FINAL REPORT

High Temperature Superconductivity Devices: Cryogenic Considerations For Utility Personnel

Developed for the
Oak Ridge National Laboratory's
Superconductivity for Electric Systems Program

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COVER GRAPHIC: The heart of all HTS devices is the new superconducting wire, actually a tape shown on the cover.

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July 25, 2004

Contract # 4000018930

Prepared for

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Disclaimer

This report is to be used only as a guide and orientation tool to potential users of HTS devices and systems. HTS device and cryogenic liquids suppliers will provide detailed instructions and procedures as part of their obligation to buyers and as an essential element of their respective O&M and servicing warranty and liability limitation requirements.

Descriptive Brochure: Utility Personnel

This brochure/manual serves as an introduction to High Temperature Superconducting (HTS) devices and systems, an initial personnel training guide, and orientation source to the enabling technology, cryogenics, required for superconducting equipment operation. As market clearing prices are achieved when fully commercialized, HTS equipment and systems will be employed by the electric utility and industrial sectors throughout the U.S. and worldwide.

This material is intended to familiarize technicians and management personnel, involved in installation, operation and maintenance functions of HTS devices, with the basic characteristics and operating principles of both the equipment and their required cryogenic systems. This brochure/manual is not intended to supplant the more detailed operational and safety instructions normally supplied by the HTS equipment suppliers.

Appendix A presents thoughts on important issues and planned further refinement of the brochure in subsequent revisions. The areas identified are highly dependent on the progress made on HTS equipment and the cryogenic support system commercial designs.

1. Introduction to HTS

Superconducting power applications range from transmission lines to generators, motors to fault current limiters, transformers to flywheels. Because of their extraordinary energy-saving efficiency, implementation of superconducting power applications into our nation's electric infrastructure is projected to provide benefits of over $12 billion annually by 2020.

The U.S industry, in cooperation with the government, is making great strides toward commercializing once-expensive renewable energy technologies such as wind, solar, geothermal and biomass. Now, government laboratories and research institutions are likewise partnering with industry to commercialize superconducting power applications.

What is superconductivity? By cooling certain materials to very low temperatures, (e.g., -320° to -370°F), specially designed equipment operates at much improved efficiencies, as electrical resistance is essentially eliminated. This results in more power getting to the end user. Transmission and distribution lines currently account for losses of 8-10%. This translates into higher electrical costs to compensate for the added fuel consumption at the generator and associated pollutant emissions cleanup. As electrical demand continues to grow (currently at approximately 2.5% annually), the need to address these losses becomes increasingly important.

After these new superconducting power applications become commercially available and widely deployed, they will bring new benefits to our nation's electric power infrastructure by providing more efficient generation, transmission-distribution, and utilization of electricity in an environmentally friendly manner. Table 1 offers a comparison of general characteristics.

Equipment	Conventional	HTS
Cable	Resistive losses = 10% Current capacity = 1x rated Overhead pole tower mounted	Resistive losses = <5% Current capacity = >5x conv. rated Underground / out of sight
Transformer	Overload-life limitation Oil-filled/cooled: fire, pollution impact	Overload tolerant-no life limitation No oil
Motor, generator	Baseline	55% lighter than baseline 50% smaller than baseline >2% more efficient than baseline
Misc. HTS	Baseline	Higher efficiency (less windage loss)
- Flywheel	None	Fast response VAR/voltage support
ES*	Breakers, switches, relays	Eliminates conventional, integrated with power transformer (multi-function)
- SMES**		
- FCL***		
- MRI	X-ray, sonic imaging	Non-invasive, high resolution imagery

Legend: * ES - Energy Storage
****SMES - Superconducting Magnetic Energy Storage**
***** FCL - Fault Current Limiter**

Table 1. Comparison of Conventional and Superconducting (HTS) Equipment

Some of the benefits of superconducting power applications have been identified as being environmentally related, primarily because the higher efficiency of electric generation, transmission, distribution, and utilization results in a lower generated power requirement, resulting in lower greenhouse emissions to the atmosphere.

Most importantly, superconductivity offers the potential of more than tripling the amount of power that can be transmitted through existing rights of way as the conductors also facilitate higher energy density (more power/unit area of wire). With the increasing frequency of brownouts and blackouts, this unique feature of superconducting cables extends the usefulness of existing rights-of-way. In addition, these features make electricity generation from renewable resources and from generators located in remote locations more economically viable.

Should superconducting transmission and distribution cables be widely deployed in the future, our nation's grid security from malicious acts or accidents would be significantly enhanced, as most superconducting power installations would likely be located underground or in protected/enclosed settings such as secure areas, inside buildings, or dedicated housing. Other benefits from these underground facilities include: 1) freeing up valuable property for development, now prevented by towers and overhead lines and safety/clearance easements; and 2) removal of flammable, potentially polluting oil-cooled transmission and distribution voltage regulating transformers from poles to more secure and visually friendly enclosures.

For more information on power applications of high-temperature superconductivity, visit the U.S. Department of Energy's Superconductivity Program website at **http://www.eere.energy.gov/superconductivity/**.

There are two major technical and economic challenges to realizing the many benefits of superconducting equipment. The first, and most critical, is the common element in all the new superconducting products: wire. This sounds simple, but the materials that make up the wire have properties that result in no resistance to electrical current (at very cold temperatures). At the heart of these new products, the wire is the basis for the manufacture of windings and cables. The new wire, actually a narrow tape, is wound into cables for transmission and distribution lines, windings for rotors on motors and generators, and in coils for use in transformers and flywheel electrical storage units.

The second area is the refrigeration system, consisting of two elements, the cryocooler and the cryostat. The cryocooler must cool down and maintain the very low operating temperature for the wire-based equipment, usually 65° to 77° Kelvin (K), or -196° to -208° Celsius (C). This cooling equipment uses liquid nitrogen and/or liquid helium as the refrigerant, in order to reach the required low temperatures of operation.

The cryostat is another way to define the insulation around the cooled section. To minimize heat losses at these very low temperatures, the "insulation" consists of surrounding the super-cooled sections with a vacuum and thermal blanketing. The vacuum is an ultimate insulator; in the absence of any solid matter or dense gas, there can be no passage of heat, hence little loss of cooling effect. The outer layer or covering provides some additional thermal isolation and a surface that allows for safe handling of the lines/cable and equipment.

Presently, the cooling equipment and new wire/tape are the highest cost elements of the new superconducting equipment and systems. In the case of the cryocoolers, there is an existing capability of suppliers. Their major challenge lies in improving the refrigeration performance (efficiency) and offering models compatibly sized for the new products in quantities that drive the capital costs to more manageable levels. The superconducting wire consists of new materials and compounds never before formed or fabricated for their target products -cables, motors, generators, and transformers, i.e. for power production, transfer and utilization by the electric industry and other large power users.

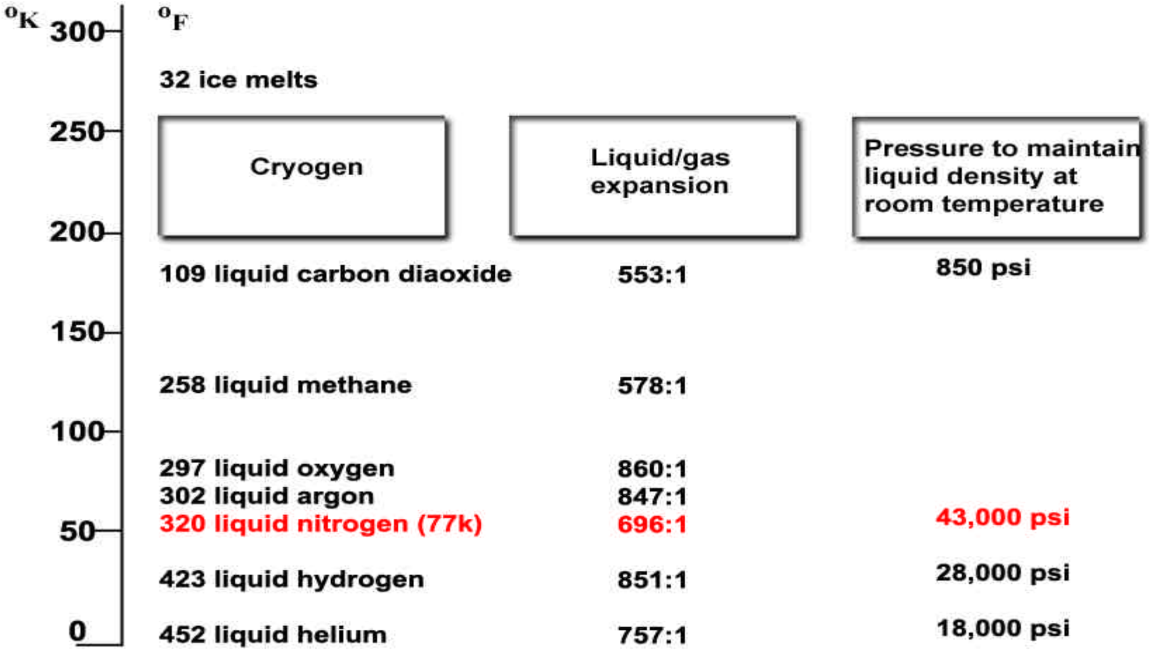
With this as a very general background, the cryogenics portion is the part that presents the superconducting equipment end-using customers with a new equipment technology. The sections that follow, therefore, present a primer on the cryogenic interface that would be experienced by O&M personnel.

2. Cryogenics and Cryogens

Cryogenics may be defined as low temperature technology, or the science of ultralow temperatures. To distinguish between cryogenics and refrigeration, a commonly used measure is to consider any temperature lower than -73.3°C (-100°F) as cryogenic.

Cryogenic temperatures are primarily achieved by the liquefaction of gases, called cryogens. There are more than twenty-five cryogens in use in the cryogenic area, i.e., gases with a boiling point below -73.3°C (-100°F). Seven liquefied gases account for the greatest volume of use and application in research and industry: helium, hydrogen, nitrogen, fluorine, argon, oxygen, and methane (natural gas). Table 2 shows the essential properties of cryogens.

Table 2. Characteristics of Common Cryogens



Cryogen	Liquid/gas expansion	Pressure to maintain liquid density at room temperature
109 liquid carbon diaoxide	553:1	850 psi
258 liquid methane	578:1	
297 liquid oxygen	860:1	
302 liquid argon	847:1	
320 liquid nitrogen (77k)	696:1	43,000 psi
423 liquid hydrogen	851:1	28,000 psi
452 liquid helium	757:1	18,000 psi

Cryogenics is applied to a wide variety of application areas, some of which include food processing and refrigeration, rocket propulsion fuels, spacecraft life support systems, space simulation, microbiology, medicine, surgery, electronics, data processing, metalworking, and now HTS devices.

3. General Rules

Cryogenic liquids present significant hazards because of their intense cold and substantial gas production when warmed. The extreme cold not only can cause tissue damage to personnel, but also can bring about changes in the properties of metals and other materials. Risk of asphyxiation and over-pressure hazards are created by the potential for production of large quantities of gas. These hazards require that careful attention be given to the storage, transfer, and use of cryogenic liquids in order to assure the safety of personnel working with them.

Cryogenic Fluid Vaporization

Due to the extremely low critical temperatures, when cryogenic fluids are heated (i.e., exposed to room temperature), they can revert to a gas (vapor phase) and expand very rapidly. If cryogenic fluids are confined inside a container, the pressure buildup from the vaporization of the liquid can be significant.

Controlling Pressure Releases

To eliminate high-pressure releases of cryogenic vapors, containment systems with special pressure-relief devices are used. They typically consist of pressure-relief valves and/or breakable "Burst or Rupture Disks" to allow over-pressures to release safely. Also, some containment systems have valves that maintain seals by atmospheric pressure and will eject contained materials forcefully during an accident.

Containment System

The containment systems used for cryogenic liquids include an insulated container where the cryogenic liquid is stored as well as delivery lines and a vacuum jacket. The typical container used to store and handle cryogenic fluids is the dewar, which is designed with a vacuum jacket for insulation and includes pressure relief valves to protect against over-pressurization.

Vacuum Jackets

The vacuum jacket acts as an insulating layer for the cryogenic fluid and sometimes includes a system of coiled pipes between the inner and outer walls. The vapors from the cryogenic fluid circulate through the piping system and cool the inner and outer walls of the containment. The vacuum jacket protects workers from the extreme cold of the cryogenic liquid and protects the cryogenic fluid from the ambient temperature of the surrounding environment.

Pressure Relief Devices

The pressure relief devices found on the dewar usually consist of spring-loaded valves and burst disks. These types of pressure relief devices should be used between components of the containment system where cryogenic liquid is enclosed, including all delivery lines and cut-off valves.

Dewars

Liquid helium dewars are designed with two over-pressure relief valves and an over-pressure rupture disk. The over-pressure reliefs are initiated at 0.5 PSI (pounds per square inch) to 10 PSI at room temperature, respectively. The 0.5 PSI relief valve can be used to perform liquid transfers. If the vessel's pressure increases to 38 PSI, the rupture disk will relieve vessel pressure to the atmosphere. **Liquid nitrogen** dewars have one pressure-relief valve set at 22 PSI and a rupture disk that bursts at 189 PSI.

3.1. General Safety

Watches, rings, bracelets, or other jewelry should not be worn when personnel are working with cryogenic fluids. Basically, personnel should avoid wearing anything capable of trapping or holding a cryogenic fluid, or conducting the very cold temperature, via clothing or metallic articles in close proximity to the flesh.

3.2. Personal Protective Equipment (PPE)

Splash goggles or combination splash goggles and full-face shield (note: safety spectacles without side shields do not give adequate protection) shall be worn when handling or transferring cryogenic liquids in open containers.

Gloves may or may not be worn, but if they are necessary in order to handle containers or cold metal parts of the system, they should be impervious, and sufficiently large to be easily tossed off the hand in case of a spill. A more desirable arrangement would be hand protection of the potholder type.

Gloves shall be worn when handling objects that are in contact with cryogenic liquid. The gloves should fit loosely, so that they can be thrown off quickly if liquid should spill or splash into them (cuffs on gloves should be avoided). When handling liquids in open containers, it is advisable to wear high-top shoes. Trousers (which should be cuffless, if possible) should be worn outside the shoes.

3.3. Handling/Transfer

Moving cryogenic liquids from, for example, a storage tank to a cryocooler must allow for the possible pressure buildup that normally occurs when the super-cold fluid is introduced to a warm/room temperature transfer hose and downstream equipment. As the cryogen enters the warmer hardware, vaporization is the dominant action as the colder liquid yields its cooling effect and turns to the vapor phase (latent heat of vaporization) very violently.

To safely continue the cooling of the warmer surfaces, the liquid-gas circuit must include venting valves and relief (back-up venting) as the internal pressure, unless controlled, can rise to extremely high and dangerous levels. Consequently, there must be no closed loops when cryogens are moved in a system. Both an automatically actuated relief valve and a rupture disc, designed to vent above a specified pressure, are required between any two circuit segments that can be isolated (closed).

During transfer and cooldown, uninsulated surfaces (usually hoses and valves) will accumulate an ice coating as moisture from the ambient environment condenses onto the surface. After a while, the ice will vaporize as the surface's temperature is lowered and the area immediately surrounding the hardware approaches the temperature of the cryogen. In fact, other liquids form on the surface: liquid air and liquid oxygen (LOX). LOX, with a liquefaction temperature of -297°F, higher than that of nitrogen (-320°F), introduces another potential hazard; the concentration of oxygen creates a flammability hazard in the presence of any ignition source. Due caution and awareness of this by operating personnel is required.

4. Cryogenic Hazards

Conditions that indicate problems:

- Venting of large amounts of gas or liquid
- Dewar disk ruptures

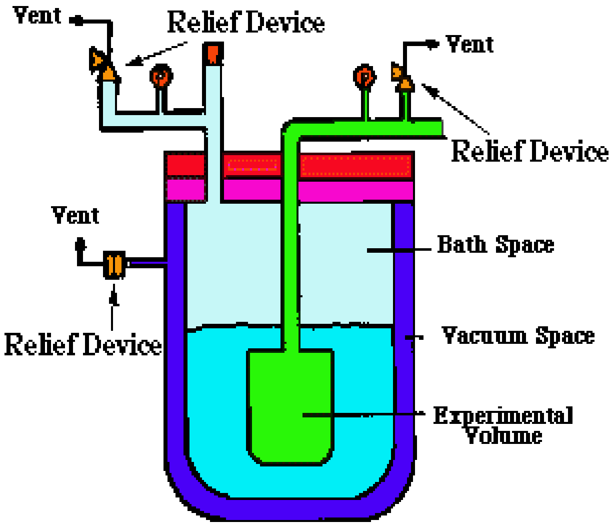
Signs that a large amount of cryogen is being vented include increased background noise levels and condensation of air around the escaping gas into a white, fog-like plume.

When a large volume of excess internal liquid or gas is released to the atmosphere, the immediate vicinity of the dewar will have a high concentration of low temperature vapor. In addition, released cryogenic vapors pose a great potential for asphyxiation due to oxygen deprivation in areas with poor fresh air circulation. The most likely immediate personnel hazard associated with dewar disk rupture is frostbite burns resulting from contact with low temperature gas or liquid.

Five main safety hazards associated with the use of cryogenics are:

4.1. Pressure Buildup

A high-pressure gas hazard is always present when cryogenic fluids are used or stored. Since the liquefied gases are usually stored at or near their boiling point, there is always some gas present in the container. The large expansion ratio from liquid to gas provides a source for the build-up of high pressures due to the evaporation of the liquid. The rate of evaporation will vary, depending on the characteristics of the fluid, container design, insulating materials, and environmental conditions of the atmosphere. Container capacity must include an allowance for that portion which will be in the gaseous state. These same factors must also be considered in the design of transfer lines and piping systems. This is the greatest cryogenic hazard. Cryogens expand in volume as they heat up. One unit of liquid nitrogen, for example, can quickly become 700 units of nitrogen gas.



Remedy:
Each space in contact with the cold must have a pressure-relief device.

4.2. Freezing (Thermal) Hazards

Cryogens can freeze tissue:

- Rarely occurs due to gas film, but don't handle too long

Cold metal parts can freeze tissue:

- No protective gas film
- Skin moisture freezes (like a tongue on a frozen flagpole)

Remedy:
Wear protective gear/clothing as specified in the sections following.

4.3. Ice Buildup and Material Properties

Ice buildup, the most common atmospheric effect of cryogenic systems, can become a serious hazard.

At extremely low temperatures, some materials become brittle and can break or fracture.

4.4. Asphyxiation

While a number of the gases in the cryogenic range are not toxic, they are all capable of causing asphyxiation by displacing the air necessary for the support of life. Even oxygen may have harmful physiological effects if prolonged breathing of pure oxygen takes place.

Asphyxiation can happen around cryogenic systems because cryogens can flash into very large volumes of gas. And, if more dense than air, the cold vapor will displace the air, traveling to the lowest point of elevation creating a seriously oxygen-lean environment.

Remedies:

Respiratory - Supply air via emergency ventilators or purge air where drenching is possible. These provisions should be located proximate to where oxygen deficiency or asphyxiation may occur. (These types of exposures should be, and are usually, prevented through the implementation of engineered controls.)

- Ensure good ventilation
- Avoid low places, confined spaces, air intakes
- Use oxygen monitors, as required

4.5. Cryogenic Burns

As living skin tissue is rapidly cooled, local pain may be experienced. This may be transient. Affected areas can become pale yellow and waxy because local blood circulation closes down and skin lipids solidify. When cold burns thaw, intense pain can occur and, if the area affected is large, the subject may go into shock. Contact with surfaces at cryogenic temperatures tends to cause the flesh to "stick," so do not remove clothing or free hands or limbs from uninsulated equipment.

First aid

The aim is to slowly raise the temperature of the area affected back to normal. For minor injuries, make the subject comfortable and loosen any clothing that may restrict blood circulation. Do not pull clothing away from the burned or frozen area. Place the affected part in tepid water (<40°C). The skin should gradually change color -back to pink via blue. Use a sterile burn dressing to protect the injury and get the patient to the nearest hospital.

4.6. Other: Oxygen Concentration

Liquefied inert gases such as liquid nitrogen or liquid helium are capable, under the right conditions, of condensing oxygen from the atmosphere, and causing oxygen enrichment or entrapment in unsuspected areas. Extremely cold metal surfaces are also capable of condensing oxygen from the atmosphere.

5. Personal Protective Equipment (PPE)

Splashes must not be trapped against the body, so avoid gauntlet-style gloves. Pull sleeves down over glove wristbands, avoid open pockets, and put trouser bottoms over the tops of safety shoes or boots. The precautions listed below should be followed to protect the eyes and skin from the hazards associated with cryogens.

- Always wear protective gloves over jewelry because, if exposed to cryogenic fluids, a ring can freeze to the finger.
- Protect your eyes by wearing safety goggles or a face shield whenever working with cryogen fluids.
- Wear a cryogen apron when working with cryogen liquids.
- Always wear a face shield when working around pressurized cryogenic systems, connecting or disconnecting cryogenic equipment lines, or venting containment systems.
- Wear insulated gloves whenever working around uninsulated pipes or handling dewars.
- Try to cover all exposed skin by wearing long-sleeve shirts, cuffless pants, safety boots, and gloves. Gloves should be loose fitting so that they can be quickly removed if cryogenic fluids are spilled on them.

5.1. Hand Protection

- Loose, non-asbestos, insulating gloves that can be tossed off readily
- Special gloves made for cryogenic work
- Leather gloves without gauntlets

General Use:

All-cream-hide cryogenic gloves, fully lined with 3M 'Thinsulate'. Knitted wrist, vein patch. Welted front seams. Moisture-resistant.

For handling liquid transfer hoses:
Cream-hide cryogenic gloves with blue-coated nylon backs. Hide-reinforced fingertips and back straps. 3M 'Thinsulate' lined. Knitted wrist & hide vein patch. Moisture-resistant leather.

5.2. Head/Face Protection

Brow guard & polycarbonate face-shield

5.3. Body Protection

- Long-sleeved clothing made of nonabsorbent material
- Cuffless trousers worn outside boots or over high-top boots
- Leather or other non-asbestos apron when
- handling large quantities of cryogens
- Full-length, anti-splash decanting apron (shown)
- Full protective suits where exposure to drenching is possible

5.4. Feet

- Closed-toe shoes that cover the top of the foot
- Boots (extend trousers over the boot)

5.5. Ears

- Earplugs or earmuffs where excessive noise levels may occur near filling and venting operations

5.6. Materials Handling

- Tongs or other tools to lift objects out of the liquid or liquid baths

6. Facility Environment

6.1. Air Quality

Asphyxiation Hazard

Cryogens will rapidly boil and convert from liquid to gas at room temperature. As the gas warms to the temperature of the surrounding air, it rapidly expands. In confined or poorly ventilated areas, the expanding gas will displace/dilute the oxygen concentration. Lacking adequate ventilation, this can lead to stages of asphyxiation-dizziness, loss of consciousness, and death. Therefore, you should use caution when using liquid nitrogen and helium indoors. These gases are colorless, odorless, and tasteless.

OSHA specifies that workers cannot be inside a workspace that contains less than 19.5% oxygen without supplied air respiratory protection. Below this level, workers start to experience early warning signs of oxygen deficiency. Specifically:

Between 15 - 19% oxygen, workers may feel:
- A loss of coordination and energy
- An increase in pulse rate and breathing
- A sense of euphoria and clumsiness

At oxygen levels between 12 - 14% the worker's:
- Breathing becomes much deeper and faster
- Judgment becomes impaired
- Physical coordination is deteriorated
- Lips turn blue.

Usually at levels below 12%, the worker will become unconscious and eventually die.

6.2. Physical Safety

Insulate all containment system pipes.
Use care when filling portable dewars.
Be aware of potential mechanical interference actions (especially impacts) around cryogenic systems.

7. Utility Operations

All apparatus used in the storage and handling of cryogenic liquids shall meet the appropriate requirements of the Compressed Gas Association, the National Fire Protection Association, the American Petroleum Institute and ASME Boiler and Pressure Vessel Code, as applicable.

7.1. Storage

1. Only containers that have been specially designed for holding cryogenic liquids shall be used. Such containers are made from materials that can withstand the rapid changes and extreme differences in temperature characteristically encountered when working with cryogens. They are typically of double-wall construction with an insulating vacuum space or other insulation between the inner vessel and the outer vessel.

2. Many small dewars are made of glass, while larger units are generally made of metals such as stainless steel, copper and aluminum. (Ordinary glassware shall neither be used to store cryogenic liquids nor shall beverages be place in cryogenic containers.) All unprotected glass dewars shall be wrapped with a heavy adhesive tape to prevent fragmentation and to provide a better gripping surface.

3. Containers designed for cryogenic liquids are built to withstand normal operating pressures. However, all containers shall be open, or protected by a vent or other safety device that permits the escape of gas.

Containers of cryogenic liquid shall never be closed so that they cannot vent. Where a special vented stopper or venting tube is used, as on some small portable containers, the vent shall be checked at regular intervals to assure it has not become plugged with ice formed from water vapor condensed out of the ambient air.

4. Cryogenic liquid dewars shall be stored in well-ventilated places. The evaporation of gas into an unventilated space can produce dangerously low concentrations of oxygen.

7.2. Transfer and Handling

Hazards Caused by Air Condensation

There is always a chance that air surrounding a cryogen containment system can condense, especially when liquid nitrogen is transferred through uninsulated metal pipes, or when relieving pressure in liquid helium dewars. Air condensation can cause hazards to workers and equipment. These include the following:

- It can create a liquid condensate that falls on materials, particularly organic materials, susceptible to cold embrittlement.
- It can increase the oxygen concentration around a containment system, which can increase the flammability of materials near the system. For example, nitrogen, which has a lower boiling point than oxygen, will evaporate first, leaving an oxygen-enriched condensate on the surface.
- Clothing saturated with oxygen from air condensed by cryogenic fluids readily ignites and will burn vigorously. Personnel close to this situation should immediately leave the area and avoid all ignition sources.
- Based on air condensation effects, equipment containing cryogenic fluids, in order to minimize the fire hazard potential, must be kept clear of combustible materials.

Controlling Air Condensation

The frost that accumulates on containment system components is integral to controlling air condensation. Frost insulates the containment system from the surrounding air, reducing the possibility that the air will condense. Another way of reducing air condensation is by applying an insulating material on system components. This not only reduces air condensation, but also protects workers by preventing contact with cold cryogenic containment system surfaces.

Cold Embrittlement

Many materials become very fragile at very low temperatures. At cryogenic temperatures, materials such as rubber, plastic and carbon steel can become so brittle that very little stress can compromise the material's structural integrity. To avoid problems with cold embrittlement, materials like stainless steel, copper, brass and most alloys of aluminum should be used in cryogen containment systems.

7.3. General Handling Guidelines

1. Cryogenic liquids shall be handled carefully. Their extremely low temperatures can produce frostbite. The gases released from these liquids are also extremely cold and can produce frostbite. Delicate tissues, such as the eyes, can be permanently damaged by only brief exposure to these cold gases.

2. Boiling and splashing of cryogenic liquids always occur when charging a warm container or inserting warm objects into the liquid. Such operations should be performed slowly to minimize boiling and splashing.

3. All parts of the body shall be protected from uninsulated pipes or vessels containing

cryogenic liquids; the extremely cold metal may stick fast to the skin and result in torn flesh when the skin is withdrawn. Tongs shall always be used to withdraw objects immersed in liquid. In addition to the hazard of frostbite, objects that are soft and pliable at room temperatures usually become very hard and brittle at cryogenic temperatures and are very easily broken.

4. The movement of dewars filled with cryogenic liquids shall be conducted with great caution. Many dewars are somewhat unstable when tilted and movement over door sills and other floor obstructions can be hazardous.

7.4. From Storage to HTS Devices

1. Piping or transfer lines should be so constructed that it is not possible for fluids to become trapped between valves or closed sections of the line.

2. Evaporation of the liquid in a section of line may result in pressure build-up and eventual explosion. If it is not possible to empty all lines, they must be equipped with safety relief valves and rupture discs.

3. When venting storage containers and lines, proper consideration must be given to the properties of the gas being vented.

7.5. Within HTS Equipment/Systems

Proper Use of Dewars

All cryogen containers (dewars) should be operated in accordance with the manufacturer's instructions. Proper personal protective equipment must be worn whenever handling cryogenic liquids. Dewars are designed to protect workers from physical contact with cryogenic fluids while preserving the cryogen's liquefied state. However, proper dewar handling practices must be used to ensure worker safety. Safe dewar handling practices include the following:

- Never cross contaminate in-service dewars with other cryogenic liquids.
- Ensure dewars are properly labeled with the identity of the housed cryogen.
- Keep the dewar upright.
- Do not bump or drop the dewar from an elevation. This could ruin the insulating properties of the dewar. Dewars that fall onto their side could rupture if the inner vessel cracks and cryogenic material flows into the vacuum space between the inner and outer vessels. The cryogen will contact the warm metal and boil rapidly, substantially increasing the pressure in the dewar.
- When using a hand truck or fork truck for dewar transport, the dewar must be strapped onto a dewar transport pallet. Never use chains to secure the dewar to the transport pallet.
- Never slide or roll a dewar.

- When using a crane to lift dewars, use approved lifting devices specifically designed for dewars. Never lift dewars by their handles or by means of slings wrapped around the shell of the dewar.
- Use cryogen-rated personal protective equipment when filling, venting, and transferring dewars and cryogenic fluids.
- Ensure dewars are positioned so that the pressure-relief valve and rupture disk vent paths are directed away from personnel, critical equipment, or designated work areas.
- The fill and vent ports of the dewar should be kept closed at all times to minimize the formation of ice, which may plug the pressure relief devices.
- The pressure relief devices should be periodically inspected for ice. If dewar vent ports are shut, periodically monitor dewar pressure. If indicated pressure exceeds 15 PSI, relieve pressure by cycling vent valve.
- When filling dewars or transferring cryogenic liquid, use a phase separator or special filling funnel. The top of the funnel should be partly covered to reduce splashing. If the liquid cannot be poured, use a cryogenic liquid withdrawal device for the transfer. Be sure to follow all instructions provided with the device.
- Maintain all cryogenic equipment in accordance with manufacturer's recommendations. Any equipment not meeting manufacturer's operating specifications shall be removed from service.

7.5.1. Thermal Stress

The parts of a cryogen containment system sometimes experience great differences in temperature. These stresses, known as thermal stresses, can cause many problems for poorly designed containment systems.

The design of a cryogenic containment system must take into consideration the normal thermal contraction of the containment system when exposed to the temperature difference between the inside (cryogenic liquid) and the outside of the containment system (room temperature).

As a cryogenic liquid proceeds down the length of the pipe, the piping material experiences changes and stress resulting from the extreme temperature differences between the inside and outside of the pipe. The degree of stress and potential for failure depend upon the properties of the pipe material and the flow rate of the cryogenic liquid.

Controlling Thermal Stress

- The following steps should help you minimize the risk of failure due to thermal stress:
- When starting up the system, allow for gradual cooling of the system.
- Use only cryogen-approved materials for the containment system.
- Select materials and equipment that can accommodate the causes and effects of thermal stress.

8. Emergency Procedures

8.1. Personnel

Frostbite Injuries

Any time cryogens come into prolonged contact with exposed skin, medical assistance should be sought as soon as possible.

Immediately after exposure, the frozen skin appears waxy and yellow and usually is not painful to the subject. As the skin thaws, it painfully swells and blisters. When this occurs, immediate emergency treatment is required. While waiting for medical assistance, follow these first aid procedures:

- Remove the victim from the cryogen hazard.
- Remove any clothing that may interfere with the circulation of blood to the frozen tissues. The clothing must be removed in a slow, careful manner to prevent salvageable skin from being pulled off.
- Do not rub the affected areas of skin. Rubbing may further damage the tissue.
- Immerse the affected area in a warm water bath (approx. 105 °F). Do not apply dry heat, such as from electric heaters, which may superimpose a thermal burn, further damaging injured tissue.
- If massive exposure has occurred, such that overall body temperature is reduced, the subject should be wrapped in blankets until paramedics arrive. In cases of extreme exposure, the subject should be totally immersed in warm water. Treatment for shock may be necessary. The rewarming, or thawing, of affected area(s) should be done gradually, requiring up to 60 minutes to thaw the affected area(s) and bringing back the natural colors of the skin.
- If the frozen tissue thaws before medical help arrives, cover the area with dry sterile dressings and large bulky protective clothing.
- Do not apply ointments.
- Do not allow the exposed worker to drink alcohol or smoke. Alcohol and nicotine decrease blood flow to the frozen tissues.
- You may give the affected worker warm drinks and food.
- Try to make the subject feel as comfortable as possible.

8.1.1. Disk Rupture Safety Procedures

In the event that a dewar releases cryogenic liquids to the atmosphere via a ruptured disk:

- All personnel in the immediate vicinity of the release should be informed of the dewar disk rupture.
- All personnel in the immediate vicinity are required to evacuate to a safe distance.
- The disk rupture must be reported to the Safety Officer and/or Safety Department

immediately by the person filling the dewar or anyone witnessing the disk rupture.

8.1.2. Minor Leak Response

In the event of a minor leak from a dewar, the following steps must be taken:

- When filling a dewar, shut down the containment system.
- Disconnect the dewar from the system, avoiding physical contact with the cryogenic fluids. If the dewar cannot be disconnected without contacting the liquid, evacuate the affected area.
- Once disconnected, remove the dewar to the nearest door and allow the vapor to be released to the atmosphere.

8.1.3. Major Leak Response

In the event of a major leak from a dewar, the following steps must be taken:

- Immediately evacuate the area containing the dewar, establishing a safe distance or buffer zone.
- If you are in a cell, push the emergency shutdown switch and leave the area.
- Report the dewar leak and any injuries or illness to the Safety Officer immediately.
- Try to determine whether there is adequate ventilation in the affected area. If it cannot be determined, exit the area immediately.
- Never re-enter the area until it has been determined "Safe" by the Safety Officer.

8.2. Facility

Though quite rare, there have been numbers of incidents where large amounts, thousands of gallons, of non-flammable cryogens have spilled. Most common are incidents associated with transportation, both rail and semi-trailers. The cryogen storage equipment normally located adjacent to the using installation is not vulnerable to massive spills as the intrinsic design of the equipment and required clearances (safety area) rule out all but the most improbable threats.

However, assuming that a sudden rupture and spill does occur, the dissipation of the rapidly forming vapors, from the liquid to gas transition, is dangerous only if personnel are too close to the event. This would mean they are engulfed in the plume formed, have come into prolonged contact with the boiling liquid cryogen, or are thermally exposed to the very cold gas. Even this is not probable as convective air movement acts to rapidly dilute any concentration, diminishing the duration of an oxygen-deficient atmosphere and low temperature exposure.

According to government records (OSHA, DOT), no fatalities or serious injuries have been noted due to cryogen spills in rail or trailer accidents. Any personal injury and/or fatalities involving non-flammable cryogens, were the result of the incident and not the spill.

8.3. Environment

As noted earlier (Facilities), the introduction of large amounts of nitrogen or, more rarely, helium, resulting from a major spill, is quickly absorbed/diluted into the environment, already comprising 80% nitrogen by volume. Therefore, there is no deleterious impact on the environment should a nitrogen spill occur.

9. Applications[1]

HTS equipment and systems applications are designed to replace more conventional ambient temperature-operated hardware customarily associated with industrial and utility operations. This equipment can be broadly categorized into three groups: rotating machinery (motors, generators), transformers and power lines/cables. A fourth group is also identified and includes electrical energy storage (flywheels, magnetics) and fault current limiters. The latter device is a newer concept that takes advantage of the effects of superconducting phenomena. That is, at low temperatures, resistance is negligible, allowing high current transfer. When the low temperatures are allowed to rise (by planned reduction of supercooling), the resistance increases and limits current flow, hence protecting the downstream equipment from unusually high/fault currents. Basically a variant of a transformer, or as a goal integrated into a power transformer, this would significantly reduce fault currents and lower switch/breaker ratings in multiple circuit systems to the offending source within a given circuit.

In general, HTS rotating machines and power conversion devices are smaller (about 50% less volume) and lighter (about 40-50% less weight) than their present counterparts. The HTS power lines/cables are expected to carry much more current (about 5-10 times for the same conductor diameter) and to be installed below grade in underground conduits. Common to all HTS devices is, of course, a cooling/refrigeration subsystem whose primary function is to keep the power carrying materials at superconducting temperatures. It is under these conditions that the devices provide their maximum electrical performance in terms of high capacity and power transfer with negligible resistance, hence high efficiency and little heating associated with resistance (I^2R losses). So, the key element to enabling this new technology is the cryogenic cooling function, or cryocoolers.

9.1. Cryocooling and HTS Devices

There are several approaches to providing the refrigeration or cooling to the very low temperatures required for HTS device operation. Though the commercial configuration for each HTS device is still evolving, the following section describes the present thinking on these new systems.

Cryocooling options: The likely options for each of the HTS devices are shown in the table below; each is described in the following sections.

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[1] Much of the following material is freely excerpted from the "Cryogenics Assessment Report;" M. J. Gouge, J. A. Demko and B. W. McConnell, ORNL;J. M. Pfotenhauer, University of Wisconsin, May 2003

HTS Device	Cryocooling options
HTS Industrial Motor	G-M single-stage, pulse tube
HTS Generator	Same as above
HTS Transformer	Same as above, LN^2 with sub-cooling
HTS Cable	Reverse Brayton, Claude, large capacity cooler
Fault Current Limiter	G-M single-stage, pulse tube
SMES, FESS*	G-M single-stage, pulse tube

* S/C Magnetic Energy Storage (SMES), Flywheel Energy Storage System (FESS)

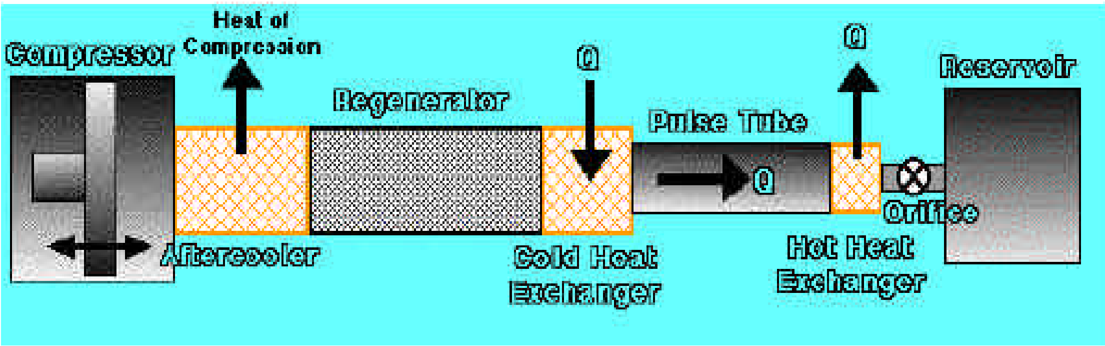
Gifford-McMahon ("G-M") and *Pulse Tube* coolers are based on creating an oscillating gas flow and a regenerative heat exchange. The heat extraction depends on the oscillating frequency of the gas flow and the phase angle between pressure (p) and volume (V) during an oscillation period. In G-M coolers, a piston is moving in the cold part in which the regenerator is usually already integrated.

Coolers of the *Gifford-McMahon* type are sold worldwide in numbers of ~10,000 per year for cryopumps to the electronics industry and for the cooling of MRI magnets in medical equipment. The Mean-Time-To-Failure (MTTF-operation including switching the machine on and off once a day) of commercial G-M coolers is ~60,000h, over seven years, a huge advantage for unattended operation. Routine maintenance is recommended every year to replace the displacer seals and every 15,000 hours to replace the compressor oil absorber. These preventive maintenance actions can be done in less than one day.

Pulse-tube cryocoolers: these refrigeration systems are the state-of-the-art, containing no moving parts and achieving significant improvements in reliability and reduced maintenance than earlier technologies. However, there are applications that may favor improved versions of the current cryocooler options, namely reverse Brayton Gifford-McMahon machines.

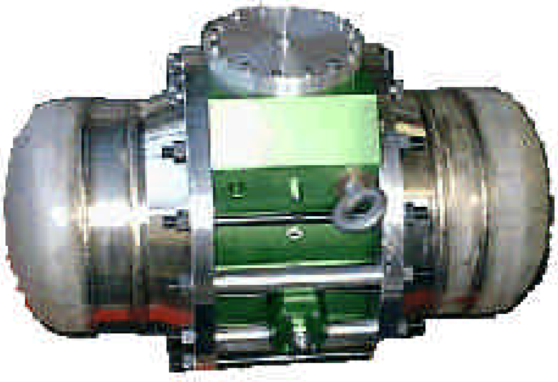
The *pulse tube cooler* can be conceived as a G-M cooler where the gas flow is steered in such a way as if a "gas piston" were moved according to the particular cooler operation mode. Unlike G-M cryocoolers, there are no moving parts in the cold section, a feature that should result in lower scheduled maintenance and higher reliability. Therefore no expensive high-precision seals are required and the cold head can be operated without any service inspection.

Pulse tubes have been designed and tested in a wide variety of configurations. A sketch of the Stirling-type orifice pulse tube follows. An effective gas piston in the pulse tube section implements the cycle.



Pulse tube cryocooler components

A drive unit currently used on a prototype pulse tube under development is shown below. This is a valveless, electroacoustic device that produces alternating pressure and volume flow in a pressurized gas. It is oil free, has non-wearing surfaces, and produces low noise and vibration. The unit shown has 20 kW input power, weighs 1000 lbs with all ASME code required structure, and has dimensions of 24" x 24" x 38".



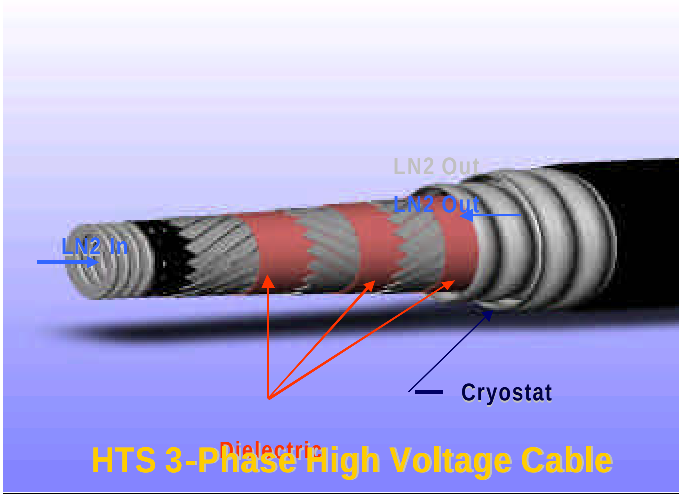
Pulse Tube Cryocooler Drive Unit
(courtesy of CFIC, Inc.)

A third and most direct scheme involves bath cooling (submersion) in liquid nitrogen (LN_2) for operation at 77K. The LN system can in principal be operated in an open cycle with replenishment of the stored LN_2 or in a closed cycle with cryocooling, that can not only recover and liquefy spent LN_2 (gases), but also support lower temperature operation, allowing the HTS coils to be cooled to as low as about 25K.

The second, or hybrid, approach (using LN_2 and cryocoolers) in supporting lower operating temperatures provides improved current capacity in any of several candidate HTS conductor types and allows optimization of the combination of conductor cost and refrigeration cost. The cryocooler would employ liquid helium as the working refrigerant in a closed cycle, to achieve these very low temperatures and to recover and recycle the LN_2.

9.2. HTS Cables

An HTS cable assembly (one concept shown below; courtesy of Southwire Co.) consists of a cryostat, usually a vacuum jacketed, coaxially mounted enclosure surrounding the HTS cable, and a cryocooled conductor within the cable winding to transfer the liquid nitrogen (or helium) through the entire active length of the cable section. The thermal loads that determine the refrigeration capacity required come from the heat transferred at the terminations and along the cable length. The typical operating temperature range is expected to be between 65K and 80K. The refrigeration to these low temperatures is the price that must be paid to achieve very low resistive losses, hence high transmission efficiencies of these cables.



The cryostat's function is to insulate the conductor and minimize thermal losses between the supercooled conductor(s) and the ambient environment. This is usually a coaxial design of an outer shell and an inner cable covering with a vacuum in between the two, called vacuum jacketing. Except for the cable supports, the vacuum is an almost perfect insulator in that the annular space isolates the cable from convective and conductive thermal losses.

A cryocooler is connected to the assembly to provide the refrigeration. Using LN_2 as the working fluid and (optionally) a downstream condenser to recover the nitrogen gas, the cryocooler will liquefy the gas and return the liquid to the cable's cooling channel to sustain the operating temperature of the cable. These "cryostations" may repeat every 100-300 meters (final length remains to be determined) as the thermal losses are too great to maintain superconducting temperatures much beyond these distances. There are two methods for providing cable cooling to their normal operating temperatures (between 60-80K), LN_2 baths with replenishment and hybrid LN_2 systems (bath + pulse-tube cryocoolers).

Because these are active stations with (moving) parts that can malfunction and need repair/replace attention, O&M access (for personnel and equipment), as well as leak detection systems, is required. This access would likely be co-located with the active equipment nodes (e.g., cryocooler placement) periodically along the full length of the cable assembly.

Response to Loss of Cooling

There are various modes of possible failure in the cooling system (for example, circulation pump or compressor failure). Commercial cryocooling systems are routinely designed to deal with these various contingencies. In the event that the cooling system for an HTS cable fails (and assuming the line is not broken), under most conditions the line can be operated normally for a period of several minutes, allowing time for orderly reconfiguration of the grid and de-energization of the circuit. In a de-energized state, because of its thermal mass, the cable will then gradually warm over a period of hours or days. Although the cable can continue to operate for some period after a loss of coolant, it is important to take the cable out of service promptly before this occurs, to avoid permanent damage to the cable.

As would be the case with any type of conductor, in the event that a line is severed (for example, due to a dig-in), service will be immediately interrupted. Underground placement clear marking and encasement in a protective conduit, can reduce but not eliminate the risk of severed lines.

Service Restoration

A disadvantage of HTS cables is that they cannot be immediately restored to service after a repair to a circuit. Because of the need to reach cryogenic temperatures to achieve the superconducting state, a cool-down period of at least several hours is likely to be required following the repair of an HTS cable, and service to customers in the vicinity of an HTS cable that has been subjected to such an outage will need to be provided through alternate pathways until the design operating temperature is achieved.

9.3. Motors and Generators

HTS rotating machinery includes motors and generators. Typically, today's generators operate at efficiencies between 97% and 98% while typical motors operate at efficiencies between 90% and 96%. In conventional motors and generators, coils of copper wire generate magnetic fields. Since superconducting wire can carry larger currents, motors could be smaller and lighter. Substituting superconducting wires for copper wires also eliminates energy loss due to electrical resistance. Since the potential for improvement in the efficiency for motors is greater than for generators, it is likely that first industrial applications of superconducting technology will occur in the large motor industry.

Common to both motors and generators are the use of a stator, the stationary portion that includes field windings and their support structure, and the rotor, the moving portion that also includes a moving core with windings around the rotating structure. This latter assembly, the armature, contains the HTS wire that gives these devices their lower resistance and higher efficiency characteristics.

9.4. Transformers

Electric current is transmitted at high voltages, usually at potentials of least 115,000 volts (115KV). To provide electric power at the voltages needed by most conventional applications, such as appliances, the voltage needs to be reduced (stepped down) to between 110 and 220 volts, which is accomplished by transformers. Step-up transformers (to 765KV) enable generated power to be transmitted over long distances at high voltage, which saves energy. Step-down transformers bring the voltage down to safe levels for distribution to end-users. It is estimated that about 2% of all generated electricity is lost due to inefficiencies in transformers.

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

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

For cooling transformer coils, there are two basic approaches. One approach involves a bath cooling of the transformer coils in LN_2, and the second, a hybrid approach using cryocoolers/LN_2 to support lower operating temperatures. Either method provides improved current capacity in any of several candidate HTS conductor types; selection of the preferred approach is a trade-off that considers optimization of the combination of conductor and refrigeration costs. The cryocooler would employ liquid helium as the working refrigerant in a closed cycle, to achieve these very low temperatures and to recover and recycle the LN_2.

9.5. Fault Current Limiters

One of the most intriguing potential applications for HTS is for current limiting. When lightning or some other event sends a power surge through the utility grid, the grid's circuit breakers shut down the system to protect it from severe damage. It is envisioned that a large HTS-based fault current limiter (FCL) installed in a utility grid could act as an energy-absorbing device, reducing the current surge and the duty on circuit breakers to isolate the fault. This type of protection would allow utilities to increase system loads without increasing the number of transmission lines and still provide reliable and uninterrupted service to their customers.

Superconducting current limiters could have the potential to reduce the need for system upgrades. As utilities attempt to stretch their current capacity without improving existing infrastructure, their systems move closer and closer to maximum capacity. The systems then become more and more vulnerable to power surges that cause them to become overloaded and shut down-a phenomenon known as a trip. This function is now provided through very expensive power switches and circuit breakers. When a trip occurs, all power downstream of the fault is interrupted. Unless an alternate path is found, electric service is shut down until corrective actions are completed.

With fault current limiters, high currents are reduced, minimizing the need for expensive circuit breakers with high interrupting capability. HTS fault current limiters would reduce the need for costly upgrades to handle power surges that cause systems to fail. By allowing the superconducting circuits/wires to experience reduced refrigeration, hence heating up, the very low resistance feature of the windings is purposely compromised in order to increase the resistance and thus reduce its normally high current carrying advantage. This, in turn, checks the high fault current to more acceptable levels and spares the downstream system from the potentially damaging power. With resumption of normal power levels, e.g. removal of fault currents, the super-cooling refrigeration system resumes and normal operations are reestablished.

With the employment of this unique power limiting feature of HTS transformers, significant cost savings accrue due to eliminating special high current-rated protection systems such as breakers, switches and flow controllers.

9.6. Flywheel Energy Storage Systems (FESS)

The flywheel rotor is a rapidly spinning disk attached to a permanent magnet ring that floats above high-temperature superconducting material. The superconductor generates a magnetic field "cushion" when it is cooled to -321°F (77K). This cushion allows the flywheel rotor to hover above the superconductor without touching it. The entire assembly -a high-speed rotor with this superconducting magnetic bearing combined with an efficient motor/generator -is called a flywheel energy storage system. The flywheel is contained in a vacuum chamber, to eliminate air friction. Because the magnetic bearing floats above the superconductor, frictional drag is one-tenth that of any conventional bearing system.

There are two primary markets for an HTS flywheel system:

- continuous power
- power-quality improvement

Continuous Power: In a typical application, during the day the spinning flywheel would release energy to meet the increased demands of electricity, and at night, the disk would act as a storage system. It would provide a consistent stream of electricity, called load leveling, avoiding the usual peaks and valleys of electrical demand during a 24-hour period.

In many circumstances, the end user of critical power has a strong desire to eliminate the requirement for electrochemical batteries due to environmental restrictions, maintenance concerns and/or limited space. If the power quality configuration includes a standby engine/generator for long-term protection, a flywheel energy-storage system may be well-suited for providing power until the start and synchronization of the genset.

Power-Quality Improvement: Due to the phenomenon of the vast majority of power quality events having a duration of only a few seconds, some power users have the opportunity to improve the quality of their power in all but long-term outage situations with minimal cost and space outlays. Batch or process manufacturing sites with a history of short-term power glitches or sags (which have remained unprotected due to the high costs or space requirements of traditional energy storage) are ideal applications for high-power flywheel systems.

Flywheel systems contain power-dense integrated motor-generator-flywheels that are both cost-effective and safe. Ride-through requirements for the power quality industry fall into two main categories:

- time to power the load until standby generator startup (~10 to 45 seconds)
- time to power the load through the vast majority of events (~5 seconds)

By designing the product for applications that require relatively short power delivery times, the system delivers what the application demands at the lowest possible cost. The product covers a broad range of power classifications with single or paralleled systems to extend power and/or runtime as needed.

10. HTS equipment O&M

The most profound impact of HTS devices on power equipment maintenance organization operations centers around the cryogenic portion of the installation. The fundamentals of the equipment's functions are, of course, the same. The presence of the refrigerant, in this case liquid nitrogen or helium, or one of the refrigeration systems described above (Section 8.1), requires some new monitoring, servicing and repair attention.

One of the two most critical parameters to any of the cooling systems is the temperature difference between the refrigerant, the cooling system outlet temperature, and the device operating temperature. The second would be the state/integrity of the vacuum that isolates the external/ambient thermal environment and the HTS device. A diminished vacuum might indicate a leak that, along with a temperature rise, means that the sealing integrity of the cryostat has been compromised.

11. Short Courses

Additional resources are offered for more direct education and training. Among these are:

1. Cryogenic Engineering: Short Courses offered by Cryoco, Inc., 511 North Adams Ave., Louisville, Colorado 80027; tflynn3113@aol.com

2. The Advanced Learning Environment (ALE), an online program on Cryogenics, the Florida State Research Institute (FSRI), Kennedy Space Center, Florida 32899; **http://www.fsri.org/lifelong_learning_ale.htm**

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1990 - 2002 Incidents involving Liquid Helium - Cryogenic; U.S.; Department of Transportation, HAZARDOUS MATERIALS SAFETY HAZARDOUS MATERIALS INFORMATION SYSTEM

1990 - 2002 Incidents involving Liquid Nitrogen - Cryogenic; U.S. Department of Transportation, HAZARDOUS MATERIALS SAFETY HAZARDOUS MATERIALS INFORMATION SYSTEM

Incident Database, U.S. Chemical Safety and Hazard Investigation Board - Chemical Incident Reports Center

> In the aftermath of the March 1998 nitrogen asphyxiation incident at Union Carbide in Hahnville, LA, the Board initiated a review of similar incidents nationwide. The CSB study identified a total of 85 incidents that occurred in the U.S. between 1992 and 2002 and involved exposure to a nitrogen-enriched atmosphere. Together these incidents caused 80 deaths and 50 injuries. The CSB developed a safety bulletin on nitrogen asphyxiation hazards, highlighting a variety of good practices to avoid such incidents.

NASA USA Ground Safety Operating Procedures; GSOP 5400 REV. F; May 15, 2002

HAZARDS OF NITROGEN ASPHYXIATION Safety Bulletin No. 2003-10-B, U.S. Chemical Safety and Hazard Investigation Board; June 2003

Standard for Design of Cryogenic Ground Support Equipment, KSC-Std-Z-0009C, NASA; August 22, 1994

Accident Search Results - Nitrogen, 1985-1997; OSHA, Washington, DC

Appendix A

Cryogens in a Utility Environment: O&M & Safety Items

References:

- BL&A Analysis
- Cryogenic Assessment Report, Final Draft, 4/9/2002
- Cryogenic Roadmap, 6/18/2001

General:

1. Compressor system performance is key pacing item in HTS applications
    a. Need variable/turndown capability or several smaller machines to provide redundancy and be staged to provide a stepped variable capability
    b. Efficiency of cycle is highly compressor dependent: seeking >30% of Carnot efficiency
2. Define fail operable options for each HTS device and system
3. It is reported that pulse-tube cryocoolers have >80% turndown ratios
4. HTS operations below 77K use sub-cooled LN2 (down to 66 K) or helium; different cycles means diverse equipment, parts inventories and training
5. Long lead items must be inventoried to minimize MTTR
6. Training is required for routine and emergency maintenance
    a. Handling - Procedures, special equipment and tools
    b. Apply experience from current cryogen-using markets
7. Any special permits required?
8. Responses and impacts of significant cryogen (LN2, helium) spills

Projected commercial cryocoolers for HTS devices:

- motors, generators - single stage G-M, reverse Brayton, hybrid
- transformers, SMES- single stage G-M, hybrid, pulse tube
- FESS - pulse tube
- cable - reverse Brayton cycle, hybrid, large capacity cryocooler
- fault current limiter - single stage G-M, pulse tube

For each cryocooler type:

1. What are scheduled maintenance tasks and frequency?
    a. Cryogen replenishment
    b. Special skills or tasks
2. What are failure modes (unscheduled maintenance) and response options?
3. Provide FMEA and safety issues definitions.
4. For (1) and (2): What are MTTRs? (Impacts availability)

Transformers:

1. Find case histories of transformer fires, oil spills, accidents
2. Cooling options:
   a. Closed cycle cryocooling (25 K)
   b. Hybrid: LN2 in closed subcooled cycle with cryocooler
3. Two cooling loads: static = 60-70% (Ref. Cryo Assess. Rpt)) of dynamic loss:
   a. static: Maintain transformer at s/c temperature (no load loss)
   b. dynamic: Cool under load changes (AC + dielectric losses)
4. Maintenance objective/needs: Remove/replace cryocooler in situ and w/o thermal cycling of operating transformer
5. Monitor and maintain cryostat integrity (vacuum, etc.)

Cables:

1. Widespread commercialization of refrigeration/cryocooling systems requires on-standby skilled field service teams
2. Nominal loads: Terminal and cable cooling (in cryostat)
3. Additional cooling proportionate to changing (increasing) loads
4. Cryocooler station spacing = 100s meters (spacing needs to be optimized. It will depend upon cryocooler size and capital costs, cryogenic pumping loads, and the manner in which the cryocooler is powered)
   a. requires cooling water and power source for temporary operations at higher temperatures under failed primary system conditions at each cryocooler station
   b. manhole or other access provisions for regular and unscheduled maintenance
5. What is cryogen inventory required and replenishment frequency?
6. Can there be standardization of critical (spare) parts and interfaces across cryocooler suppliers?
7. Cryostat integrity and performance monitoring

Synchronous machines (motors, generators):

1. Operating temperatures below 77 K (50-65 K) requires helium (or other noble gas)-based refrigeration systems
2. Two cooling functions:
   a. external cryocooler or refrigeration cycle at TOP
   b. built-in/integral heat transfer system - not expected to be customer maintained
3. Availability is key to cryocooler/refrigeration system; cooling s/s cost to total cost not critical