of the projects to fold at early stages. The more successful projects would move on to stages where the government steps aside and the private sector takes over entirely on the path to full commercialization.

If two or more different cryogenic systems are striving to capture market share, each will sell fewer units and the corresponding economy-of-scale factor will be less influential. However, competition has always helped to drive down prices. The urgency to innovate in a cost-saving way is enhanced by competition.

***The "No-Action" option*:**

When a state highway department begins to design a new freeway, one option that is always considered is the "no-build" option, that is: do nothing. The superconducting equivalent of that is to let market forces alone set the direction and determine the outcome. There is a body of opinion that prefers this scenario, on the grounds that the cryogenic industry is strong enough to respond to whatever orders customers send its way. The 1998 Workshop was the first appearance of a nifty slogan from the movie

Field of Dreams: "If you build it, they will come." In other words, given enough market demand, adequate cryogenic systems will be built.

En route to completing the Mulholland Report, calculations were done that simulate such a "no-action" condition. Both the operating efficiency and the capital cost (per kW) were allowed to remain at today's levels until naturally occurring increases in the number of units manufactured enabled the price to drift downward. Built into the Mulholland model is a feedback loop that links the degree of market penetration to the profitability of buying any new device; obviously losing investments are never made deliberately. The outcome of that calculation was that there was *zero* market penetration, because the high cost of cryogenics destroyed the profitability. Consequently there was no increase in the number of units produced, and the price of cryogenics *never* dropped. The HTS electric power devices vanished from the marketplace.

Because of this (and because there is good reason to believe that the Mulholland model has validity), we feel that the "no action" scenario would lead only to frustration and disappointment. It is ***not recommended***.

There is one way that the "no action" scenario might yield eventual sales: If an entirely new market, outside the scope of the Mulholland report (outside of the efficiency driven applications in the electrical utility industry), were to come into existence, and that market brought with it a large demand for cryogenics, then there would be increases in the number of refrigeration systems produced, and their price would drop. The cellular telephone industry may be such a model because if hundreds of thousands of base-stations are installed nationwide using HTS-coated bandpass filters, and each base station required cooling at 77 K, a substantial production level of cryogenics would come into existence. This economy-of-scale would clearly benefit the electrical utility market. Since this market is itself developing and the cryogenic refrigeration systems are smaller, to presume such an indirect bonanza wouldn't be prudent, at this juncture.

Conclusions

In this *Implementation Plan*, we have presented a picture of where we are and what needs to be done to provide the refrigeration necessary for HTS power devices to become part of the U.S. electrical grid. To do so, we have collected inputs from previous studies, workshops and road mapping efforts.

An assembly of interested parties from national laboratories, universities, industry and utilities met in two workshops (July 1998 and July 1999) to share their diverse expertise about cryogenics to support superconducting electric power systems. Following that, a steering committee prepared a *Cryogenic Roadmap* in late 1999, and that document delineated the central issues facing both scientific researchers and business entrepreneurs in the time ahead.

The steering committee discerned that the three foremost technical criteria involve *cost, reliability,* and *efficiency*. Drawing upon widespread backgrounds of contributors, and following extensive discussion, explicit numerical goals were set for all three parameters. Those numbers came from a combination of both engineering and business factors, and are very ambitious. However, for HTS devices to be accepted by utilities, all three goals have to be met.

The *Cryogenic Roadmap* went on to discuss different possible technology paths, identify certain research directions, and define a timetable. The recommended way to achieve the research goals was to establish *Superconducting Partnership Initiatives* (SPIs) involving National Labs, cryogenic equipment manufacturers, and utilities.

There are obstacles in the path toward commercial success of cryogenics for HTS devices. The foremost *technical* obstacle is the efficiency: commercial cryogenic systems operate near 15% of *Carnot Efficiency*, but HTS devices need refrigerators having 30% efficiency. This is no easy task, and requires very substantial advances in R&D. Other technical obstacles include the problem of removing heat via convection, and the severe wear associated with moving parts at low temperatures.

HTS devices tend to generate between 100 and 1000 Watts at the cold end, and cryogenic systems must be sized accordingly. The major *business* obstacle is that there is insufficient incentive for cryogenic manufacturers to invest in sufficient mass-production capacity to bring down the unit price of refrigerators of this size range. Moreover, until there is mass production and the price comes down, the systems will be too expensive to allow the associated HTS devices to be profitable. This is a "feedback loop" that leads to an impasse, and the way out is not apparent.

The absolute requirement for *reliability* among utilities creates an *institutional* obstacle that deters introduction of new technology. The usual way to assure reliability is through redundancy, but that escalates the cost and destroys profitability. Moreover, under electricity deregulation, utilities are only *deliverers* of electricity, and cannot afford the R&D needed to advance HTS devices, including their cryogenic systems.

In this *Implementation Plan*, we consider the government role in the future of cryogenics for HTS. We construct three scenarios, which span the various possible levels of government participation. In the "no-action" option, the evolution of cryogenics is left entirely to the free market, and nothing happens; it is not a recommended approach. The "standard" option envisions SPIs for another generation of HTS devices that include the cryogenic system. The "aggressive" option features SPI projects devoted *entirely* to cryogenics. In all cases, we emphasize that the government must not try to "pick winners". We have great confidence that only *industry* leadership can assure that the cryogenic systems produced will eventually be commercially successful.

Our central conclusion is that cryogenics for HTS devices can best be advanced via National Lab cooperation with industry and utilities, using the SPI mechanism.

Appendix 1

A Comparison of LN_2 Cooling vs. High-efficiency Cryocoolers

Given any specific purchase price for liquid nitrogen, it is possible to produce a dollar figure for the cost of carrying away a certain amount of heat. Similarly, given a cost of electricity per kWh, it is possible to look at any proposed cryocooler and determine what its cost would be to carry away that heat. In this manner it is possible to compare the two cooling techniques on an "apples to apples" basis.

The Latent Heat of vaporization (L_v) of LN_2, is 198 kJ/kg at atmospheric pressure. However, since LN_2 is sold by the liter, one must convert kg to liters, using the density of LN_2 (ρ = 0.808 g/cc = 0.808 kg/liter). Electricity is priced by the kWh and 1 kWh = 3600 kJ. Hence, L_v = 198 kJ/kg x 0.808 kg/liter /3600 kJ/kWh = 0.044 kWh/liter at 77 K and 1 Atm.

Note, however, that the nitrogen gas is at 77 K and can be used to cool the system further as its temperature slowly rises toward room temperature under appropriate controlled conditions. Thus, the total heat carried away by a mass, *m,* of nitrogen as it warms up from the liquid state is given by:

$$\Delta Q = (L_v + C_v \Delta T) \times m,$$

where C_v = 1.038 kJ/kg- ^oK. Of course, the unknown in this analysis is *how much* of an increase in ΔT the gas experiences while it is still usefully cooling its surroundings. If, for example, we take ΔT = 10 K, then the factor ($L_v + C_v \Delta T$) rises from 198 to 208, but if ΔT = 100 K, then it rises to 302. Evidently some amount of information is required about the exit path for the gas and the continued cooling effects of the vaporized nitrogen.

Once a value for ΔT is chosen, one can calculate how much heat will be removed by a liter of LN_2. Alternately, by imposing a fixed heat removal rate, such as dQ/dt = 10 kW, then the formula can provide the flow rate of LN_2 required to remove this heat load.

For a heat load of dQ/dt = 10 kW, consider the following three examples:

- If ΔT = 0 K (liquid L_v alone), 0.063 liters/sec will be evaporated.
- If ΔT = 10 K, 0.059 l/s will be consumed; alternately, 10 kWh will require 213.8 liters of LN_2 for its removal.
- If ΔT = 100 K, the LN_2 is much more efficient, requiring only 0.041 l/s and removing 10 kWh will require only 147.6 liters of LN_2.

To make monetary comparisons, it is necessary to estimate the useful temperature rise, and settle upon one value for the effective average heat capacity. For purposes of comparison, assume that 150 liters can remove 10 kWh of heat, which corresponds to a useful temperature rise of slightly less than 100 K. While it may be argued that this is too generous toward liquid nitrogen, the objective of this calculation is to set upper bounds.

In the most favorable case (i.e., truckload quantities) LN_2 sells for about 6 cents per liter. In smaller quantities, such as a laboratory Dewar, it might be 40 times that much. Assuming a feed system of pipes and controls that functions perfectly at all times and the $ 0.06 figure for an HTS device installed in a utility application, one can calculate that it costs $9.00 to remove 10 kWh of heat, or $0.90/kWh. While specific costs of components are very uncertain, adding in a reasonable capital cost for any storage tanks, heat exchanges, pumps and control equipment and applying appropriate carrying charges increases the effective cooling cost of LN_2 to about $1.20/kWh.

For the next stage of the comparison, it is necessary to ask about the *specific* power of a hypothetical cryocooler operating electrically between 300 K and 77 K. A cryocooler with a *specific power* of 15 draws 15 watts from the wall to remove one watt of heat from the cold end. If the cost of electricity is $ 0.04/kWh (the wholesale price, which a utility would charge itself) then it costs $ 0.60/kWh to remove heat this way. If an external customer is paying $ 0.08/kWh for electricity, then heat removal costs $1.20/kWh, which appears to be "a dead heat." But adding in the capital costs for the cryocooler increases the effective cost to $1.00 and $1.60 respectively for a cryocooler capital cost of $35/W and capital carrying cost of 10%/yr. These two prices bracket the figure for LN_2. The entire analysis depends upon assumptions about ΔT, the price of LN_2, cryocooler costs, cost of money, etc. Change any of these assumptions and the results can be very different.

How realistic is a *specific power* of 15? Using the standard *Carnot* factor between 300 and 77 K, $\eta_c = 0.345$, a total efficiency of 1/15 corresponds to a cryogenic system operating at about 20% of Carnot efficiency. That is within the plausible range for cryocoolers now emerging into the marketplace. The capital cost of $35/W is about 33-50% of current capital costs for cryocoolers of this size and could be within reach if the number of cryocoolers produced increased to expected levels.

A hypothetical future cryocooler operating at 30% of Carnot efficiency would have a *specific power* of only 10. In that case, if any cost at all were assigned to handling LN_2, then even at an electricity price of $ 0.09/kWh, it would be better to go with the cryocooler instead of LN_2.

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