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PERFORMANCE TESTING OF A CRYOGENIC REFRIGERATION SYSTEM FOR HTS CABLES

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ABSTRACT

A novel Cryogenic Refrigeration System (CRS) has been developed to provide the refrigeration for an in-grid 350 m HTS cable demonstration in Albany NY. Refrigeration is provided by a closed cycle refrigerator (cryocooler) with a nominal cooling capacity of 6 kW at 70 K. The CRS is designed to meet both the stringent operating and reliability criteria necessary for the utility industry, while demonstrating the commercial requirements of a cost effective and compact design. Integral to the operation of the CRS is the continuous monitoring and control provided by BOC's remote operations infrastructure. The skid mounted CRS has been installed at host utility Niagara Mohawk's site in Albany. Field trials of the CRS and its remote operation were conducted prior to the HTS cable installation using a simulated heat load. A wide variety of operating conditions and modes of operation were tested, including back up and accelerated recovery from fault current conditions. This paper describes the integrated system design and field testing results.

KEYWORDS: Cryogenic, high temperature superconductivity, refrigeration, cryocooler.
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INTRODUCTION

The development of high temperature superconducting (HTS) power distribution and transmission cables has progressed to the stage where large scale demonstrations in utility grids are feasible. Three such projects in the United States [1-3] have varying design characteristics in terms of cable length, voltage, and cable/cryostat arrangement. Common to all three is the integration into the electrical grid, and therefore the requirement to meet stringent operating and reliability criteria. A reliable and cost effective cryogenic refrigeration system (CRS) is therefore a critical enabler for HTS systems. The CRS represents the only aspect of the HTS cable system that requires continued operation and maintenance following the cable installation. During the early development phases of HTS cable systems, the CRS could be considered a relatively well understood enabling technology. However, as HTS cable systems enter into long term operation in real utility grid applications, consideration must be given to their cost effective design, and long term operation and support.

All HTS cable designs use a circulating loop of subcooled liquid nitrogen, which is not expected to boil, to maintain the HTS in its superconducting state. The operating temperatures range from just above the freezing point of liquid nitrogen, 63.2 K, to the normal boiling point temperature of 77.4 K. To ensure the liquid nitrogen remains subcooled, the operating pressure is typically maintained above atmospheric pressure. The function of the CRS is relatively simple. It must supply and circulate the subcooled liquid nitrogen, and provide a refrigeration source to remove the heat absorbed from the cable system. The heat load, not including terminations, is typically between 2-5 w/m. Therefore a 1 km cable will require between 2-5 kW of refrigeration.

The overall cost and reliability of the CRS is a strong function of the refrigeration source and how it is supported and integrated. The two options are either bulk liquid nitrogen supply and onsite mechanical refrigeration. Bulk liquid nitrogen has the advantage of simplicity of design, and a plentiful and reliable supply infrastructure. The bulk liquid nitrogen is generally supplied to a heat exchanger and reduced in pressure using a vacuum pump to achieve the low temperatures generally required. Many HTS cable projects, and most early stage demonstrations, have used this well known arrangement [4-5]. The primary disadvantages are a relatively large onsite storage tank and routine liquid nitrogen deliveries. The alternative is an onsite mechanical refrigeration plant or cryocooler. The primary advantage of onsite mechanical refrigeration is independence from routine liquid nitrogen deliveries. Reliability becomes a potential issue with cryocoolers because it is generally not cost effective to provide complete redundancy. Several arrangements have been proposed that provide a hybrid refrigeration arrangement where bulk liquid nitrogen is used as a backup refrigeration source [3,6]. The Albany CRS uses a novel thermosyphon arrangement [7] to efficiently and compactly provide this type of hybrid refrigeration.

This paper describes the installation and testing of the CRS that has been designed for the Albany HTS cable project. The system has been installed and commissioned using a temporary heated test section to simulate the HTS cable. The overall HTS cable system, including the CRS, will be monitored and controlled remotely from the BOC Remote Operations Center (ROC) located in Bethlehem, PA. The primary interface between the HTS cable system and the host utility will be provided by the ROC.

ALBANY PROJECT OVERVIEW

The Albany HTS cable project [1,7-8] is scheduled to begin the initial cooldown of the 350 meter cable in early 2006. The cable will be installed in the power grid of host utility Niagara Mohawk. SuperPower, Inc. is responsible for the overall project management, site infrastructure, and the second generation (YBCO) wire for a 30 m portion of the cable. Sumitomo Electric Industries is responsible for the HTS cable and terminations, and the first generation (BSCCO) wire for the cable. The BOC Group is responsible for the design and operation of the CRS, and overall cable monitoring and control interface with Niagara Mohawk. The underground cable is designed to operate at 34.5 kV and up to 800 Arms. The HTS cable will use a similar design to the three phases in one cryostat design successfully demonstrated in an earlier 100 m cable project [9]. The 350 m cable will initially use entirely first generation wire. An underground cable joint is provided which splits the cable into 30 m and 320 m sections. The 30 m section of first generation cable is scheduled to be replaced with a second generation cable in 2007.

CRYOGENIC REFRIGERATION SYSTEM

The detailed operating characteristics and design features of the Albany CRS have been previously discussed [7]. The overall specifications for the CRS are summarized in TABLE 1. The primary performance features of the CRS that will be discussed in this paper are its cooling capacity, temperature stability, and backup modes of operation. The most rigorous control requirement is to maintain ±0.1 K during normal operation, which is required to enable calculation of the system heat load and AC losses. The temperature stability requirement is relaxed during backup operation to ±1 K.

Albany Site

The CRS has been installed and commissioned at the cable site in Albany, NY. FIGURE 1 shows the Albany project controls and equipment building which also houses the CRS. The 5,700 liter (1,500 gallon) liquid nitrogen storage tank is shown outside the building. This capacity liquid nitrogen tank will provide approximately two days of backup refrigeration capacity. A nearby BOC liquid nitrogen plant (ASU) in Selkirk, NY can assure unlimited backup operation through regular nitrogen deliveries. The trained staff at the Selkirk ASU will also provide local support as required. A temporary heated section of insulated piping has been connected between the inlet and outlet of the CRS to simulate the heat load that will be associated with the actual HTS cable. The heat load is provided by thin film Kapton heaters. The heaters, combined with the insulation heat load, provided up to 8 kW heat load in approximately 500 W increments. These heaters have the advantages of almost instantaneous response, and assurance the heat is provided only to the process fluid when properly mounted. This temporary arrangement represents a worst case control scenario because temperature instabilities or process disturbances are almost immediately seen by the CRS. In practice, the subcooled liquid nitrogen will take over an hour to circulate through the cable and any temperature disturbances will generally be seen as a ramp change.

TABLE 1. Cryogenic refrigeration system minimum requirements

Item	Specification
Coolant supply temperature	67 to 77 K
Temperature stability	±0.1 K – normal operation ±1.0 K – backup operation
Refrigeration capacity	5 kW at 77 K 3.7 kW at 70 K
Minimum coolant pressure	1 to 5 barg ±0.2 (cable outlet/CRS inlet)
Maximum coolant flow rate	50 liter/min ±1

FIGURE 1. Albany controls and equipment building with temporary heated section and liquid nitrogen tank.

CRS Process Design

FIGURE 2 provides a simplified process diagram for the CRS. The central feature of the design is the thermosyphon, which serves as the heat exchange interface between cable coolant and both the normal cryocooler refrigeration source and the bulk liquid nitrogen backup refrigeration source. The thermosyphon also has the advantage of adding thermal stability and improved temperature control. During normal, cryocooler, operation the nitrogen in the

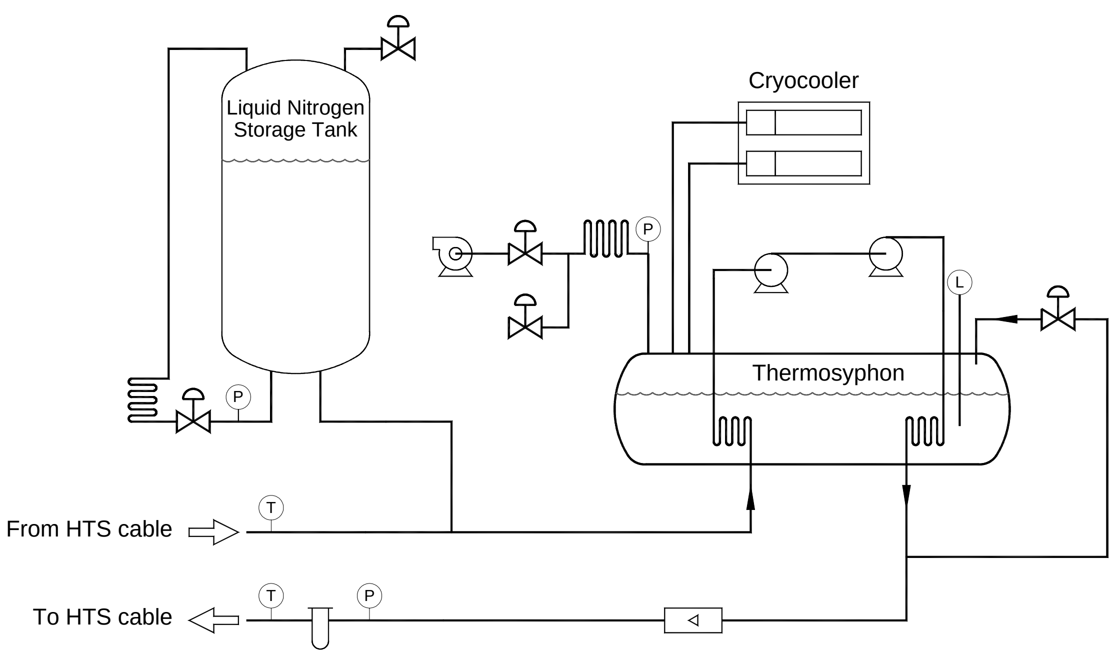

FIGURE 2. Simplified schematic of the cryogenic refrigeration system.

thermosyphon is in a state of quasi-equilibrium. There is a balance between the evaporation occurring at the cable heat exchange surfaces, and the condensation that occurs in the cryocooler. Nitrogen mass is neither gained nor lost in the thermosyphon. The purpose of the liquid nitrogen tank during normal operation is to maintain stable cooling loop operating pressure, as well as providing a buffer for liquid expansion and contraction. Some HTS cable cooling systems have used an alternative arrangement for pressure control employing pressurizing helium gas. The advantage of helium is that it can be maintained as a gas at the cable operating temperature and pressure. However, there is recent evidence that shows this pressurizing arrangement runs the risk of forming a helium bubble downstream in the HTS cable cryostat through a combination of absorption and desorption driven by small temperature and pressure differences over an extended period of time [10].

In the event of cryocooler failure or maintenance, the thermosyphon switches from a closed to open mode operation. Nitrogen evaporated from the heat exchange surfaces is removed from the thermosyphon with the aid of a vacuum pump to maintain low operating pressures required for this subcooler mode of operation. The level of liquid nitrogen is maintained by withdrawing liquid nitrogen from the subcooled loop. The purpose of the liquid nitrogen tank is now two-fold, by passively maintaining both the subcooled loop temperature and liquid inventory. Relatively warm liquid nitrogen from the bulk liquid nitrogen tank is cooled to cable operating temperature by first passing through the thermosyphon.

CRS Mechanical Design

The core elements of the CRS are housed in a vacuum insulated cold box that measures approximately 1.4 m high by 1.6 m long. The principal elements housed in the cold box are the thermosyphon, two BNCP-53 Barber-Nichols liquid nitrogen pumps, and associated valves and piping. FIGURE 3 shows a cutaway of the cold box, and the overall skid arrangement for the cold box and cryocooler. The cryocooler selected for the CRS is a Stirling cycle LPC-8 manufactured by Stirling Cryogenics & Refrigeration BV. The LPC-8 consists essentially of two identical LPC-4 units, with a common control system. The LPC-4 has a nominal cooling capacity of 4 kW at 77 K, which means the LPC-8 is the smallest standard unit that met the specification of 5 kW at 77 K for the Albany project. The individual cryocoolers are connected to the cold box through a ‘plug and play’ arrangement using flexible vacuum jacketed lines. The lines are arranged to allow the cold heads to be removed without isolating them from the

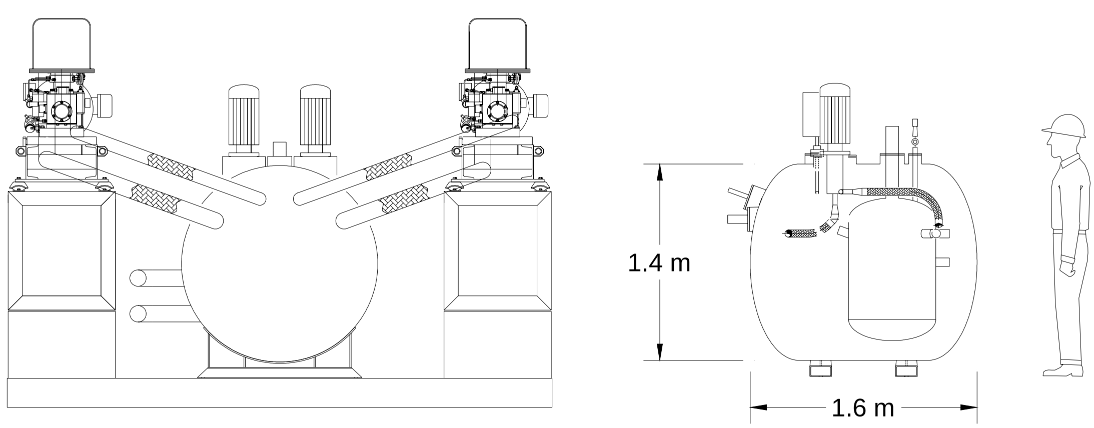

FIGURE 3. Scaled mechanical drawing of cold box and skid arrangement

a) b)

FIGURE 4. Internal view of cold box (a) and skid mounting arrangement (b).

thermosyphon. All serviceable components are then accessible for maintenance. FIGURE 4 shows pictures of the cold box and skid that were fabricated by CVIP, Inc.

The backup cooling arrangement uses a GV-400 Drystar vacuum pump manufactured by BOC Edwards. The vacuum pump operates warm, with the cold vent nitrogen heated using an electric heater. Calculations indicated the GV-400 would have an equivalent cooling capacity of more than 5 kW at 70 K.

CRS Control

The Albany CRS has two levels of overall control. Direct control of all equipment is provided by a Siemens Simatic TI545 PLC at the Albany site. This PLC then communicates to the secure BOC intranet using a Wonderware 9.0 interface. The Wonderware interface is available both onsite in Albany and remotely at the BOC ROC as shown in FIGURE 5. The ROC is an existing BOC resource which provides 24/7 operation for BOC plants throughout the United States. The protocol adopted for the Albany HTS project is that the ROC will have sole responsibility for the operation of the CRS, as well as provide the interface between the

a) b)

FIGURE 5. Local Albany (a) and Remote Operation Center (b) control interfaces.

TABLE 2. Overall test results

Item	Result
Maximum cryocooler capacity at 70 K	> 6.0 kW
Maximum backup (vacuum) capacity at 70 K	> 5.5 kW
Temperature stability during normal cryocooler operation	< 0.1 K
Temperature stability during backup (vacuum) operation	< 0.7 K
Minimum operating temperature	< 67 K

HTS cable project and the Niagara Mohawk Eastern Regional Control Center. All data associated with the HTS cable, from the CRS and otherwise, will be processed and stored on a BOC server. That data will then be available globally on a secure, read-only basis to the project partners.

Test Results

Installation of the CRS was completed by the end of June 2005, with commissioning and performance testing performed over the following six weeks. The most important performance parameters are the cooling capacity and temperature stability at design conditions. Most tests were conducted with a CRS outlet (cable inlet) temperature of 70 K, although stable operation has been achieved at temperatures below 67 K. Coolant flow rate during the tests was nominally 40 liters/min. In all cases, the project requirements have been met or exceeded. TABLE 2 summarizes key performance test results. Maximum cooling capacity is over 6 kW and 5.5 kW for the cryocooler and backup vacuum system, respectively, at 70 K. The control stability and thermosyphon heat exchanger efficiency remained excellent at all operating temperatures from 77 K to below 67 K. The maximum thermosyphon heat exchanger capacity has not been verified because of the 8 kW heating limit. Stable operation was achieved with a combination of cryocooler and vacuum pump producing 8 kW cooling at 67 K. This combination of cryocooler and vacuum pump operation is potentially important as a means to recover quickly to acceptable temperature levels following a fault current event. The combined cooling capacity is expected to be nearly 11 kW at 70 K.

Overall control stability was testing using a worst case step response scenario. Following establishment of stable operating conditions at 3.5 kW cooling and 70 K coolant temperature,

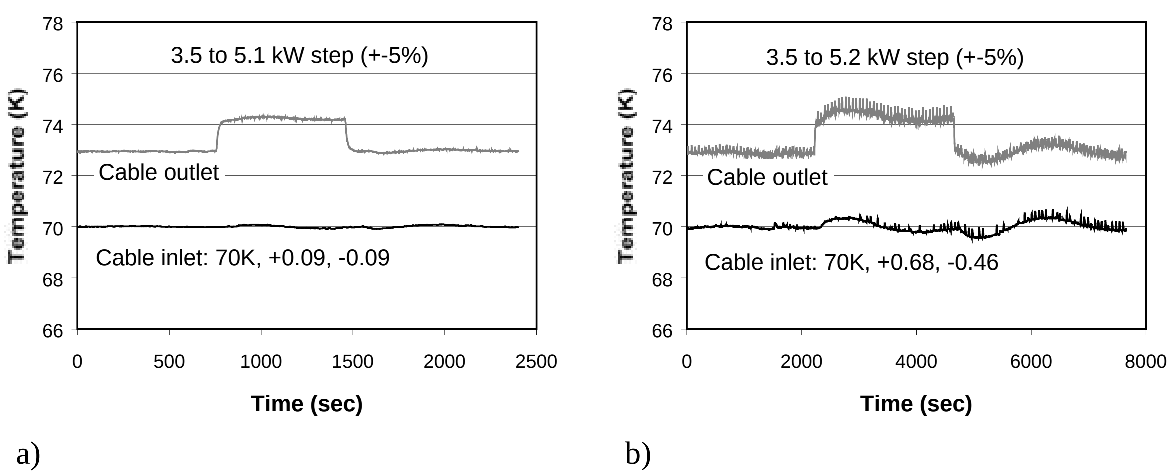

FIGURE 6. CRS step control response during cryocooler (a) and vacuum pump (b) operation.

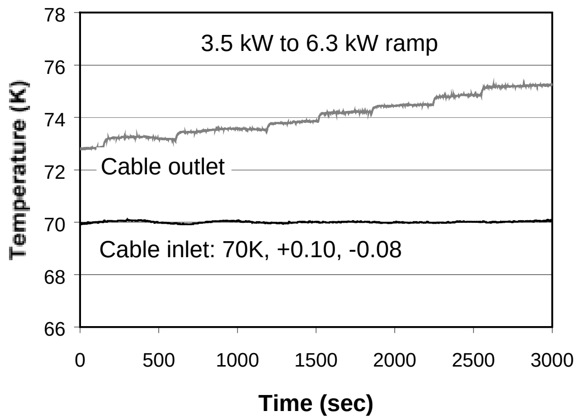

FIGURE 7. Ramp response of CRS with cryocooler.

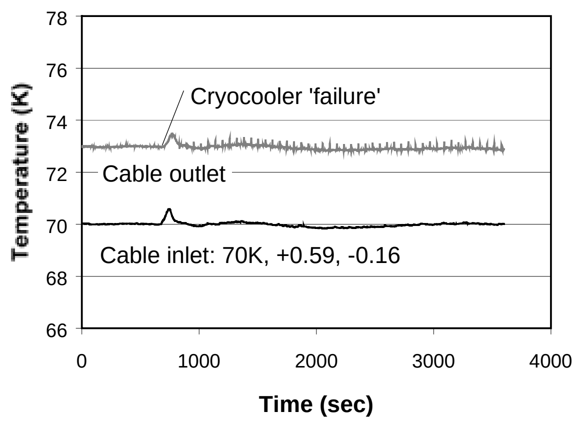

FIGURE 8. CRS response to cryocooler failure.

the heater power was step increased by approximately 1.6 kW. As soon as stable conditions were again achieved, the heater power was reduced to its original 3.5 kW value. The results are shown in FIGURE 6 for both cryocooler and vacuum pump operation. In both cases, the temperature stability requirements for normal/cryocooler (±0.1 K) and backup/vacuum pump (±0.1 K) were met. The increased 'noise' evident during backup operation is due to the action of the thermosyphon liquid nitrogen fill valve and associated small temperature and flow variations.

FIGURE 7 shows the result of a relatively gradual increase in cryocooler cooling capacity from 3.5 kW to 6.3 kW at 70 K. The temperature stability during this test remained within specifications, and the final operating point represents nearly the maximum cryocooler cooling capacity (6.3 kW at 70 K). FIGURE 8 shows the response of the system, in fully automatic mode, when the cryocooler abruptly 'fails'. The small temperature rise (0.59 K) following the simulated failure is due to the control logic needing to determine that there has been a cooling failure, and automatically switching to the backup vacuum pump operation. The temperature rise seen during this switchover is much larger than would occur in practice because the warming CRS outlet coolant would not immediately feed back into the CRS as warming return coolant.

SUMMARY

The cryogenic refrigeration system for the Albany HTS cable has been installed and commissioned using a temporary heated piping section representing the cable. The overall performance of the system has in all cases met or exceeded project requirements. All controls have been implemented and the system is operational in fully automatic and remote operation. During the remainder of 2005, the final interface with the HTS cable and the Niagara Mohawk Eastern Regional Control Center will be completed. Installation of the HTS cable and terminations is expected by the end of 2005, and the first cable cooldown is scheduled for early 2006.

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