PSFC/JA-09-22

COOLANT TOPOLOGY OPTIONS FOR HIGH TEMPERATURE SUPERCONDUCTING TRANSMISSION AND DISTRIBUTION SYSTEMS

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September 22, 2009

Supported in part by a grant from the MIT Energy Initiative

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ABSTRACT

This paper investigates coolant topologies for High Temperature Superconducting (HTS) transmission and distribution cable systems. We explore options that allow for flexibility of operation, low temperature rise in the superconductor and low refrigerator power consumption. Topologies for cooling the cryostat and HTS in long-distance electric power transmission systems are explored. For transmission, the goal is to achieve long spans between cooling stations along the transmission line, and low power consumption. For HTS distribution systems, the issue is cooling the superconductor and the current leads and the goals are to minimize the power consumption and to prevent excessive heating of the superconductor. Means are explored to cool distribution systems where cryogenic loads are dominated by current lead loss. Use of multiple fluids or multiple coolant circuits of the same fluid to decrease the energy ingress in the low temperature environment is described. Potential alternative coolants are proposed. We show that it is possible to reduce electrical consumption by about a factor of 2, while also decreasing the temperature rise of the superconductor.

KEYWORDS: cryostat cooling; high temperature superconductors; intermediate temperature

INTRODUCTION

Recent advances in superconductors, and in particular, high temperature superconductors, has rekindled interest in the application of superconductivity to electrical power transmission and distribution. Several demonstration projects in the US and overseas have been recently implemented [1]. Most of these applications are AC, although there is also interest in DC [2, 3].

HTS transmission and distribution systems require cooling to remove thermal loads from the current leads, cryostat and superconductor. In this paper we concentrate on the first two, as would be the case for DC systems with very small superconductor losses.

Short distance SC distribution systems have characteristics that make them very different from long-distance transmission lines, as the cryogenic loads are dominated by the current leads losses. For long distance transmission lines the heat load is dominated by distributed cryostat losses. A second difference is that the short distance distribution grid is characterized by a large number of secondary spurs or branches.

The two main coolants of interest for cooling HTS cables are liquid nitrogen (subcooled), and gaseous helium. Liquid nitrogen has the advantage of much smaller temperature rise in the coolant for a given volumetric flow, but it is limited in the minimum temperature at which it can operate, at around 65K. Cooling by gaseous helium requires comparable the mass flow rates as those provided by liquid nitrogen. However, because gaseous helium has much lower density, the corresponding volumetric flow rates and the operating pressure drops are higher. The high flow rates result in increased pressure drop and the changes in density with temperature are much larger than for liquid nitrogen. In a subsequent section of this paper we consider other fluids and temperatures for cooling the cryostat and the current leads.

There is a substantial literature on the minimization of the cryogenic load on conduction-cooled current leads, starting with the work of McFee [4]. Iwasa has systematically reviewed work on this field [5]. Recently, there has been work to try to minimize further the cryogenic load. Yamaguchi has proposed and tested the use of Peltier elements at the high temperature side of the current leads [6]. Bromberg has optimized the use of intermediate temperature stages as further means of decreasing the cryogenic load [7]. These studies indicate that it may be possible to decrease the cryogenic loads due to the current leads to about half that of conventional systems.

In the case of current leads, the thermal refrigeration requirement from room temperature to near liquid nitrogen temperature is ~ 0.1 W_T/A per current lead pair. Depending on the voltage of the transmission line, the cryogenic requirement for the primary feeder current leads could be as high as 2.5 kW per set of power leads (for 25 kA SC bus, 400 V). A similar heat load appears in the secondary spurs (as the integrated current of the secondary spurs is the same as that of the primary feeders). The secondary spurs result in distributed losses along the distribution line. Removal of these large cryogenic loads presents a significant challenge. For one, it would be best if the superconductor temperature could be maintained as low as possible to minimize the

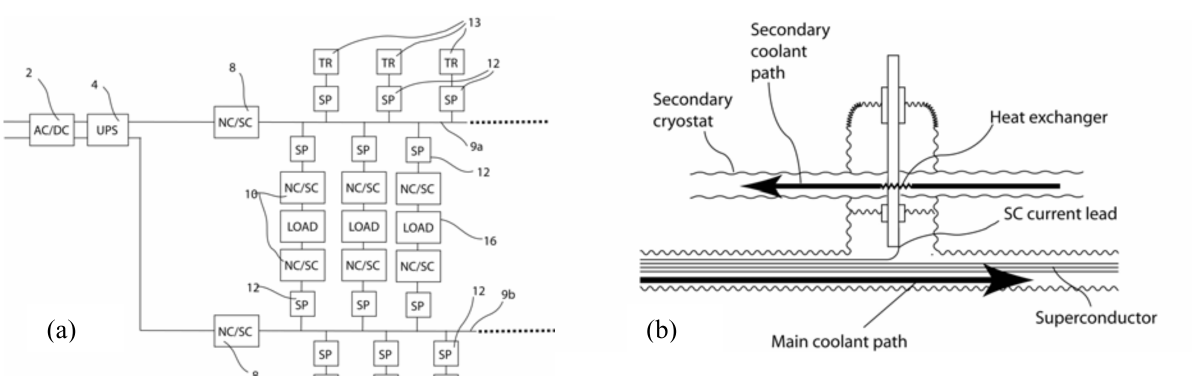


FIGURE 1. (a) Circuit diagram for an HTS DC distribution system. (b) Cooling topology with separate cooling paths for the HTS bus and for the secondary feeder (a single spur is shown) current leads.

amount and cost of superconductor required. The present cost of the superconductor is a substantial fraction of the system cost, and thus its performance needs to be maximized.

In this paper approaches are investigated that address the unique cooling needs of HTS distribution and transmission systems. The use of multiple cooling stages for minimization of cryogenic heat load is analyzed. Also, means of facilitating long transmission lines are discussed.

DISTRIBUTION NETWORKS COOLANT TOPOLOGIES

Figure 1(a) shows a HTS DC distribution system, such as those proposed for a data center [2, 3]. With respect to Figure 1, the power may come to the site through a high voltage transmission line, and then it is reduced to low voltage by an onsite transformer (not shown). The AC power output from the AC transformer is converted to DC by an AC/DC converter, followed by an uninterruptible power supply (UPS). The uninterruptible power supply can be a SMES, capacitor banks, ultracapacitors, battery, diesel generator set with AC/DC conversion, or similar. A set of current leads, 8a and 8b are used to introduce the current through the cryostat to the HTS. A large number of spurs 12 provide connectors to the HTS distribution bus 9 (composed of elements 9a and 9b). Some of these spurs may be terminated by terminations 13, within the cryostat, that are not immediately active, to provide for future expansion of the distribution bus. Most of the spurs are active and connected to current leads 10 that transfer the current from the superconductor to a normal conductor through the cryostat. These currents power the loads. The current is then returned by a similar HTS electrical distribution bus.

For DC distribution, it is desirable to have the current return also be at voltage to maximize the transfer of power for a given amount of superconductor. If this arrangement is chosen, then the voltage polarity of bus 9a and 9b are opposite. To accommodate unbalanced loads, faults or transients, a small ground return is needed (not shown). This approach is attractive when the transmission is at high voltage, as the voltage is halved for constant power delivery capability.

In the near term the cost of the superconductor dominates the cost of the system by a wide margin. In the longer term, the cost of the HTS is expected to become comparable to the cost of the cryogenic system [8]. The reason for the relative change of the costs is that it is expected that the cost of the superconductor, a recent technology, will experience much faster cost reduction than either the cryostat or the cryocoolers, which are more mature technologies.

In a distribution network (short length cryostats) the cryogenic heat load is dominated by the current leads. This paper investigated means to decrease the thermal load due to the current leads and cryostats (for distribution networks) and to investigate means to minimize the temperature rise in the superconductor coolant.

In the conventional approach [see, for example 9, 10] a single coolant cools simultaneously the superconductor, the cryostat, and the current lead of a spur along the line. This geometry has the disadvantage that the superconductor downstream from a lead experiences increased temperature and thus decreased current carrying capability. High coolant speeds and large excess coolant capability can be used to mitigate this problem.

Multiple topologies can be considered that avoid this problem. The main feature of these topologies is that the superconductor be cooled with a separate fluid (or upstream using the same coolant) from the coolant that cools the current leads. One option it to use a fraction of the main coolant to cool the current lead through a heat exchanger, the warm coolant is removed from the cold cryostat and returned through a separate coolant channel.

TABLE 1. Comparison between base case, separate coolant and go-and-return

				Go and return	
		Base case	Only current lead	Low T	High T
Distributed load, total	W/m	6.26	6.26	0.31	6.26
$\dot{m}$	kg/s	0.1	0.1	0.02	0.02
Ac	cm^2	2	2	1	1
T_{inlet}	K	65	95	65	67.6
T_{exit}	K	71.5	101	67.6	98.7
p_{exit}	MPa	0.9	0.91	0.97	0.94
Refrigerator power	kW	21.5	13.1	1.1	17

It should be noted that the two separate coolant paths could be located within the same cryostat, to minimize the cost of the cryostat. Multiple current leads can be cooled in this manner, with the return path of the warm coolant returning through a single path towards the inlet of the cold coolant. One advantage of this geometry is that the coolant is returned to the inlet, where it can be recooled and reused.

Although better than the conventional arrangement, flow control of the coolant through multiple parallels paths is challenging. A better arrangement is the one illustrated in Figure 1(b), where two separate cooling paths cool the system, with the cold coolant path only cooling the superconductor bus, and the second, warmer coolant loop cooling only the current leads. Note that there is heat conduction and heat dissipation between the section of the current lead cooled by the warm coolant and the superconductor. The temperature difference between the two regions along the normal conductor results in heat transfer to the cold path, but because ΔT is designed to be small, the heat input is small. Although shown in separate cryostats in Figure 2, it is possible for both coolant paths to be in the same cryostat.

Calculations have been performed for a DC distribution grid, such as for a data center: cable length of 200 m, carrying 25 kA, with a cryogenic load due to current leads (assumed uniformly distributed along the cable) of 0.05 W/A and a thermal load of 0.1 W/m to the low temperature coolant (most of the heat load is intercepted at the higher temperature, as will be described in the next section). The inlet pressure is 1 MPa. We assumed that the system does not include current path redundancy for the secondary system. If a redundant system is used, the cryogenic load would increase by about a factor of 1.5 for a second set of current leads that are not carrying current, but result in increased cryogenic load. The terminations are cooled separately from the HTS.

A compressible fluid, steady state 1-1/2 D code has been used (CCAN), developed at MIT by Gierszewski [11]. 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 0.2 of Carnot (long term expectations of the Navigant study [8]).

Results from this code are shown in TABLE 1. The column titled "Base case" assumes that the current leads are cooled simultaneously with the same coolant as the HTS. Because of the relatively short length (200 m), the pressure drop is not an issue. Substantial flow rates can be provided, 0.1 kg/s, in small cross sectional area (2 cm^2), with relatively small pressure drops. The column title "only current lead" shows the results for the case when the current leads are cooled separately, and the heat is intercepted at around 100 K. The result of this case is to minimize the cryogenic load to the low temperature environment. Finally, the results of a system where the coolant first cools the superconductor and then the current leads are presented in last column of TABLE 1. The total length of the coolant path in this case is now 400 m. The cross section of the coolant is decreased. The coolant flow rate and the cross section area have been decreased, to 0.02 kg/s and 1 cm^2, with a much larger coolant temperature rise. The high temperature occurs in the return path. The system has been sized so that the temperature at the outlet is near 100 K, near its boiling point. There is single phase fluid through the entire length. In this case, we assumed that the HTS environment experiences a heat loss of about 1/20 that of the case when the current leads are cooled by the cold coolant. There is a substantial benefit from cooling the current leads at the higher temperature (intercepting the heat at higher temperature, resulting in substantial decrease of power requirement for the refrigerators). The savings in the coolant are about 35% for the case of separate coolant and 15% for the go-and-return case.

TWO STAGE COOLING OF CRYOSTATS

An accompanying paper [7] investigates the means to minimize the cryogenic loads due to current leads using an intermediate stage at ~ 160 K. This section investigates the use of multiple stage cooling stations for the minimization of the refrigerator electrical power to cool the cryostat. FIGURE 2 shows results of the calculations. By subdividing the warm-cold gap into two stages, the load to the 66 K refrigerator was greatly reduced, to ~ 0.1 W/m. By reducing the number of layers between the room temperature and the intermediate stage by a factor of 2 (16 layers instead of 32 layers), the radiated power intercepted by the intermediate temperature approximately doubled. The higher efficiency of the higher temperature refrigerator more than makes up for the increased radiation, reducing the electrical power, but with a net reduction of only 38% compared to the single stage case.

In the case of three stages, there are two arbitrarily temperatures of the intermediate stages. There is a broad minimum for a temperature of the upper stage of about 230 K and the second stage temperature about 150 K. The electrical refrigerator power is reduced to less than 5 W/m, mainly due to a decrease of the higher-temperature-stage power.

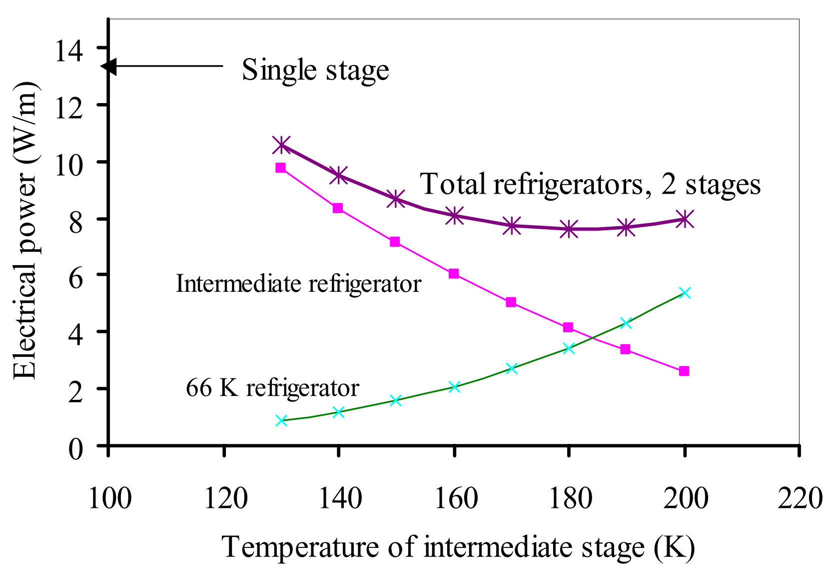


FIGURE 2. Electrical power of refrigerator for the cases of single stage with 32 MLI layers and for two stages (each 16 layers) vs. intermediate stage temperature (emissivity = 0.07 independent of temperature)

TRANSMISSION NETWORKS COOLANT TOPOLOGIES

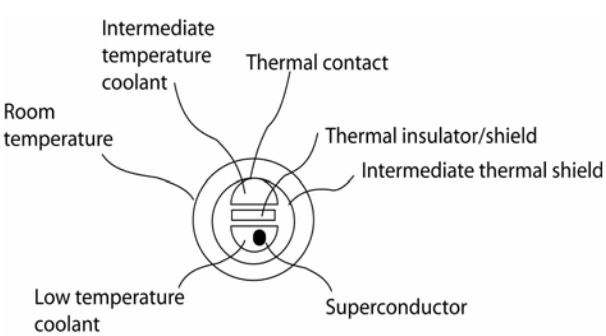
Options for achieving long distances between cooling stations are investigated in this section, using an intermediate temperature coolant. FIGURE 3 (a) and (b) show schematic diagrams of a cryostat with two cooling circuits, a low and an intermediate temperature coolant. When the separate coolants flow in opposite directions, continuity of nitrogen flow is easily established. The superconductor is in the cold circuit, with the warmer circuit cooling the cryostat. FIGURE 3(b) the cryostat has a coaxial arrangement of the different elements. 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.

In FIGURE 3 the return path is shown cooling the intermediate cryostat, as would be the case for long distance transmission. For distribution systems, the intermediate temperature coolant could also cool the current leads.

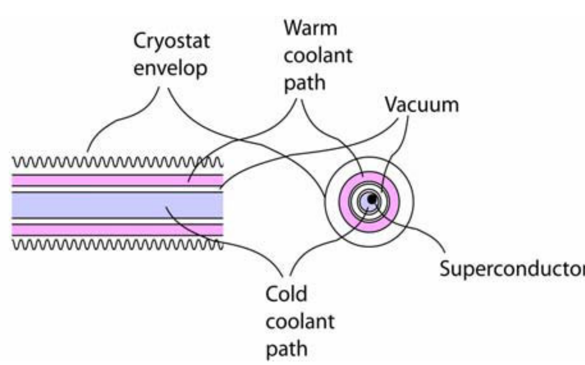
It is common to use intermediate cooling stations between ambient temperature and liquid helium environments (for example, in spacecrafts). The use of the same fluid sequentially (as in the previous section for cooling the leads) has been suggested (the coolant first cools the HTS and the return cools the cryostat) [12].

It is assumed that there are no large elevations/depressions in the line (pressure is determined by hydraulic losses) and that the inlet pressure is 10 bar. Elevation changes of 10's of meters would not change the results much. This is particularly important towards the end of the line, where two-phase flow (boiling) may result.

Table 2 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 an 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. In the baseline case, the refrigerator power (with an outlet at 65 K), is about 292 kW. In the case with the intermediate cooling station, the total refrigerator power is about 210kW. The refrigerator with an outlet temperature of 80 K consumes most of the power, with less than 2% for the low outlet temperature (65 K) refrigerator.



(a)



(b)

FIGURE 3. Schematic diagram of (a) non-coaxial two-coolant system that separates the cooling of the thermal shield from that cooling the superconductor. (b) Schematic diagram of a coaxial arrangement

TABLE 2. Summary of results comparing base case to a case with one intermediate cooling station at a temperature around 90 K (10 km long, 20% of Carnot efficiency)

		Base case	One intermediate stage	
		Single circuit	High T circuit	Low T circuit
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	292	212	3

There is a large disparity in the flows in the cryostat vs. the HTS circuit in the case with two circuits in TABLE 2. Thus, as opposed to the calculations by Demko [12], the two circuits are separate. Also, the outlet temperature of the HTS circuit is lower than the inlet temperature of the High T circuit, whose inlet temperature is set by preventing boiling at the High-T outlet (rather than the outlet temperature of the low-T circuit).

For the cases considered with LN2 cooling both circuits, it was concluded that the maximum length that can be cooled was determined, to first order, by the cross sectional area of the coolant. For a given cross sectional area and inlet pressure (assuming no boiling the circuit), increasing the flow rate increases the pressure drop, decreasing the pressure at the outlet and limiting the length by boiling at lower pressure.

ALTERNATIVE COOLING FLUIDS

The use of multiple coolants would result in a more complex cryogenic environment, but also has some benefits. Some fluids that can be used as intermediate temperature coolants are shown in TABLE 3. A figure-of-merit can be determined by dividing the rate of heat removal capability, $c\rho\, \Delta T\, AV$ (where c is the heat capacity, ρ the density, ΔT the allowable thermal excursion, A the cross sectional area of the channel, and V the velocity of the fluid), by the pressure drop per unit length, $f\, \rho\, V^2/2$ (where f is the friction factor). In laminar flow, $f \sim 1/\mathrm{Re}$, where Re is the Reynolds number, and the figure-of-merit reduces to $c\rho\Delta T\, AD/\nu$, where D is the cooling tube diameter and ν is the viscosity, independent of V. The figure-of-merit depends on the flow velocity for turbulent flow.

TABLE 3. Properties of potential cryogenic fluids (compiled from information from [13]

	Freeze temp (1 bar)	Boil temp (1 bar)	Boil temp (10 bar)	Enthalpy liquid at freezing (10 bar)	Enthalpy liquid at boiling (10 bar)	ΔT	ρ	c	ν	cρΔT/ν	Enthalpy liquid at 200 K
	(K)	(K)	(K)	(kJ/kg)	(kJ/kg)	K	kg/m^3	kJ/kg K	mPa s		(kJ/kg)
N_2	64	77	103	-148	-66	30	750	2.2	130	380	
CO	68	82	108	-26	60	25	700	2.3	110	370	
CH_4	90	110	149	-70	139	40	400	3.5	100-50	750	
C_2H_6	91	180	241	-216	147	70	500	2.3	150-100	670	39
NH_3	196	240	298	3	460	60	650	4.3	500-150	560	20
NF_3	86	170	187	-58	46	50	1500	1		250	
Ar	85	90	116	-120	-84	30	1300	1.2	120-200	310	

The light hydrocarbons are about a factor of 2 better than liquid nitrogen. For the hydrocarbons, the boiling temperature is lowest for methane, and increases with molecular weight. Ammonia shows a high performance, but its temperature is rather elevated. Other fluids of interest not included in the table are oxygen, air, hydrogen and neon.

CONCLUSION

Several topologies for cooling HTS distribution and transmission systems have been explored, separating the cooling of the HTS from the cooling of the current leads and the cryostat. The most attractive topologies use a separate coolant, around 150-200 K. The superconductor is cooled through a separate path, using much colder coolant, with minimum temperature rise. The solution results not only in an attractive solution for cooling the superconductor and the current leads/cryostat, but also in substantial reductions of the refrigerator power requirement and minimizing the use of expensive HTS.

The option of cooling the HTS with gaseous He, because of the minimal heat input to the HTS, while cooling the cryostat and the current leads with either liquid nitrogen or other cryogens, looks very attractive and needs to be explored to understand the tradeoffs, including the increased complexity of multiple cooling fluids.

ACKNOWLEDGEMENTS

This work was carried out partly under the auspices of the MIT Energy Initiative Seed Fund.

REFERENCES

1. Haught D., *et al.*, "Overview of the U.S. DOE High-Temperature Superconductivity Program for Large-Scale Applications," *International J Applied Ceramic Tech* **4** 197-202, July 2007
2. Yamaguchi, T., Mizutani, S., Moriguchi, M., Okumura, H., Nakamura, K. and Yamaguchi, S., "Experimental and numerical characteristics of peltier current lead for direct current mode," *IEEE Trans Applied Superconductivity* **14** 1719-1722 (2004)
3. Furuse, M, S. Fuchino, N. Higuchi and I. Ishii, "Feasibility Study of Low-Voltage DC Superconducting Distribution System," *IEEE Trans Applied Superconductivity* **15** 1759 (2005)
4. McFee, R., "Optimum Input Leads for Cryogenic Apparatus," *Rev Scientific Instr.,* **30** (1959).
5. Iwasa, Y., *Case Studies of Superconducting Magnets*, Plenum Press (NY) 1994
6. Yamaguchi, T., Mizutani, S., Moriguchi, M., *et al.,"*Experimental and numerical characteristics of peltier current lead for DC mode", IEEE Trans Applied Superconductivity **14** 1719-1722 (2004)
7. L. Bromberg, P.C. Michael, J.V. Minervini and C. Miles, "Current Lead Optimization for Cryogenic Operation at Intermediate Temperatures," accompanying paper.
8. Navigant Consulting, http://www.energetics.com/meetings/supercon06/pdfs/Plenary/07_Navigant_HTS_Market_Readiness_Study.pdf
9. Maguire, J.F, F. Schmidt, S. Bratt, *et al.,* "Development And Demonstration Of A HTS Power Cable To Operate In The LIPA Transmission Grid," *IEEE Tran Applied Superconductivity* **17** 2034-7 (2007)
10. Lee, R.C., A. Dada, and S/M. Ringo, "Cryogenic Refrigeration System for HTS Cables," *IEEE Trans. Appl. Superconductivity* **15** 1798 (2005)
11. Gierszewski, P.J., A.S. Wan and T.F. Yang, "CCAN and TCAN – 1 – 1/2 D Compressible flow and time dependent codes for conductor analysis", MIT Plasma Science and Fusion Center Report PSFC/RR-83-01
12. J. A. Demko, J. W. Lue, M. J. Gouge, *et al.,* "Cryostat Vacuum Thermal Considerations for HTS, Power Transmission Cable Systems", *IEEE Trans Applied Superconductivity*, **13** NO. 2, JUNE 2003
13. [NIST] E.W. Lemmon, M.L. Huber and M.O. McLinden, "REFPROP, Reference Fluid Thermodynamic and Transport Properties", NIST Standard Reference Database **23**, Version 8 (2007)