Appendix A

Members of Steering Committee

for Cryogenic Roadmap

Dick Blaugher	N R E L	303 384 6518
Phil Blumenfeld	Los Alamos	505 667 5735
Jonathan Demko	Oak Ridge	423 574 1469
Jon Jipping	Detroit Edison	734 397 4246
Nathan Kelley	Pirelli	803 951 4089
Ken Kreinbrink	PHPK Technologies	614 436 9114
Ralph Longsworth	APD Cryogenics	610 791 6708
Jim Maguire	American Superconductor	508 621 4143
Jerry Martin	Mesoscopic Devices	303 466 6968
Ray Radebaugh	N I S T	303 497 3710
V. R. Ramanan	A B B	919 856 2423
Tom Sheahen	Argonne / SAIC	301 924 6150
Phil Winkler	Air Products	610 481 4284
Burt Zhang	Rockwell Automation	216 266 7150

Appendix B

Summary of 1998 Workshop

Cryogenics Needs of Future
HTS Electric Power Equipment

July 22, 1998

This workshop addressed the question: Will practical cryogenic refrigerators be available to meet the needs of emerging superconducting power systems over the next five to ten years? Dr. Christine Platt chaired the event.

There were two panels, consisting of

a) SPI partners making HTS devices, and
b) Cryogenic manufacturers.

Marty Nisenoff of Naval Research Laboratory gave a *Keynote Presentation*, describing the R&D goals of DARPA, aimed toward low-cost, high-reliability cryocoolers. In a pair of memorable lines reminiscent of the movie *Field of Dreams*, Nisenoff characterized the current relationship between users and manufacturers as:

HTS Community: "If we will build it (HTS systems) they (cryocooler community) will come;

Cryocooler community: "If they (HTS community) will come with <u>*large*</u> *orders, we will build it (low-cost, reliable cryocoolers).*

Any goal looks much more attainable on log-log paper, and that is certainly true of cryocoolers and their cost. Figure A1 here is taken from Nisenoff's presentation, and shows where coolers are today and what the DARPA goals are.

Another useful summary appears in Table 1: this is a summary of *Cryocooler Requirements* as stated by the SPI partners building each of the HTS applications. It was compiled <u>after</u> the 1998 workshop, with entries drawn from the presentations.

Each of the two panels consisted of a series of presentations by the panelists. The slides that each speaker showed are assembled in the volume of the Workshop Proceedings, and adequately describe those talks.

Open discussion among all the attendees followed the second panel. The intent of that discussion was to identify the most important issues for further attention. Pp. 139-141 of the *Proceedings* enumerate some of the major points of discussion. The topics broke into two broad categories: *Performance Gaps* and *Technology Development Needs*. The key points are as follows:

Obvious: Reduce the heat load !

Higher efficiency, greater reliability and smaller size are always needed.

Since the electrical load varies, so does the cooling load. A variable cooling-power capability is desirable.

There is a "gap" in available cryocoolers between 100 W and 1 kW. For most SPI projects, the cooling requirement lies in between Gifford-McMahon and Brayton-cycle units. The feasibility of scaling <u>up</u> small systems or scaling <u>down</u> large systems needs to be explored. Pulse-tube refrigerators and closed-loop Stirling cycles are particularly interesting here.

The losses in transformers are so small to begin with that the available i^2R savings will be squandered on cooling losses unless the refrigeration system is very small.

Cables have a large surface area per unit length, and generate a large thermal load. 50 kW is a typical requirement, so the refrigeration system will comprise a significant percentage of the total cost.

Cryogenic manufacturers are confident they can build suitable refrigerators, but they await evidence of real demand for their systems before going ahead with the expense of development efforts.

Research needed includes: better insulation; and better transport of fluids in a cryogenic environment.

"There needs to be a collaborative approach in working with HTS equipment manufacturers, cryogenic system manufacturers, the national labs and DOE."

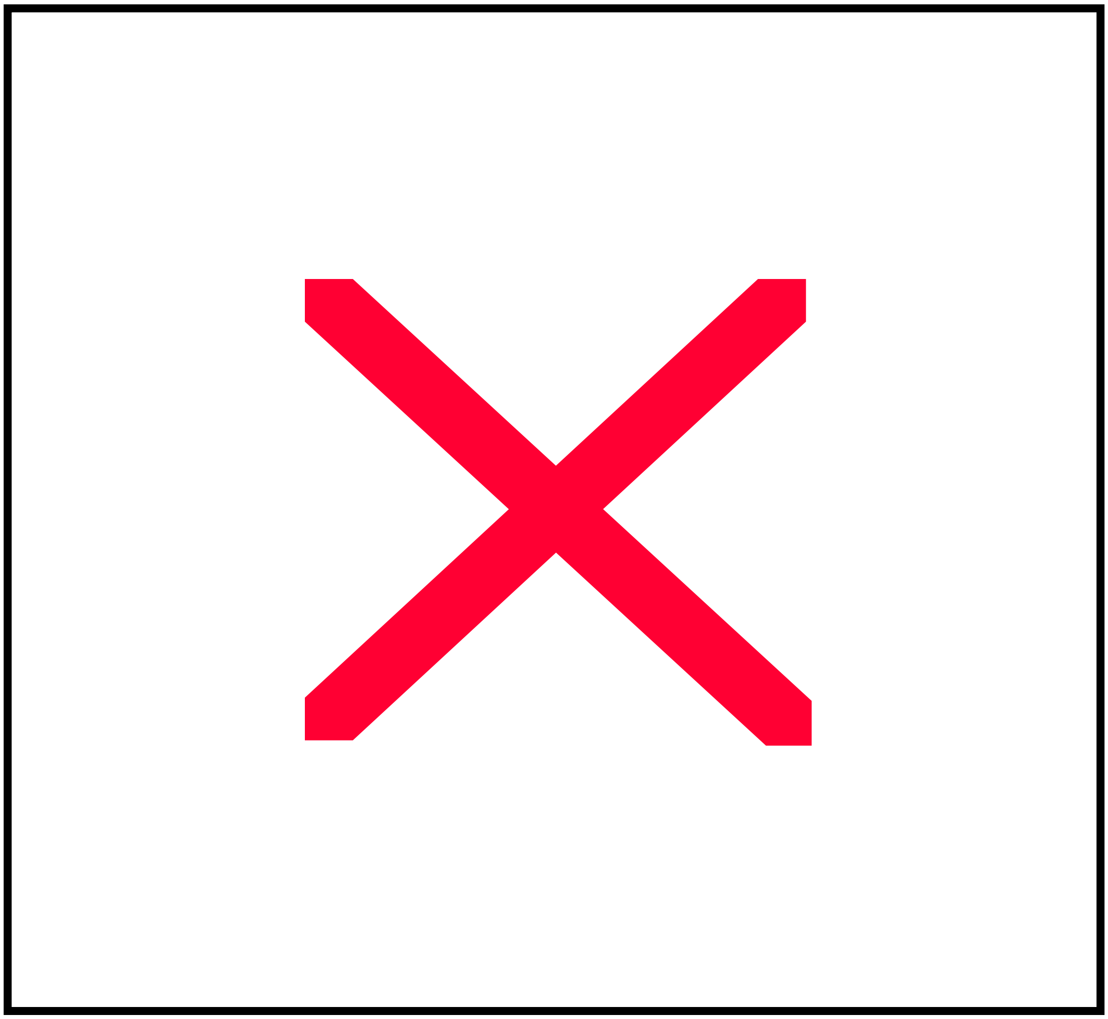
The 1999 Workshop is intended to take up where the 1998 Workshop left off. Specifically, we need to answer two questions:

What exactly is needed to meet the cryogenic needs of future HTS power devices?

And

What program of collaborative R&D will get us there?

Of course it is exceedingly difficult to say that some R&D path *will* reach a goal. The activity of *roadmapping* is an endeavor to set goals, identify the obstacles to success, and devise a plan for overcoming them. A good roadmap will say what each partner will contribute to the R&D effort, and in what time-frame. Our purpose in holding the 1999 Workshop is to begin the process of making that roadmap.



upplemental M

Figure A1 – Effects of production quantity on cost

Appendix C

Summary of 1999 Workshop

On the afternoon of July 27, 1999, a workshop was held to examine the concept of forming a "roadmap" for future cryogenics R&D. This followed two morning sessions (attended by fewer people because they were in parallel with the Peer Review sessions) in which certain aspects of the task were considered in more depth.

A year earlier, on July 22, 1998, a workshop took place that looked at the present state of the art in cryogenic refrigerators, and asked the Superconducting Partnership Initiative (SPI) participants to state what they foresaw as their future cryogenic needs. That conference (the proceedings of which have been published under the title *Cryogenic Needs of Future HTS Electrical Power Equipment)* was summarized by Tom Sheahen of Argonne National Laboratory; that summary is Appendix B.

The existence of a desired future state constitutes a goal, but so what? At this year's workshop, Dr. James G. Daley of DOE explained that we ask the question "How do we get from here to there?" Our goal is to produce a *roadmap*, and this 1999 workshop is the beginning of that process. Jim Daley also pointed out that there is no guarantee that DOE is going to conduct any particular research as a result of this effort; indeed, it is possible that DOE should *not* be involved in cryogenics research at all. Jim reminded the attendees that in 1991, OSTP basically said that NASA and DOD should lead the cryogenics effort. Thus, it is fair to ask at the outset: "What role, if any, should be assigned to the government, and to DOE in particular?" Because America already has a cryogenics industry, it must be recognized that one possible answer is "none!"

The role of NASA in contemporary cryogenics research was described by James Fesmire. NASA is focusing on *insulation*. NASA tests long lines (flexible or rigid) up to 40 m in length. For their applications, *thermal performance* dominates their criteria. Thermal insulation must be *robust*, and therefore several things need to be developed. In conventional devices, either foam or Multi-Layer Insulation (MLI) is used, and the k-values are around 30, which implies losses of about 0.1 mW/meter-^{o}K. MLI has many drawbacks, but hopes to reach a k-value of 0.01 mW/meter-^{o}K; in the lab, they've hit 0.05, but in actual devices it's more like 0.1. (All this is for systems running between 300 K and 77 K.) Mr. Fesmire showed a chart on which 150 different tests were plotted; the values tended to coalesce around a certain relationship, at least on log-log paper. Jim Fesmire pointed out that the actual performance of a flexible cryostat is 3 to 10 times worse than you would like to expect. In conclusion, he noted that an overall heat leak of 1 W/meter is achievable, but not easy. NASA will continue its testing program, in cooperation with Oak Ridge.

Dr. Marty Nisenoff described ongoing cryogenics research at DOD. The military makes infrared detectors that operate at 77 K, and there is a need to remove about 1 watt. However, the *bigger* applications are too big for the military at this time. Nisenoff reported that Carrier's *Stirling cooler* removes 350 W @ 77 K, with only 3500 W input; this means the efficiency is above 30% of *Carnot efficiency,* which is quite good. More and more people are working on small cryocoolers. Pulse-tube *Gifford McMahon* (GM) machines are used to cool to 55 K and remove 15 W.

Nisenoff also drew attention to the importance of <u>cost</u>: Knowing that large quantities drive the price down, you would have to manufacture 10,000 units to get the price down to $1,000. A market of only 1,000 such units would be too small to interest the cryogenic manufacturers.

Marty made an additional point about *reliability*: It is important to use proven design concepts that really work in *hardware*. When you get to *quantity* production (hundred's per month), then you get high reliability. Between this and the cost, you cannot "technology push" here -- there has to be "market pull" if commercial applications are ever to be realized.

(Earlier, during a morning session, Carl Rosner of Intermagnetics General Corp. had sketched the history of MRI units. Their first unit was built in the 1960s, and needed refilling with liquid Helium weekly, because it lost 1 liter/hour of He. Today, their MRI units lose only 5 - 10 cc/day, and need refilling every 3 to 5 years. That's good, sound engineering progress, of course; but it took 30 years to get there.)

Following the presentations about NASA and DOD research, Joe Badin of Energetics explained what a *roadmap* consists of: Basically, we define the endpoint and state where we are now, and then work backward. We seek to find the technology path that connects the two. To form a good roadmap, a collection of interested parties get involved. The *vision* is to be defined by industry. A *technology roadmap* is a way to achieve that vision. Implementing this requires a multi-year action plan. There are complementary roles for industry and government. Government is a *partner*, not necessarily a *sponsor*. The government tends to facilitate, coordinate, leverage and disseminate results; but the real *work* gets done by industry. Various "industries of the future" have constructed roadmaps; Joe Badin cited some examples. A workshop such as this is a *tool* to get you to the roadmap, not the roadmap itself. It is important to get the right people together for the task.

Following a break, the two morning meetings were summarized.

1. First Nathan Kelley of Pirelli Cable discussed the *vision* meeting. The basic question was "What will the cryocoolers of the future look like?" A modular, generic design would be helpful, one that meets everyone's needs; but their own project (cables) may not have exactly the same needs as other applications. To the utilities, *reliability* and *safety* are paramount. What will have to be *proved* before the cryosystem is acceptable?

We need to ask how to make the cryogenic system "transparent" to the user. Also, we must ask "What is the market?" and "Who will buy it?"

For the most part, the utilities just want to buy "cold" as a service -- they don't care about the details. However, the system needs to be unmanned, with no intervention by utility technicians required. But having the "cheapest" solution is not the only criterion. We must ask whether a customer wants on-site refrigeration, or trucked-in LN_2. The idea of a hybrid system, combining a cryocooler with LN_2 backup, was considered more reliable; the roadmap should examine the cost trade-off between hybrid and non-redundant systems.

Other criteria include *maintenance*, where 5 to 10 years intervals is expected; on the electronics side, 3 to 5 years is acceptable. It is desirable to "swap and drop" at maintenance times. Utilities are not going to have a staff of trained cryo-engineers.

Kelley also reported that the morning meeting had examined the trade-off between reliability and temperature. For example, if you're already at 77 K, is it worth it to spend money on a mechanical system to reach 70 K or 64 K? Certainly, the roadmap needs to look at temperatures other than 77 K.

Among other things, the operating requirements call for running at ambient temperatures up to 75 C. Moreover, the *footprint* must be small for the cryosystem to be acceptable.

2. The second morning session, dealing with R&D needs, was summarized by Ken Kreinbrink of PHPK Technology. He enumerated several priorities:

1. The first goal is to reduce cost. The cryogenics needs to comprise less than 10% of the total system cost. For example, a 600 W system should cost under $ 70,000.

2. Efficiency needs to increase. We think we can get 30% of Carnot efficiency; we'd like to reach 40%.

3. Most operating systems will be at 77 K or above.

4. The system needs to operate for 5 years without maintenance, so it must be very simple and very reliable. We want fail-safe performance, too; can that requirement tolerate delivery of cryogens?

5. There must be *system integration*, for example in the design of a hybrid system.

Another way to express this is to observe that there are five things to do:

A. Cut the heat leak in half.

B. The cryogenic substation needs to be integrated together.

C. Efficiency: understand the losses, in order to get 30% or 40% efficiency.

D. Dynamic environment: study cool-down and recovery of the cryosystem in case of perturbations.

E. Equipment R&D: new types of compressors with less power consumption, etc.

Following these presentations, Tom Sheahen presided over a general discussion from the floor, wherein the concerns of the HTS community could be voiced.

The next step is to form a working group who will actually produce the roadmap.

Appendix D

Issue Definition and Resolution

In section 5, the appropriateness of various candidate technologies was addressed. One approach to overcoming obstacles is to identify a problem, set up a proposed action, and follow it to completion. To facilitate this approach, this appendix presents a typical form that might be used to define a problem and initiate action to solve it. Figure D-1 is a blank form, and figure D-2 is a sample, partially filled in. This methodology has already been used by Oak Ridge National Laboratory on other programs, with considerable success.

Figure D-1

CRYOGENIC REFRIGERATION SYSTEM ROADMAP
ISSUE DEFINITION AND RESOLUTION TASK PROPOSAL

- Transmission Lines
- Transformers
- Motors
- Fault current limiters
- Flywheel Energy Storage

Urgency: (1 = not needed until production, 5 = needed now) _____

Problem statement:

Proposed action:

Special facilities required:

Estimated cost:

Schedule:

Relevance to HTS power application: (i.e. efficiency improvement, reliability improvement, application not possible without solving this problem).

Figure D-2

SAMPLE

CRYOGENIC REFRIGERATION SYSTEM ROADMAP
ISSUE DEFINITION AND RESOLUTION TASK PROPOSAL

g Transmission Lines
c Transformers
c Motors
c Fault current limiters
c Flywheel Energy Storage

Urgency: (1 = not needed until production, 5 = needed now) ___4__

Problem statement:
Two types of cryogenic refrigeration systems have been widely proposed for the HTS transmission cable. One uses a reversed Brayton cycle refrigerator, and the second option uses bulk stored liquid nitrogen. The thermodynamic performance, percent Carnot, of these two options should be compared in realistic terms.

Proposed action:
Prepare a comparison of the two systems based on standard / real hardware. This should include results on efficiency, reliablility, and cost for the two systems. The task should be based on an assumed baseline, say a 1 km transmission line installation. If time permits, the system analysis should be scaled to different lengths.

Special facilities required:
None

Estimated cost:

Schedule:
3 months

Relevance to HTS power application: (i.e. efficiency improvement, reliability improvement, application not possible without solving this problem).

This would address the issues of cost, reliability, and efficiency for utility installations of HTS power transmission cables.

SAMPLE