

Draft

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**Cooling topologies for superconducting power systems:
II. Long-distance electric transmission**

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Abstract

In this and its accompanying reports, the topologies for cooling superconducting systems are investigated. The goal is to explore options that allow for flexibility of operation, low temperature rise in the superconductor and low refrigerator power consumption.

In this report we explore means of cooling the cryostat in a long-distance electric power transmission systems. Use of multiple fluids or multiple coolant circuits of the same fluid to decrease the energy ingress in the low temperature environment are described.

The goal is to achieve long lengths between cooling stations along the transmission line.

I. Introduction

The use of superconductivity for long distance transmissions has been explored for many years. Superconductivity opens the possibility for high current operation with very low losses which is not possible or difficult to accomplish with normal conductors.

Recent advances in superconductors, and in particular, high temperature superconductors, has rekindled interest in the application of superconductivity to power transmission.

Several demonstration projects in the US and overseas have been done in the past.

[Haught, Maguire, Weber, Roslita]. Most of these applications are AC, although there is also interest in DC [Yamaguchi, Furuse].

One issue that is fundamental to the comparison between superconducting and normal conducting is the heat losses in the cryostat. Because a large power is required to remove thermal loads to a cryogenic environment, methods need to be developed to minimize these loads, as well as to explore means of minimizing their impact. This is particularly important for DC systems, since the superconductor heat generation is very small in comparison with AC applications, where substantial energy is dissipated by the AC current. Thus, minimization of the cryostat load could potentially make the DC superconductor application much more attractive. In this report and in the accompanying report (Part I) means of cooling these superconducting lines are discussed.

In previous reports, means of minimizing the refrigerator loads and the temperature excursion of the superconductors were investigated [Bromberg, Miles]. Means of decreasing the current-lead cryogenic loads by about a factor of 2 were analyzed, as well as means of minimization of the temperature excursion in the superconductor. The innovation consisted of the use of intermediate cooling stations to intercept the thermal load from the room temperature environment, as well as the use of different coolant and/or coolant circuits to separately cooling the current leads and the superconductor. Although the use of two-stage cooling for low temperature operation (with an intermediate temperature around 80 K) has been proposed and explored in the past [McFee, Iwasa], the contribution by Bromberg was to extend the principle to operation

between room temperature and $\sim 80\text{K}$. The temperature of the intermediate stage that cools the current leads needs to be around about 160 or below in order to minimize the heat load to the superconductor substantially. Several fluids were proposed in the accompanying paper that could operate in the region of interest [Bromberg1].

In addition to current leads, another source of heat to the cryogenic environment is through thermal radiation. The use of multiple stage cooling stations has been proposed for the minimization of the refrigerator electrical power requirement [Miles]. In that report it was shown that the use of an intermediate cooling stations can decrease the power requirement by a factor of two, while with the use of three thermal shields, the power can be decreased by a factor of 4. Although it is common to use intermediate cooling stations between room temperature and liquid helium environments, to our knowledge their use at elevated temperatures to minimize the thermal load at the $\sim 75\text{K}$ environment of HTS cables have not been suggested.

In this report, the topologies required to implement the use of using multiple cooling stages for minimization of the cryogenic load are analyzed. Also, means of facilitating long transmission lines are discussed.

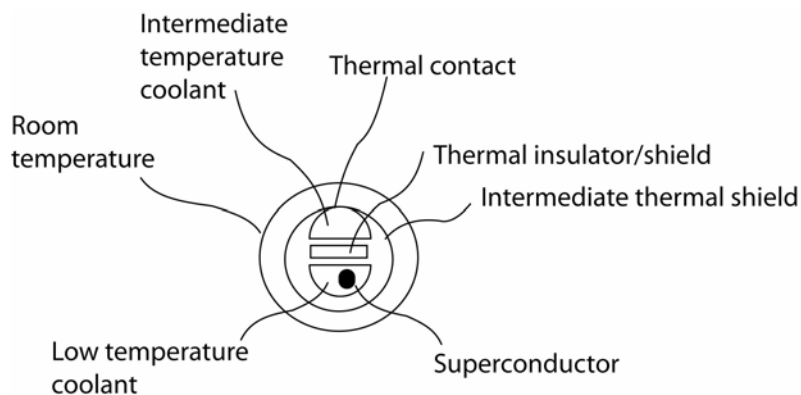


Figure 1. Schematic diagram of a non-coaxial two-coolant system that separates the cooling of the thermal shield from that cooling the superconductor.

II. Multiple temperature anchors

Figure 1 shows a schematic diagram of a cryostat where in each cryostat there are two cooling circuits, low temperature coolant and intermediate temperature coolant, either going in the same direction or in opposite directions. When in opposite direction, continuity of nitrogen flow is easily established and a single cryostat can close the loop, with a refrigerator at one end. The superconductor is in the cold circuit, with the warmer circuit cooling the intermediate cooling station. It is useful to provide thermal insulation or a vacuum gap to limit thermal conduction and convection from the intermediate temperature coolant to the low temperature coolant circuit. In Figure 1 the return path is shown cooling only the intermediate cooling station, as would be the case for long distance transmission. For distribution systems, it would be possible to use the intermediate temperature coolant to also cool the current leads, in order to intercept the thermal energy at the higher temperature that would otherwise end up heating the superconductor coolant.

It is possible to taper the flow paths, in case that there is coolant transfer from the low temperature coolant to the intermediate temperature one, as for example when cooling a secondary current lead as discussed in the accompanying report [Bromberg]. Although the current leads would operate at slightly higher temperatures than the superconductor in this arrangement, heat ingress into the cold fluid path that cools the superconductor is decreased.

An alternative arrangement would have a coaxial arrangement of the different elements, as shown in Figure 2. In this case, the thermal insulator or the vacuum gap is a concentric hollow cylinder. The intermediate temperature coolant is on the outside, while the low temperature coolant is in the central region.

The arrangement in Figure 1 does not require that the temperature anchor be a single solid tube, as it could be a tube with an axial cut, but with overlapping lips in order to prevent radiation from streaming between the gap that would otherwise exist. The warm coolant is in a pipe, with the temperature anchor cooled by thermal conduction to this

pipe. As depicted, the heating of the low temperature coolant, and thus the superconductor, would come from convection in the vacuum, conduction through support and from losses in the superconductor, if any. In the absence of losses in the superconductor, (as would be the case for DC systems), the heat ingress into the low temperature coolant path can be decreased by approximately two orders of magnitude.

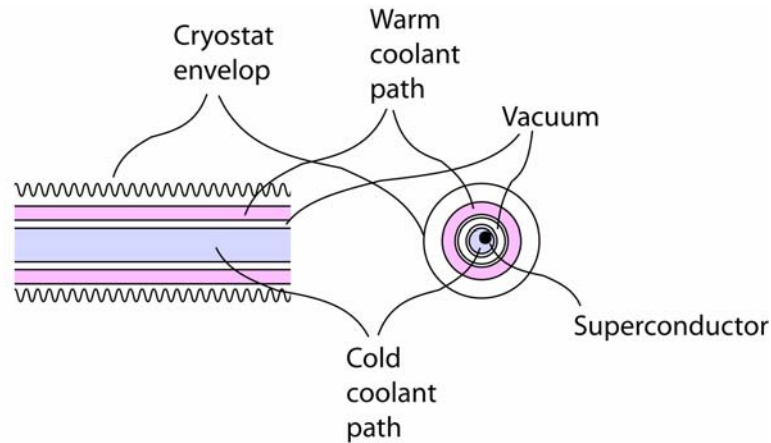


Figure 2. Schematic diagram of a coaxial arrangement

The minimization of the heat ingress into the cold coolant path allows for the minimization of the low temperature coolant throughput or would allow for increased lengths of transmission line for a given throughput.

It is possible to use two different fluids for the cold loop and the warm loop. Miles described the optimal temperature of the intermediate cooling station (around 170K for a single stage) [Miles], while Bromberg [Bromberg] identified potential fluids that could be used.

III. Calculation of performance of cooling topologies for transmission systems

In this section, the performance of the several option discussed in Section II is assessed. It is not the goal of these calculations to fully optimize the system, as much more work needs to be done, including detailed investigation of the performance of the refrigerators.

Instead, the goal is to provide insight into the potential of the different options for reducing the heat load.

The calculations have been performed for a long transmission line. The distributed cryostat losses dominate the thermal input in the case of the DC transmission. In this case it is also important to control the pressure drop along the line. It is also desirable to minimize the power requirements for the refrigerators.

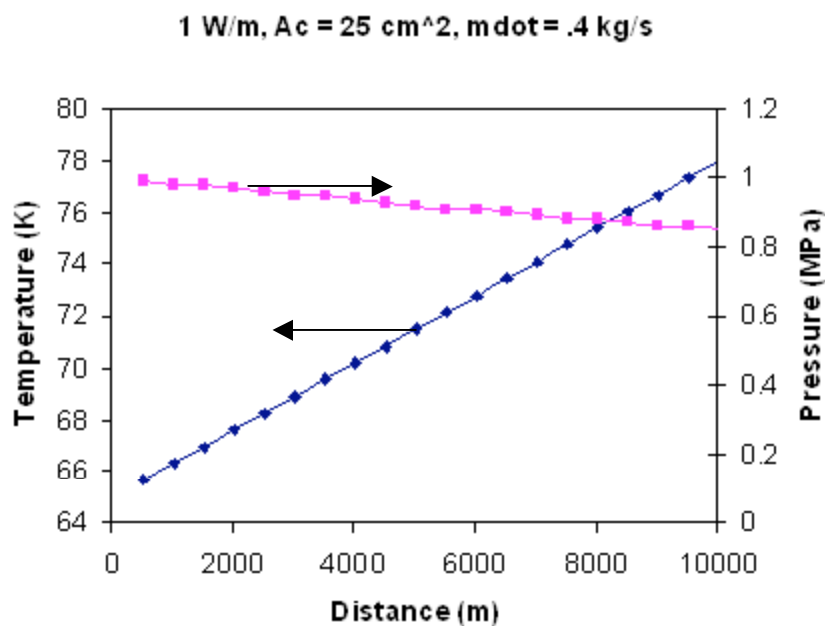


Figure 3. Temperature and pressure along a 10 km transmission line. Cross sectional area of coolant is 25 cm^2 and the flow rate is 0.4 kg/s .

For the calculations, a compressible, steady state 1-1/2 D code has been used (CCAN), developed at MIT by Gierszewski [CCAN]. CCAN calculates the temperature, pressure, power and other engineering quantities along the length of an actively cooled electrical conductor. The code was developed to perform engineering analysis of internally cooled conductors, so it is particularly well suited for electrical power systems with distributed thermal loadings. The code assumes single phase flow and neglects axial conductions relative to heat transfer to the coolant. It is assumed that the refrigerators operate with

20% of Carnot efficiency, an aggressive goal corresponding to the middle term expectations from the Navigant study [Navigant].

It is assumed that the inlet pressure is 10 bar, and that there are no large elevations/depressions in the line, so that the pressure is determined mainly by hydraulic losses from the flow. Elevation of 10's of meters would not change the results much, but much larger changes in elevation would require more detailed calculations. This is particularly important towards the end of the transmission line, where two-phase flow may be generated with decreased pressure due to an increase in elevation.

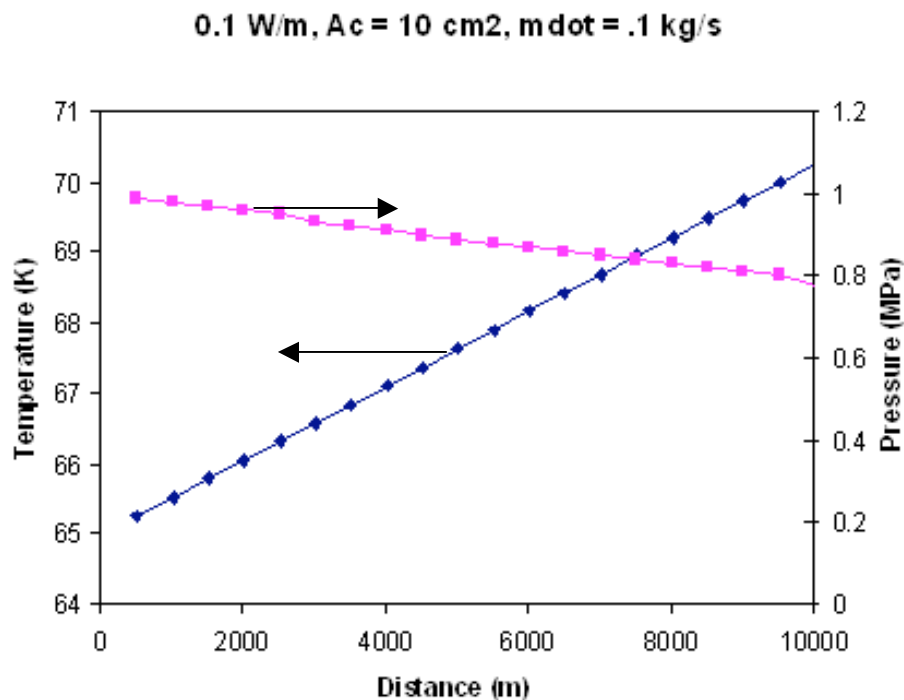


Figure 4. Temperature and pressure along the line for the low temperature coolant circuit, when there is an intermediate cooling station at 160 K.

Figure 3 shows the results of the calculations for a conventional [Lee, Maguire, Rostila] transmission line, where a single coolant cools the superconductor and the inner cryostat. It has been assumed that the length of the section to be cooled with a single refrigerator is 10 km. This number is arbitrary, but it is felt that much lower distances for each independently cooled section would not be an attractive solution for transmission. In

order to be able to remove the heat over 10 km (~ 10 kW) with a small ΔT , the mass flow rate needs to be ~ 0.4 kg/s. In order to prevent an excessive pressure drop, the cross sectional area of the coolant is ~ 25 cm². Although the temperature rise of the coolant is not excessive (around 13 K), it has substantial impact on the superconductor performance. For fields perpendicular to the tape, the critical current density of second generation HTS drops by about a factor of 2.5-3 in the presence of a modest field (0.4 T) when the temperature is raised from 65 K to 77 K. The pressure drop has been limited to about 0.2 MPa (2 bar).

Figure 4 shows the results of the simulation when there is an intermediate cooling station at 160 K. In this case, the thermal energy input to the low temperature coolant is reduced by more than an order of magnitude (reduced by a factor of $\sim (160/300)^4$), resulting in ~ 0.1 W/m. In this case, it is possible to cool long lengths of the transmission line with relatively small temperature rise in the cold stream, ~ 5 K, with substantially smaller cross sectional area (10 cm²). The flow rate of the coolant is about 4 times lower in the cold stream, resulting in comparable pressure drop.

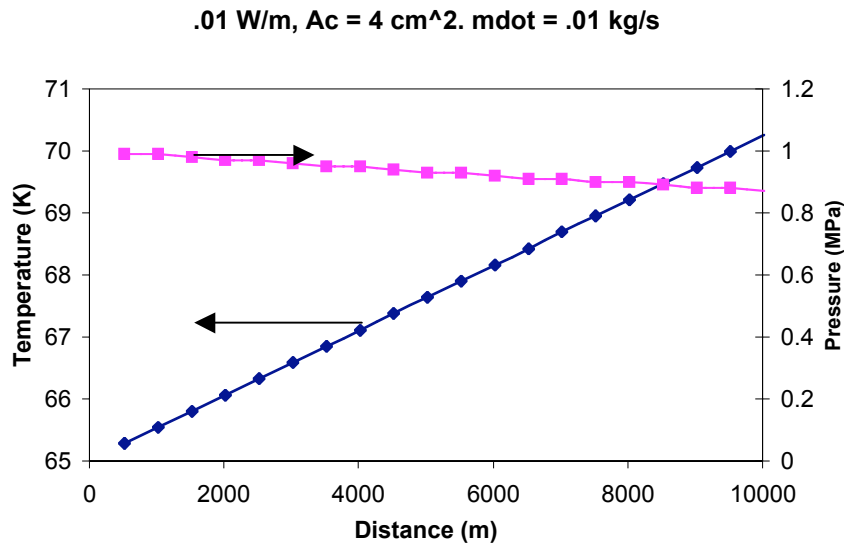


Figure 5. Temperature and pressure along the low temperature coolant circuit for the case of an intermediate cooling station at around 90K.

Figures 5 and 6 cover the case when there is a intermediate cooling station is at 90 K, which further decreases the radiated power to the environment of the low temperature coolant. In this case, it is assumed that radiated power to this environment is 0.01 W/m ($\sim (90/300)^4$). The 90 K environment, on the other hand, is removing 1 W/m (the full thermal load from the room temperature environment). Figure 5 shows the temperature and the pressure on the low temperature coolant circuit, while Figure 6 shows those parameters for the intermediate temperature circuit.

For the low temperature coolant circuit, the flow rate requirements, as well as the cross sectional area for coolant, have decreased substantially for the low temperature coolant circuit, to 0.01 kg/s and 4 cm², respectively. The pressure drop is a modest 1 bar, over 10 km. The temperature rise has been kept constant to about 5 K. By comparison, the high temperature coolant circuit, which needs to remove 1 W/m, has a temperature rise of 20 K, a cross sectional area of 19 cm², and a pressure drop of about 2 bar.

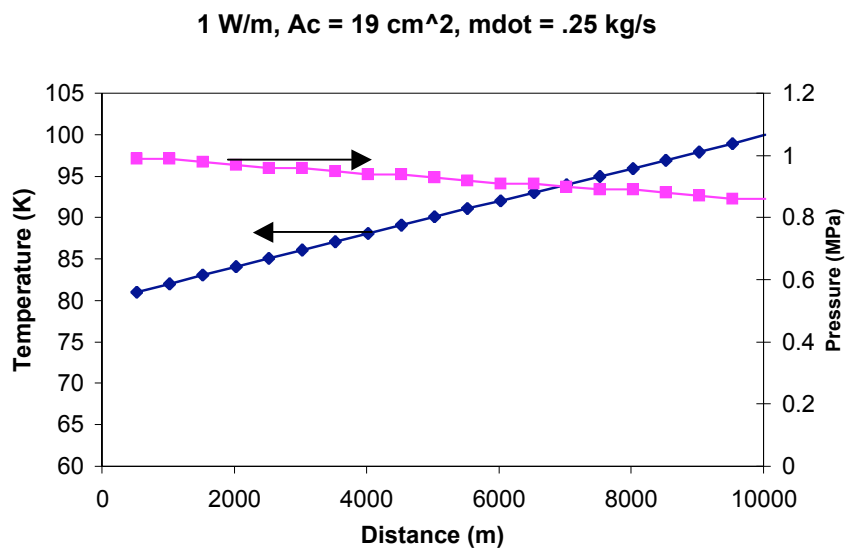


Figure 6 Temperature and pressure along the intermediate temperature coolant circuit.

It is interesting to note that the total cross sectional area did not change much (24 cm² in Figures 4 and 5, vs 25 cm² in Figure 5). The reason for this is that the total heat that needs to be removed is the same (1 W/m), and the temperature rise is comparable (13 K in Figure 3, 20 K in Figure 6). The total required refrigeration power is reduced, however,

because of the heat appears mostly in the high temperature stream, resulting in a high thermodynamic efficiency. In order to be able to decrease the cross sectional area, other fluids can be used. As shown in Table 2 in the accompanying paper [Bromberg], methane or argon are attractive candidates, as they could remove about twice as much heat for the same pressure drop. The intermediate temperature circuit would operate at higher temperatures.

Table 1 shows the comparison between two of the cases analyzed in this section. The baseline case, which uses the same coolant for cooling the superconductor as well as the cryostat, with no intermediate cooling station, and a case with a intermediate temperature station operating at 80-100 K (*i.e.*, using liquid nitrogen). The main parameters of the simulation are presented, including energy ingress (Q), mass flow rate (\dot{m}), inlet and outlet temperature of the respective topology (T_{inlet} and T_{outlet}), pressure drop (Δp) and cross sectional area (A_c). Also shown is the refrigerator power (assuming 20% Carnot). In the baseline case, the refrigerator power (with an outlet at 65 K), is about 160 kW. In the case with the intermediate cooling station, the total refrigerator power is about 120kW. The refrigerator with an outlet temperature of 80 K consumes about all of the power, with less than 2% for the low outlet temperature (65 K) refrigerator.

Table 1 Summary of results comparing base case to a case with one intermediate cooling station at a temperature around 90 K.

		Base case	One intermediate stage	
			High T	Low T
Q	W/m	1	1	0.01
\dot{m}	kg/s	0.4	0.25	0.01
T_{inlet}	K	65	80	65
T_{outlet}	K	78	100	70
Δp	MPa	0.18	0.18	0.18
A_c	cm ²	25	19	4
Refrigerator power	kW	162	118	1.8

It should be noted that the reduction in the refrigerator power of about 1.4 in Table 1 is substantially lower than the reduction predicted by Miles [Miles]. The reason is that the purpose of the minimization in this section is to decrease the thermal ingress to the low temperature circuit, rather than minimizing the refrigerator power. The refrigerator power is minimized by operating the intermediate circuit around 160 K, with a substantially lower outlet temperature for the cold stream than the single stream in the baseline case.

IV. Calculations of maximum length cooled with single coolant

The above model can be used to determine the limits to the cooling lengths, for fixed conditions. In this section, the maximum cooling length is calculated for a thermal load of 1 W/m, for constant elevation (so that there are no excursions in pressure due to gravity), and for two different cross sections of the coolant flow.

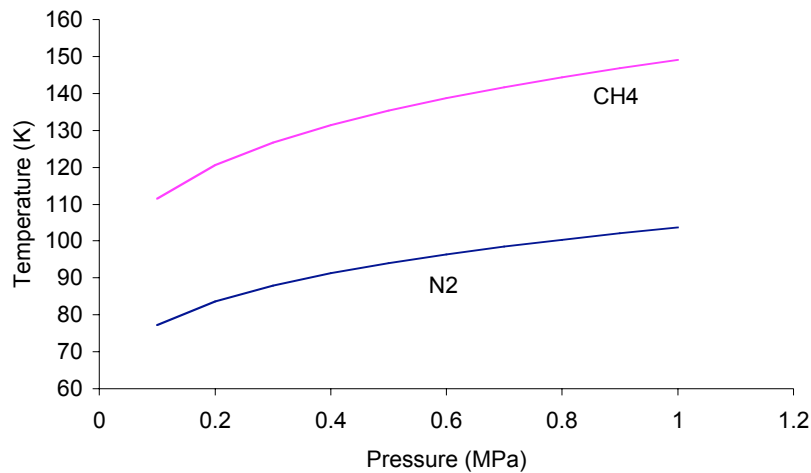


Figure 7. Boiling temperatures of nitrogen and methane as a function of pressure

There are multiple limitations, but in this section the one due to subcooled boiling is investigated, with only single-phase flow permitted. Boiling occurs at a temperature that increases with pressure. Figure 7 shows the boiling temperature of nitrogen and methane for different pressures, produced from the NIST database [NIST]. Methane is an attractive alternative coolant for the intermediate cooling station, as discussed in the

accompanying paper [Bromberg1]. Although phase change offers large changes in enthalpy (200 kJ/liter for nitrogen), gas generation within the line results in unpredictable flow, and the possibility of vapor lock, although Ashworth has proposed the use of two channels with gas on one channel and liquid on the other [Ashworth].

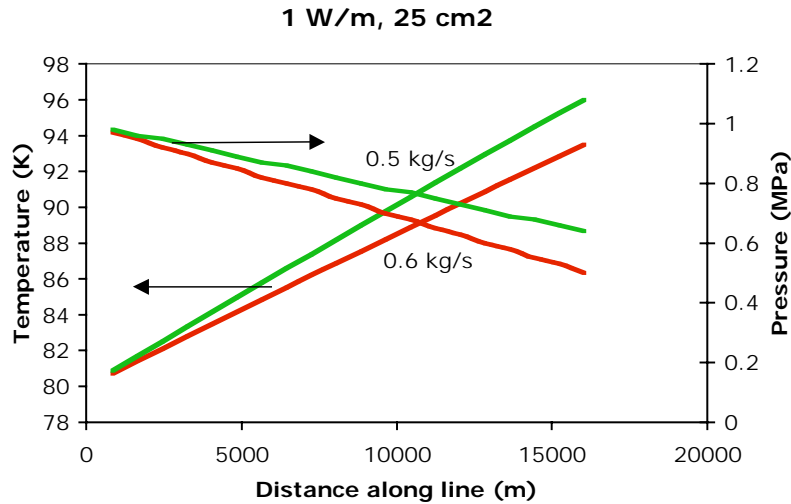


Figure 8. Temperature and pressure for 1 W/m and of 25 cm² coolant cross sectional area without subcooled boiling.

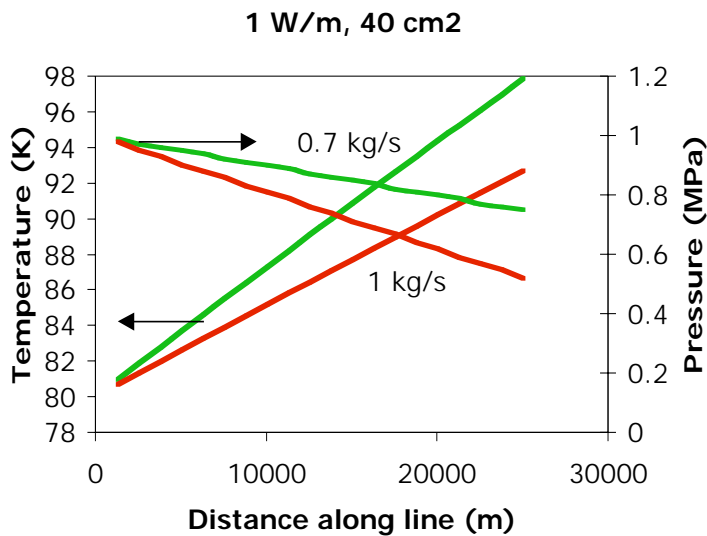


Figure 9. Same as Figure 7, but for a cross sectional area of the coolant of 40 cm².

On the one hand, faster flows result in lower temperatures at the exit, but on the other hand, faster flows result in lower pressure at the outlet due to increased pressure drop at the higher flow rates. The goal of this section is to explore this tradeoff. Larger cooling cross sections for the intermediate temperature stage allow increased flow rates, or lower pressure drop for a given flow rate. In this section, the two arbitrarily chosen cross sections are 25 cm² and 40 cm².

The temperature and pressure along the transmission line are shown in Figure 8 for the case of 25 cm² and in Figure 9 for the case of 40 cm². In both cases, the results are limited by avoidance of subcooled boiling. In Figures 8 and 9, there is little difference between the high flow rates and the lower flow rates, as the lower temperature in the case of higher flow rates results in lower pressures (and thus lower subcooled boiling temperature) than the case with lower flow rate. There is little difference in the length of the transmission line that can be cooled without recool for the different flow rates chosen in Figures 8 and 9.

Table 2 summarizes the results for the limited cases investigated in this section. The main conclusion is that subcooled boiling represents a limitation that, for a given cross section, seems to limit the cooling length to about 15-25 km, for the case of 1 W/m, 10 bar inlet pressure and little changes in elevation. The row marked Power (W) in Table 2 refers to the electrical power at room temperature, assuming 20% Carnot efficient refrigerators, The pumping power is a very small fraction of the total electrical requirements.

Table 2. Comparison of high and low flow rates, for two different coolant cross sections

	25 cm ²		40 cm ²	
	High flow rate	Low flow rate	High flow rate	Low flow rate
Length (m)	16000	16000	25000	25000
Flow rate (kg/s)	0.6	0.5	1	0.7
Inlet temperature (K)	80	80	80	80
Outlet temperature (K)	93.5	96	92.7	97.8
Inlet pressure (Mpa)	1	1	1	1
Outlet pressure (Mpa)	0.5	0.64	0.52	0.75
Power (W)	204	197	321	302

V. Conclusions

Different cooling circuit topologies for long-distance distribution systems have been evaluated in this report. Means of eliminating substantial temperature rise of the superconductor have been found, through the use of multiple coolants or multiple coolant circuits (operating at different temperatures). Long transmission lines can be cooled in this manner, using either liquid nitrogen both circuits, or liquid nitrogen for the low temperature circuit and a different fluid for the intermediate temperature circuit.

The purpose of this report, and the accompanying one, is not to optimize the system. To do so requires substantially more work, better understanding of refrigerator performance as a function of capacity and temperatures and inclusion of the small but finite thermal conduction and convection thermal ingress, especially to the low temperature circuit. However, the work does show the potential of the method for addressing key issues on implementation of HTS cables for transmission and distribution.

It has been determined that it is possible to decrease the refrigeration power by about a factor of 2 for both cryostat loads (this paper) and the current leads (the accompanying paper), while allowing for low temperature rise in the low temperature circuit, facilitating long sections between recool for transmission lines.

Acknowledgement

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