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ABSTRACT

High-temperature superconducting (HTS) cable systems for power transmission are under development that will use pressurized liquid nitrogen to provide cooling of the cable and termination hardware. Southwire Company and Oak Ridge National Laboratory have been operating a prototype HTS cable system that contains many of the typical components needed for a commercial power transmission application. It is being used to conduct research in the development of components and systems for eventual commercial deployment. The cryogenic system was built by Air Products and Chemicals, Allentown, Pennsylvania, and can circulate up to 0.35 kg/s of liquid nitrogen at temperatures as low as 67 K at pressures of 1 to 10 bars. Sufficient cooling is provided for testing a 5-m-long HTS transmission cable system that includes the terminations required for room temperature electrical connections. Testing of the 5-m HTS transmission cable has been conducted at the design ac conditions of 1250 A and 7.5 kV line to ground. This paper contains a description of the essential features of the HTS cable cryogenic system and performance results obtained during operation of the system. The salient features of the operation that are important in large commercial HTS cable applications will be discussed.

INTRODUCTION

A series of tests of the Southwire Company's first 5-m high-temperature superconducting (HTS) transmission cable were conducted at Oak Ridge National Laboratory (ORNL). A simplified diagram for the HTS cable cryogenic system is provided in Fig. 1 that shows the main flow loop and instrumentation locations used in the pressure drop and calorimetric measurements of the HTS cable system. Figure 2 illustrates how the liquid nitrogen flows through the cable in a counterflow cooling mode.

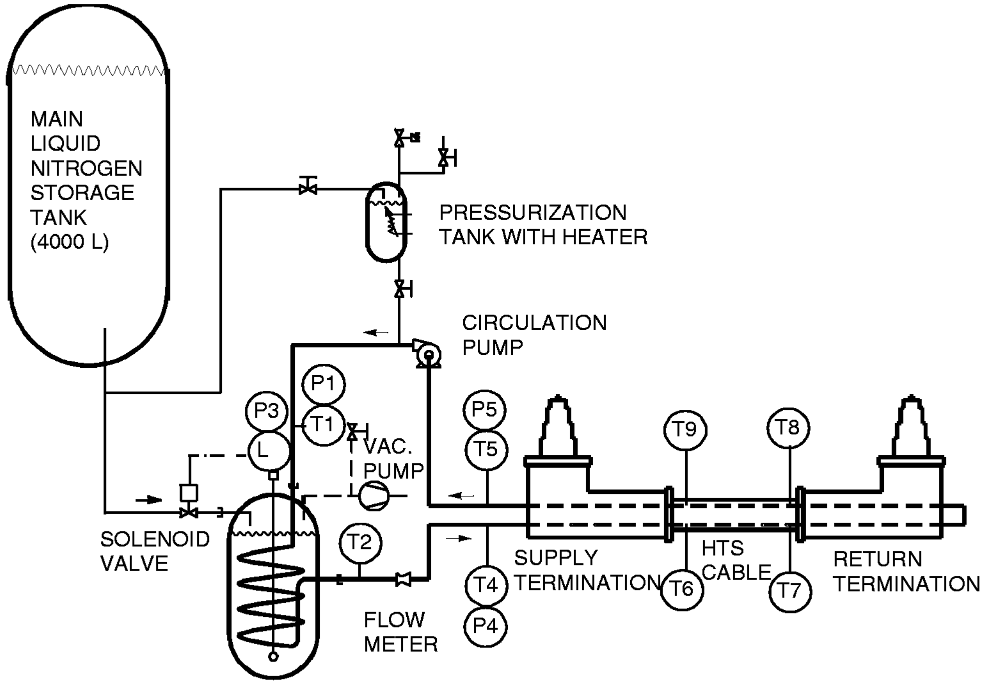

Figure 1. Simplified schematic of the cryogenically cooled HTS cable system.

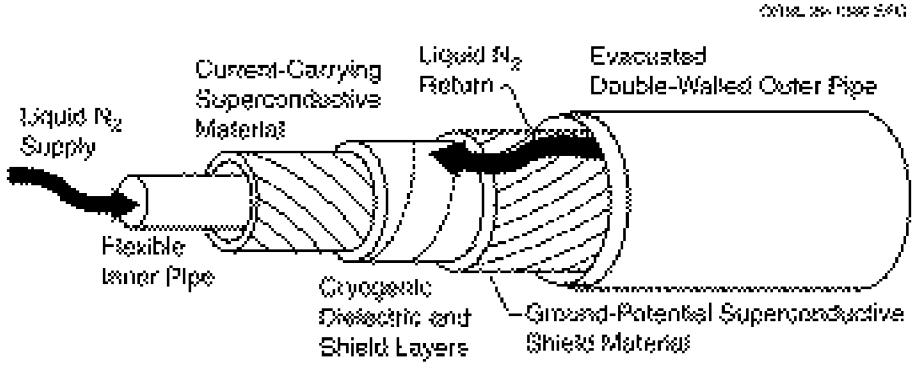

Figure 2. Simplified schematic of the cryogenically cooled HTS cable.

This paper presents the results of five runs of the system. The main operating parameters for the runs are listed in Table 1. The electrical characteristics and ac loss of the cable are discussed in another paper by Lue et al.[1] The first run was conducted to establish a baseline of the system performance without any current applied to the cable. This permitted measurement of the background heat loads and pressure drop dependency on flow rate. The second and third runs were conducted to extend the operating time of the cable. Steady state operation was not confirmed, so the fourth run was undertaken to

Table 1. Description of main operating parameters for each test run

Run	Duration (h)	Flow (kg/s)	Current (A rms)	Voltage (kV)
1	8	Varied	0	0
2	10	0.187	1250	7.5
3	12	0.210	1250	7.5
4	26	0.206	1250 to 0	7.5 to 0
5	80	Varied	1250 to 0	7.5 to 0

operate the cable at voltage and current for 26 h to achieve steady state operation for an extended period. A fifth run, conducted for 72 h, demonstrates the capability of operating the cable for extended periods at current and voltage. These runs simulated the normal operation of the cable expected in the field.

INSTRUMENTATION

This section is a brief discussion of the placement and accuracy of the instrumentation used in the HTS cable system. Table 2 lists the sensor types and accuracies as listed by the manufacturers. Thermometers T4 and T5 are factory-calibrated platinum resistance temperature devices (RTDs) mounted in stainless steel sheaths. They are installed in the liquid manifolds on the terminations as shown in Fig. 1. Thermometers T6 and T7 are factory-calibrated platinum RTDs mounted on specially designed Teflon™ holders to measure the temperature of the liquid nitrogen going into and out from the HTS cable through the HTS cable former. The Teflon™ holders were required to provide electrical isolation from the HTS cable when it is at high voltage. Thermometers T8 and T9 are factory-calibrated platinum RTDs that are mounted on the cable centering spiders and measure the liquid nitrogen temperature of the return flow over the outside of the cable. The flow rate of liquid nitrogen is measured with a turbine flowmeter given in Table 2 and has a factory calibration. The inlet and outlet pressures are measured with strain gage pressure transducers.

HTS CABLE CRYOGENIC SYSTEM TESTS

The pressure drops in the HTS cable system were measured as a function of flow without carrying current in Run 1. The HTS cable pressure drop is measured across the supply and return lines to the HTS cable (P_4 - P_5). The data fit well with the following expression for the pressure drops in the system:

$$\Delta P = \Delta P_g + K_L \dot{m}^2 \quad , \tag{1}$$

where the pressure drop ΔP is a combination of the contribution due to changes in elevation within the system ΔP_g and the mass flow rate through a modified loss coefficient K_L for the HTS cable and terminations [$K_L = 2.8 \times 10^{-6}$ bar/(g/s)^2].

Table 2. Instrument list and accuracies

Instrument	Type	Range	Accuracy	Vendor
T-4				
T-5				
T-6	Platinum RTD	14 K–325 K	±20 mK at 100 K	Lakeshore
T-7	(PT-103)		±35 mK at 300 K	Cryotronics
T-8				
T-9				
PS-1	Strain gage	0–10 bar gage	±1% FS	Omega
PS-4				
PS-5				
PS-3	Strain gage	0–1 bar absolute	±1% FS	Omega
T1	RTD	32.6 K–1128.6 K	±0.1 K	Doric
T2				
Flow	Turbine meter	3.7–38. L/min	±0.15 %	Sponsler Company

Temperatures are monitored at various locations throughout the system in order to perform calorimetry. During installation of the cable into the cryostat, one wire on the RTD T7 broke. Because this was a four-wire sensor, only one lead from the side with the broken lead was used to supply the measurement current and read the voltage across the sensor. This method gives the wrong resistance from the temperature. The value of T7 was corrected using either of two techniques. The first was to use the average heat load from the terminations and solve for the value of T7 based on calorimetry. For Run 1 the average termination heat load was around 291 W. A second method was to use an in-situ calibration. Both methods provide similar results, but are not accurate. Corrected values for T7 are not used in any calorimetry, but only for displaying the temperature distribution through the cable.

A 26-h test, Run 4, was conducted. The temperatures for this test are shown in Fig. 3. During the first hour, there is some cool down of the system. Temperature cycling was observed due to the periodic filling of the subcooler. During the subcooler filling process, the bath-side pressure changed either raising or lowering the saturation temperature of the bath, which in turn, changes the supply temperature of the liquid nitrogen to the HTS cable. After 14 h, the temperatures of the liquid nitrogen external to the cable (T8 and T9) reached a maximum and even decreased afterward. This demonstrates that the HTS cable system will operate stably over long time periods. Near the end of Run 4, the current and voltage were turned off, and the system was allowed to cool down. This is shown by the decrease in temperatures during the last 2 h of the run. This run provides some data for comparison of the system temperatures with and without the cable carrying full current.

The inlet and outlet temperatures for Run 5 are shown in Fig. 4 along with the corresponding flow of liquid nitrogen. At about 35 to 42 h into the run, there was an electrical problem in the power supply, and the current was turned off. This is the cause for the drop in the return temperatures during this period. This shows that the HTS cable system responds quickly to changes in current. From 47 h until the end of the run, the flow was changed to measure the cable response. The cable was operated with flows down to 9.5 L/min (0.126 kg/s) without any difficulty. Calorimetry is not reported for these flow variations because the time at each flow setting was not sufficient to ensure that steady state had been reached.

The temperatures throughout the system for Run 1 are shown in Fig. 5 for three different flow rates. For this graph, T7 was corrected using the calorimetric method using an average termination heat load of 291 W. Following the path taken by the liquid nitrogen,

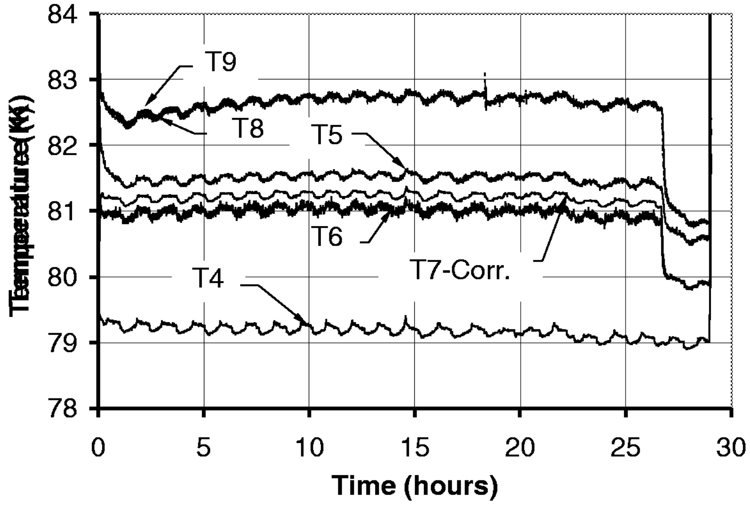

Figure 3. Measured HTS cable system temperatures for Run 4.

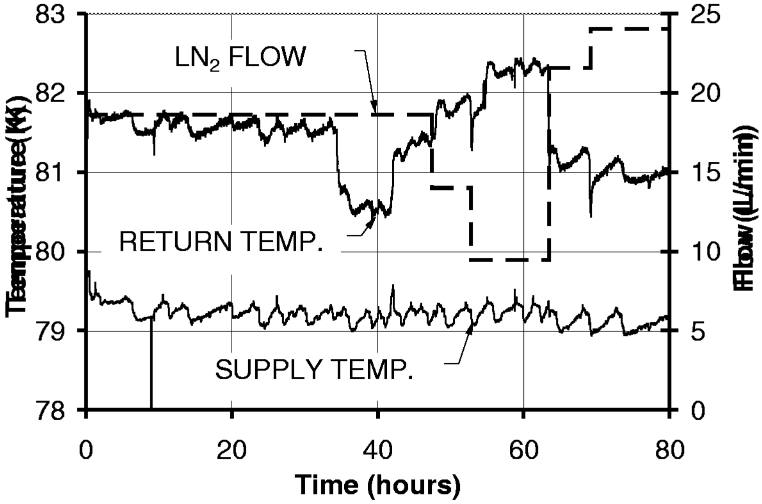

Figure 4. Measured HTS cable nitrogen supply, and return temperatures, and flow rate for Run 5.

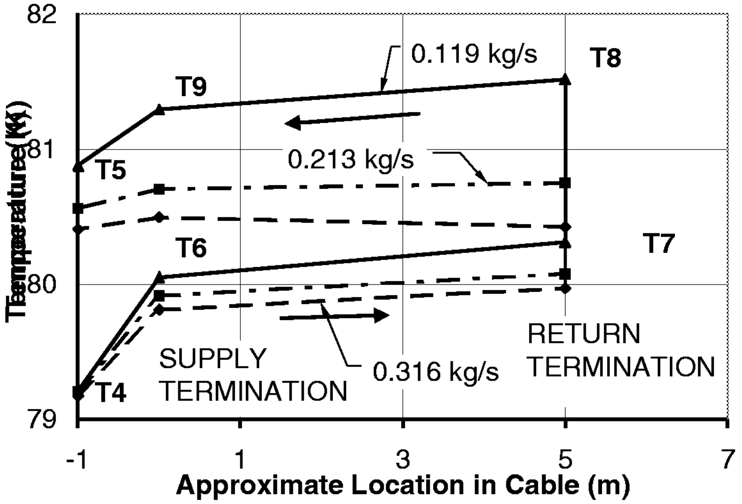

Figure 5. Measured temperature distribution in the HTS cable system for Run 1 at different flow rates using an average termination heat load of 291 W to estimate T7.

it enters the cable at T4, then leaves the termination at T6, enters the far end termination after T7, leaves the far end termination at T8, continues to flow over the outside of the HTS cable to T9, passes through the supply termination, and leaves the system at T5. The highest flow rate measured, 0.316 kg/s, produces the lowest system temperatures. In this case, the temperature of the liquid nitrogen increases all the way through the HTS cable. These temperature profiles can be expected in the non-ideal heat exchanger with heat transfer from an external source.[2] For this case, the liquid nitrogen gradually increases in temperature until it enters the supply termination where heat transfer occurs to the supply stream. The highest temperature in the system is just prior to entering the supply termination. For the medium flow case of 0.213 kg/s, the temperatures on the outside of the cable remained nearly the same. The former stream picks up most of the cable heat load. Finally for the lowest flow, 0.119 kg/s, the highest system temperature occurs at the exit of the return termination. This is what was determined earlier through analysis, because the HTS cable behaves similarly to a counterflow heat exchanger.

The portion of the flow path from T9 to T5 is the final section of the flow path for the liquid nitrogen before returning to the cryogenic skid. For the most efficient operation, it would be better if the temperature increased during this leg. This is not the case here. Instead, the stream leaving the cable heats up the stream supplied to the cable for cooling. This suggests that there may be a better way to design the cooling flow path through the termination.

The temperature distribution through the HTS cable system for Run 4 is shown in Fig. 6 for cases with and without current and voltage applied at a constant flow rate. In this figure the in-situ approximate calibration was applied to correct T7. The maximum system temperature is about 1.7 K lower for the zero current and voltage case. The overall system temperature drop is about 0.9 K.

Cryogenic system heat loads have been measured on large-scale systems such as in a prior study [3]. This reference covers many issues surrounding the accuracy of these measurements, and similar procedures are followed for the HTS cable system.

For the HTS cable the application of the first law of thermodynamics results in several energy balances for the heat loads on different components of interest in the HTS cable system. For the entire system, including the cryogenics, the heat load is given by:

$$Q_{TOT} = Q_{HTS,SYS} + Q_{CRYO} = \dot{m}(h_1 - h_2) = \dot{m}c_p(T_1 - T_2) \ . \tag{2}$$

The overall energy balance for the cable is obtained from measurements of the temperature rise and pressure drop across the entire system. From the piping and instrumentation diagram in Fig. 1, the appropriate measurements are the mass flow, P4, T4, P5, and T5. The resulting energy balance is given by Eq. (3).

$$Q_{HTS,SYS} = Q_{Terms} + Q_{HTS} + Q_{C-STAT} = \dot{m}(h_5 - h_4) = \dot{m}c_p(T_5 - T_4) \ . \tag{3}$$

In the energy balance, Q_{Terms} is the heat load for both terminations, Q_{HTS} is the cable heat generation, which is mainly the ac loss, and $Q_{C\text{-}STAT}$ is the heat transfer through the walls of the 5-m cable cryostat.

One difficulty is encountered with calorimetric measurements because of the large uncertainties present when small temperature differences are present, such as normally occur in low-temperature systems. In general, the total uncertainty is calculated by a square root of the sum of the squared uncertainty terms. The temperature difference across the HTS cable system is small so that the specific heat of the liquid nitrogen is approximately constant. The heat load uncertainty can be estimated from the following equation in terms

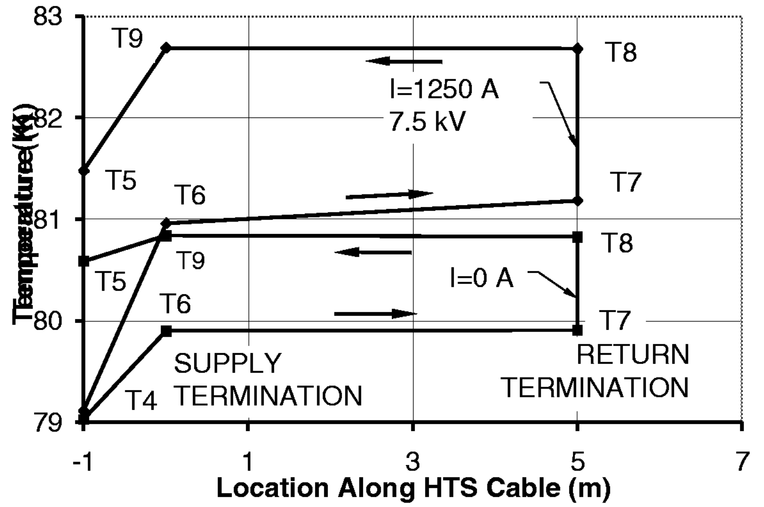

Figure 6. Temperature distributions throughout HTS cable system at the same flow rate with and without current applied. Data are from Run 4.

of the specific heat of liquid nitrogen, the measured quantities, and their respective errors as

$$\delta Q_{HTS,SYS} = \sqrt{\left(c_p\left(T_5 - T_4\right)\delta\dot{m}\right)^2 + \left(\dot{m}c_p\delta T_5\right)^2 + \left(\dot{m}c_p\delta T_4\right)^2} \qquad (4)$$

The measured heat loads and their respective experimental uncertainties, for a 95% confidence limit, are provided in Tables 3 to 6 for Runs 1 to 4. In each case the uncertainty has been broken down into the contributions due to mass flow errors and temperature errors. It is clearly shown that the measurement error is far more sensitive to the accuracy of the temperatures than to the mass flow. Therefore, for accurate heat load measurements using a calorimetric approach, precision thermometers are required.

An estimate of the termination heat loads can be obtained using the available data as well, if it can be assumed that the heat loads from the pipe are on the order of 1 W/m, similar to values given elsewhere [4], or 5 W for the total 5-m cryostat. Also assuming the ac loss to be near 1 W/m or 5 W total at 1250 A rms, the load from the HTS cable section is estimated as 10 W. This value can be subtracted from the total measured HTS cable system heat load. This can be halved to estimate the average termination heat load. Using these measured data, the average termination heat loads with and without current are 491 W and 305 W, respectively. This is an increase of 186 W per termination due to joule heating and corresponds to an apparent termination resistance of 0.00031 Ω.

Table 3. Experimental heat load measurement uncertainties from Run 1

	Q at 0 A rms (W)	δM term (W)	δT term (W)	δQ (W)
Total system	1503	130.9	331.1	356.1
HTS cable and terminations	586	51.0	40.8	65.3
Terminations by average	291	-	-	-

Table 4. Experimental heat load measurement uncertainties from Run 2

	Q at 1250 A rms (W)	δM term (W)	δT term (W)	δQ (W)
Total system	1665	11.9	338.3	338.6
HTS cable and terminations	873	6.2	106.1	106.3
Terminations by average	432	-	-	-

Table 5. Experimental heat load measurement uncertainties from Run 3

	Q at 1250 A rms (W)	δM term (W)	δT term (W)	δQ (W)
Total system	1862	96.9	170.8	196.4
HTS cable and terminations	1116	58.1	81.6	100.2
Terminations by average	553	-	-	-

Table 6. Experimental heat load measurement uncertainties from Run 4

	Q at 1250 A rms (0 A rms) (W)	δM term (W)	δT term (W)	δQ (W)
Total system	1709 (1400)	27.5	174.0	176.2
HTS cable and terminations	985 (652)	24.0	92.3	92.4
Terminations by average	487 (320)	-	-	-

IMPLICATIONS TO LARGE-SCALE INSTALLATIONS

Using the measured heat load data for the terminations and existing commercially available vendor data for vacuum-jacketed flex hose, the refrigeration load can be extrapolated for large-scale installations. Normally, power transmission systems have three electrical phases. An estimate of the required refrigeration load can be performed assuming that each phase requires two terminations making the transition to room temperature and a separate, evacuated, multilayer, superinsulated cryostat is used for each phase of the cable. On a 1000-m basis, the heat loads are shown in Table 7. The ac loss was taken to be 0.5 W/m at the operating current. The cable cryostat heat loads become dominant at longer lengths. A study by Longsworth and Skoch[5] for a liquid-nitrogen-cooled aluminum conductor cable with a 2000-MVA rating shows that using a closed cell urethane foam insulation instead of evacuated multilayer superinsulation as used in this study resulted in cryostat losses an order of magnitude higher. The development of low heat leak, flexible cryostats for use in HTS cable applications is an important task to increase the benefits of these systems.

Table 7. Heat loads for a 1000-m-long, three-phase HTS cable installation at ~80 K

	I = 0 A	I = 1250 A
Number of HTS phases	3	3
Length, m	1000	1000
Total three-phase heat load cable only, kW	6.9	8.4
Total termination heat load, kW	1.8	2.9
Total heat load, kW	8.7	11.3

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