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Coupled Cryogenic Thermal and Electrical Models for Transient Analysis of Superconducting Power Devices with Integrated Cryogenic Systems

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Abstract. Benefits of an integrated high temperature superconducting (HTS) power system and the associated cryogenic systems on board an electric ship or aircraft are discussed. A versatile modelling methodology developed to assess the cryogenic thermal behavior of the integrated system with multiple HTS devices and the various potential configurations are introduced. The utility and effectiveness of the developed modelling methodology is demonstrated using a case study involving a hypothetical system including an HTS propulsion motor, an HTS generator and an HTS power cable cooled by an integrated cryogenic helium circulation system. Using the methodology, multiple configurations are studied. The required total cooling power and the ability to maintain each HTS device at the required operating temperatures are considered for each configuration and the trade-offs are discussed for each configuration. Transient analysis of temperature evolution in the cryogenic helium circulation loop in case of a system failure is carried out to arrive at the required critical response time. The analysis was also performed for a similar liquid nitrogen circulation for an isobaric condition and the cooling capacity ratio is used to compare the relative merits of the two cryogens.

1. Introduction

High Temperature Superconducting (HTS) power devices are attractive for applications that require high power densities such as electric aircrafts and ships [1-7]. Future all-electric ships and aircrafts will have multiple large electrical loads and the integrated power system to support the loads needs to be flexible to meet the various potential missions. The trend is to reduce the size of aircrafts and ships to increase fuel economy and operational effectiveness [6,8]. The two apparently competing interests are being met with new technologies, integrated power systems, and innovative ship and aircraft designs. The large electrical loads on ships and aircrafts are required only in certain mission scenarios. Hence, power devices with high power densities and variable power ratings that offer tunability would facilitate meeting the design challenges of future all-electric ships and aircrafts. HTS technology has the ability to support the design goals while providing operational flexibility. HTS technology is particularly suitable for direct current (DC) systems and the navy has decided to adapt integrated DC power system for future all-electric ships and aircrafts. HTS materials offer a wide operating temperature window and their current carrying capability varies significantly depending on the cryogenic operating temperature; current density of HTS materials can change up to 10 times by changing the temperature by 40 K. Use of gaseous helium as the cryogen in conjunction with the cryocooler technology allows operating temperatures between 20 and 77 K, giving a large operating temperature window for HTS devices. High performance second generation HTS materials are now commercially available in long lengths from several manufacturers who are improving their performance to even higher levels to enable electric power applications in defense, aviation, and electric utility sectors [9-10]. A variety of cryogenic technologies to support HTS applications are also being developed for higher efficiency, minimal maintenance, and higher reliability [11].

Several individual HTS devices have been successfully demonstrated for shipboard applications [12,18,17,21]. HTS devices offer significant opportunities as standalone units on ships in meeting the power density requirements while saving space and weight. However, the real benefit of HTS technology lies in providing system level design flexibility and operational advantages. Helium gas cryogenic circulation technology being developed for ship board applications facilitates a centralized cooling option to serve multiple HTS devices in a closed loop system. The centralized integrated cryogenic cooling system provides high efficiency and permits directing the cooling power to where it is needed depending on the mission at hand. The integrated cryogenic system is akin to integrated power system in providing operational flexibility. HTS power transmission systems and other devices allow power rating tunability and the integrated cryogenic system allows maintaining and controlling the operating temperature of the devices at the necessary temperature required to support the power rating demanded by the mission. The power rating tunability feature means that the devices are designed for baseline power loads and higher power ratings needed to support certain missions are derived purely by lowering the operating temperature, thus reducing the weight and volume significantly. An integrated cryogenic system also allows energy savings by operating the cryogenic plant at just enough capacity and any additional capacity can be directed to cryogenic storage [12].

To enable thorough assessment of the above mentioned beneficial features of HTS technology and to take advantage of the integrated cryogenic system and power rating tunability of HTS devices, a fast and effective modelling tool is needed. The tool should have the capability of combining electrical and cryogenic thermal aspects and should be suitable for system studies of multiple HTS devices in an integrated closed loop cryogenic circulation configuration. This paper presents the development of a fast tool that is based on thermal network methods [13]. The effectiveness of the modelling methodology is demonstrated using case studies of multiple HTS devices in closed loop cryogenic helium circulation connected in different ways to assess the relative merits of each configuration. The methodology developed in this study is based on our thermal network methods developed for individual HTS devices and components [14]. This study reported uses simplified thermal network methods for faster solutions of HTS systems with multiple devices connected in an integrated cryogenic system. The simplifications sacrifice the details of temperature gradients within individual system, but serve as useful tools for analyzing various potential system configurations and assessing the tradeoffs. Transient analysis of the system during a system contingency is also studied using the model. During critical missions, the operational time after a system breakdown needs to be increased to keep the system in superconducting state. A potential cryogenic system failure and the resulting transient behavior of temperature evolution were analyzed. Also discussed are the operational temperature windows and the associated benefits of gaseous helium compared to liquid nitrogen as the cryogen for a generalized HTS power system.

2. Modelling methodology

An effective modelling tool based on the thermal network methods to simulate the electrical and thermal performances of an HTS power cable was developed [14]. However, the tool needed to be simplified for large systems containing multiple HTS power devices and their associated cryogenic systems to enable faster simulation. The simulation of multiple HTS power devices is based on steady state analysis of the system. Transient analysis can be accomplished by repeated successive iterations of the model using the temperature dependent cryogenic thermal properties of various components.

2.1. *System components in thermal network model*

The Thermal network model (TNM) is based on the analogy between thermal and electrical fields to determine the temperature distribution with the help of Ohm's Law, Kirchhoff's Law and superposition principle and consists of thermal resistors, thermal capacitors, heat sources and temperature potentials equivalent to an electrical circuit. This analogy allows the use of a circuit simulation software package to model thermal networks. Furthermore, electrical and thermal models can be coupled to account for the inter-dependencies such as Joule heating in the electrical model that leads to heat influx in the thermal model, which in turn changes the material properties in both sub-models. TNMs have been used for the design of conventional power equipment [15-18].

The superconducting power system simulated in this study is hypothetical, but realistic in terms of heat loads and operating temperatures, and used to demonstrate the modelling methodology. The simulated system consists of a closed loop of cryogenic helium circulation that provides the cryogenic environment for an HTS ship propulsion motor, an HTS generator and an HTS power cable along with two terminations on either side of the cable. The 36.5 MW motor, a full-size ship propulsion motor, was successfully tested at the Naval Surface Warfare Center in Philadelphia in 2007 [19]. Helium gas cooled HTS power cables have been demonstrated at the Center for Advanced Power Systems (CAPS) [13].

The operating temperature dependent heat loads produced by each of the three HTS devices are important input parameters in the model. Similarly, the temperature dependent cooling capacity is also an essential parameter of the model. For the modelling and simulation efforts, the heat loads and cooling capacity curves are defined as polynomials and the basic heat load values and their variation with the operating temperature are taken from the literature and our previous experience with the demonstration of HTS devices and associated cryogenic helium circulation systems [21,27]. For the purpose of the model, the heat load of the motor is defined as

$$\boldsymbol{Q_{motor} = -1.07 * T + 433.3\ (W)} \quad [1]$$

HTS generator has relatively higher heat load due the stronger magnetic field and the associated AC losses. Also for the same reasons and to obtain high power density, the generator in the model is restricted to operate between 30-50 K with a heat load defined as

$$\boldsymbol{Q_{gen} = -0.54 * T + 782.0\ (W)} \quad [2]$$

For the 100 m HTS power cable in the model, a heat load of 1 W/m of cryostat loss and 120 W from each termination are used for the model. The cable is assumed to carry a load current of 2 kA and the corresponding heat load due to Joule heating from the resistive components present in the terminations are calculated in the model using the temperature dependent resistivities and heat capacities with the dimensions of one of the actual HTS cable at CAPS. The operating temperature for HTS power cable is assumed to be 40-77 K. The operating temperature ranges and heat loads of the three HTS devices are listed in Table 1.

Table 1. Operating temperature and heat load range of different HTS power devices.

HTS power device	Operating temperature (K)	Heat load range (W)
Motor	40-60	370 – 390
Generator	30-50	750 - 765
Power Cable	40-77	481 – 555

2.2. The cryogenic system

The cryogenic system is composed of a cryocooler(s) and the circulation cryofan. The cryogenic system design is based on Stirling cryocoolers with gaseous helium (GHe) as the cryogen circulation operating at 1.7 MPa and a total mass flow rate of 20 g/s. This is similar to the systems used in our previous HTS demonstration studies [22-25]. The heat capacity at constant pressure, C_p in J/kg/K, of helium is temperature dependent and is approximated by

$$\boldsymbol{C_p = -0.0012 * T^3 + 0.306 * T^2 - 27.511 * T + 6077} \quad [3]$$

The cooling power of cryocoolers decreases as the operating temperature is lowered. In a cryogenic helium circulation loop, the actual cooling power transported by gaseous helium and transferred to the cryocooler is also a function of mass flow rate. This relationship is determined empirically in one of our previous studies for a single cryocooler unit and is approximated to be

$$\frac{Q}{\dot{m}} = 3.9736 * T - 171.92 \qquad [4]$$

where Q is the cooling power in Watt transferred, $\dot{m}$ is the mass flow rate of GHe in g/s and T is the average temperature of the gas inlet and outlet of the cryocooler.

For configurations consisting of multiple HTS power devices, the required cooling power is provided using multiple cryocoolers connected in series. The cooling capacity curves are scaled to meet the required cooling power. For the purpose of the model, where multiple cryocoolers are used, the total cooling power is a multiple of the individual unit, maintaining similar dependence on the operating temperature.

For a system with multiple devices, there are small additional heat loads in the transfer lines between two devices and between the cryogenic systems and HTS devices. The heat leak is assumed to be from 50 - 100 W depending on the mass flow rate for each branch and hypothetically assuming equal distance between the devices. The heat leak through the transfer lines result in a temperature gradient of about 0.5 - 1 K along the length of the transfer line. It is important to note the hypothetical relationships used in the model can be replaced with the actual relations for the HTS devices and cryogenic systems to obtain realistic results. The model uses the relationships as input parameters and hence the model itself does not need to change.

3. Case studies

Several hypothetical configurations of the system consisting of the three HTS devices and the cryogenic system as discussed above in 2.1 are simulated as four different case studies. The results of required total cooling power for each configuration to maintain the operating temperatures in the allowed window of each device are derived from the models and are discussed below. The goal of the exercise is to assess the effectiveness of the modelling methodology and demonstrate its usefulness in system designs and in developing operational protocols through parametric studies and simulating operational scenarios.

3.1. Case 1: Integrated cryogenic cooling system with the three HTS devices in a serial configuration

In this case, the three HTS power devices are connected in series with a single integrated cryogenic system as shown in Figure 1. This case is used as baseline to compare with other possible configurations. A scaled cryocooler (equivalent to 9 times of a single cryocooler) is used in the setup as discussed in 2.2. The cryogenic system is needed to provide a total 2080 W of cooling power and a flow rate of 20 g/s to provide the inlet temperatures for each device as shown in the figure.

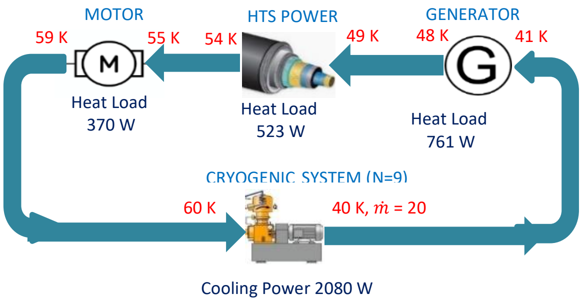

Figure 1. CASE 1: A schematic of a closed loop cryogenic circulation with a single cryocooler serving three HTS devices showing the inlet and outlet gas temperatures.

3.2. Case 2: Individual local cryogenic system for each HTS device in a serial configuration

In Case 2, the three HTS power devices are connected in series with a local cryocooler placed before each device as shown in Figure 2.a. Each device is cooled with a cryogenic system with the cooling capacity just enough to provide the required inlet temperature as show in Figure 2. In this configuration, it is easier to meet the cooling requirement for each device independently. For this case, the generator requires the cooling power equivalent to 4 cryocoolers, while the motor and power cable can be served with 1 cryocooler each. This configuration requires a total of 6 cryocoolers with a total installed cooling power of 2266 W.

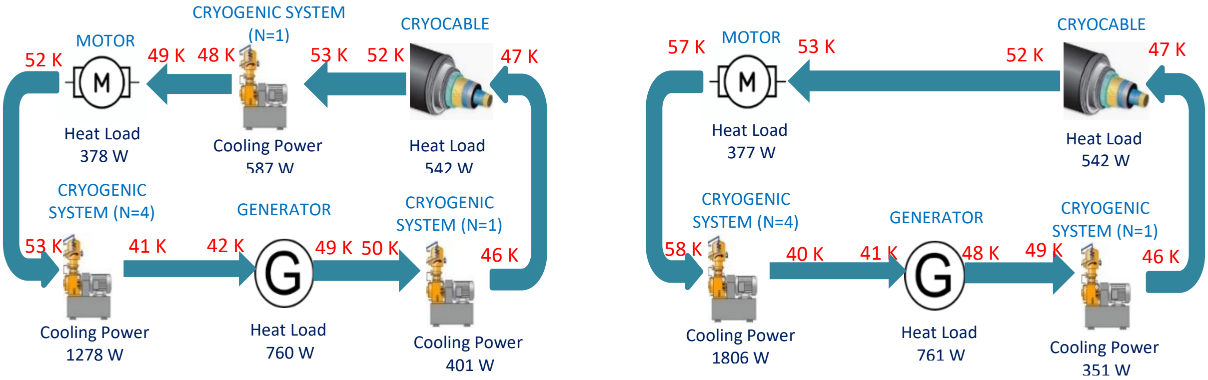

Figure 2.a. CASE 2: A schematic of a closed loop cryogenic circulation with a local cryocooler serving each of three HTS devices. **2.b**. A schematic of a closed loop cryogenic circulation with a shared cryocooler serving each of three HTS devices. The schematic shows the inlet and outlet gas temperatures.

3.3. Case 3: Individual local cryogenic system for each HTS device in a parallel configuration

Here the three HTS power devices are connected in parallel with each branch containing its own cryogenic system as shown in Figure 3.a. The cryogenic helium flow is divided into 3 branches keeping the total mass flow rate fixed at 20 g/s. If the mass flow is divided equally amongst the three branches, it may not be possible to provide sufficient cooling power to maintain the required operating temperature of each device as can be seen in Figure 3.a. Since the HTS power devices have different heat loads, the branch that has highest load is provided with the highest mass flow rate. This can be controlled using a valve as shown in Figure 3.b. For the given heat load, upon numerous iterations, optimum distribution of mass flow for the branches with the generator, motor and HTS power cable is divided in the ratio of 65:19:16. Although this configuration requires most number of cryocoolers, the total cooling power required is lower than in previous cases.

3.4. Case 4: Hybrid system with local and shared cryogenic cooling system on a parallel configuration

As discussed in 3.2, some HTS power devices do not require its own cryogenic system due to low heat load. Thus, motor and power cable are placed in series and share a cryogenic system while a generator has its own cryogenic system placed in parallel as shown in Figure 4. Since the generator has a relatively high heat load and needs to be operated below 50 K, the mass flow rate is given at the ratio of 7:3 while generator gets 14 g/s and motor and power cable is provided with GHe at 6 g/s. This configuration requires 6 cryocoolers and has an effective cooling power of 1640 W which is lower than all the cases considered previously. For the provided devices, this configuration is optimum with the lowest tradeoffs.

For the cases 1 to 4, the required total cryogenic cooling power and the number of cryocoolers required are summarized in Table 2. As seen from the data, the total cryogenic cooling capacity varies with the configuration and thus the optimal configuration needs to be decided based on the design constraints such as the total cooling power, number of cryocooler units, or the cost. In a shipboard system, the design constraints could be: total available installed cryogenic capacity, highest efficiency of the overall HTS power system, or operational flexibility.

4. Transient behaviour of the integrated HTS system following a failure in the cryogenic system

In the event of a cryogenic system failure, there will not be any additional cooling power available and

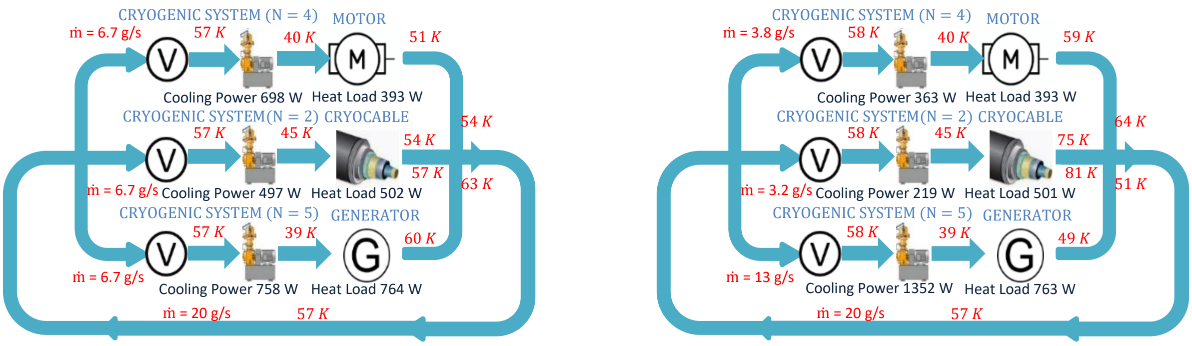

Figure 3.a CASE 3: Schematic of a closed loop cryogenic circulation with a local cryocooler serving each of three HTS devices in a parallel configuration. **A**. The mass flow rate is equal in each of the parallel paths. **B**. The mass flow rate is optimized for each of the parallel paths.

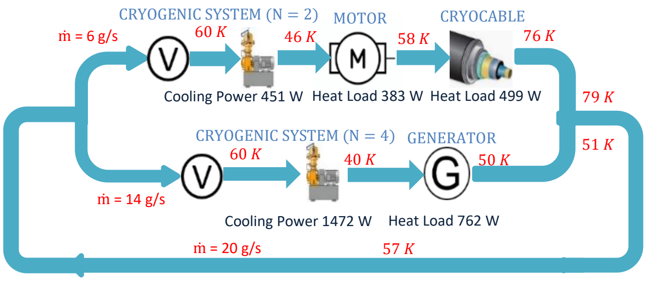

Figure 4. CASE 4: A schematic of a closed loop cryogenic circulation in a hybrid (series and parallel) configuration with a local cryocooler serving each HTS device.

Table 2. Total cooling power required for the four different configurations of multi-device HTS

Case	Cooling System	Device Configuration	Cooling Power (W)	Figure Number
1	Integrated	Series	2080	1
2	Individualized	Series	2157	2
3	Local	Parallel	1934	3
4	Local/Shared	Hybrid	1923	4

the heat capacity of the cold mass of the total system determines the temperature evolution as a function of time. A model to understand such a scenario is essential to make operational decisions on the time available to turn off the system to activate the contingency plans. A large cold mass is beneficial, but to minimize the total weight of the system, it is necessary to conduct a trade-off studies to relate the operational requirements with the weight minimization constraints. Time evolution of temperature as a function of total cold mass of stainless steel is modelled for the cryogens-GHe and LN2. The operating temperature range also plays an important role in the total time available. For the purpose of this study, the operating window of GHe is set at 40-77 K and for LN2 it is set at 64-77 K. The model is based on an isobaric system where the LN2 is operated at 0.3 MPa and GHe is operated at 1.7 MPa and the velocity of the cooling agent can be kept constant for both cryogens. The mass flow rate of GHe systems is a function of operating temperature. The flow impeller produces a fixed volume flow rate and hence the mass flow rate varies as the density varies with temperature. During the isobaric warming process, the mass of the helium is reduced to keep the pressure below 1.7 MPa, which decreases the cooling power of the helium. For this temperature ranges studied, the ratio of mass flow rate of LN2 to GHe varies from 43-430. At this range of mass flow rate, LN2 generally has higher cooling capacity than GHe when only the cryogen is considered. However, when a whole system and its cold mass is considered, this condition varies depending on the cold mass exists in the system. The structural elements of the HTS devices, the inner tube of the vacuum jacketed cryostats, and majority of the cold mass of 2G HTS devices is made of stainless steel and 2G HTS substrate is also made of stainless steel or Hastelloy. In terms of heat capacity, Hastelloy is similar to stainless steel at cryogenic temperature [28,29]. Hence, the analysis assuming that the stainless steel is the cold part mass can be also considered for Hastelloy based structures. The temperature dependent heat capacity of stainless steel is used in the model. The integrated cooling capacity ratio of integrated LN2 and GHe cases for the total system can be approximated as

$$\frac{Q_{sys,LN2}}{Q_{sys,He}} = \frac{\int_{64\,K}^{77\,K} m_{LN2}C_{p,LN2}(T)+m_{ss}C_{p,ss}(T)\,dT}{\int_{40\,K}^{77\,K} m_{He}C_{p,He}(T)+m_{ss}C_{p,ss}(T)\,dT} \qquad [5]$$

where m is a mass of the component noted by the subscript that is at the cryogenic temperature in the system. The results of the simulation are shown in Figures 5.a and 5.b. The temperature of the system following the event of unexpected cryogenic system shutdown, as a function of time is shown in Figure 5.a. The calculated total thermal capacity ratio of LN2 versus GHe system as a function of the mass of stainless steel in the system. As the mass of stainless steel in the system increases, GHe system has higher thermal mass due to its larger temperature window as shown in Figure 5.b. If the ratio of $Q_{sys,LN2}$ vs $Q_{sys,He}$ is less than 1 the helium is more resistive to being warmed up at fault. If mass of cold parts is more than 3.1 kg, helium is more beneficial than the LN2 as it has more time to stay in superconducting condition. If the thermal mass of cold part is less, LN2 system is a better option during the fault condition.

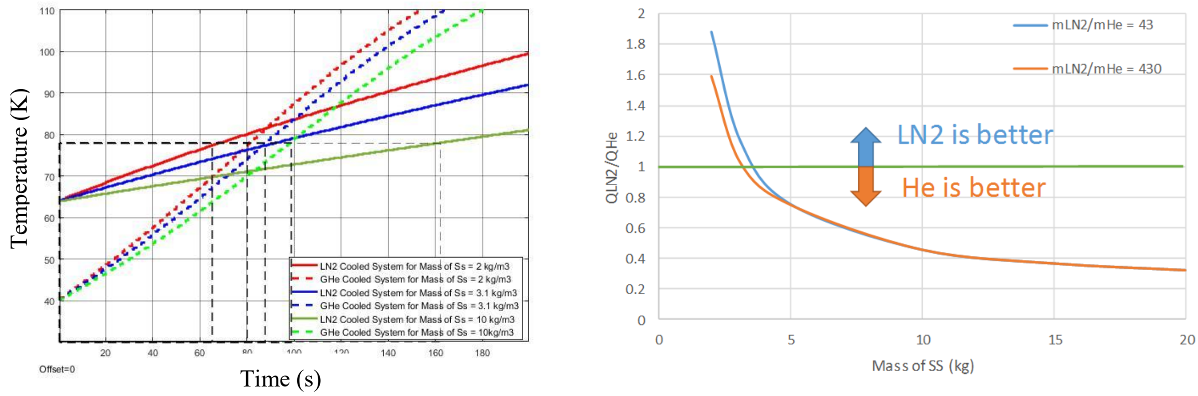

Figure 5.a. Graph depicting the temperature of the system vs time taken at fault condition. **b.** Graph depicting the ratio of cooling power of LN2 and gaseous helium vs mass of stainless steel.

Table 3. Total time required for the system to reach 77 K from the fault condition

	Time (s)	
Mass of stainless steel (kg)	Helium Cooled System	LN2 Cooled System
2	62.27	78.69
3.1	85.68	85.68
5	110.98	90.80
10	147.60	97.38
15	167.51	97.5
20	179.76	98

5. Conclusion

The system level benefits of integrating multiple HTS devices and the necessary cryogenic circulation systems in a closed loop configuration are presented. The integrated approach allows system level optimization and enables taking advantages of the tunable power rating of HTS devices. The integrated system also allows directing the cooling power as needed to serve particular mission scenarios and offers significant benefits in ship system design options and operational flexibility. The versatility of the modelling methodology is demonstrated using several case studies involving a system with an HTS generator, an HTS motor, and a power cable. The case studies discussed in this study show that the hybrid systems minimize the required total cooling power and also give the flexibility in terms of obtaining the most cooling power from cryocoolers. In case of cryogenic system failures, how the two cryogens, GHe and LN2, differ in terms of evolution of temperature is discussed. It is shown that the time takes before the system crosses 80 K, the maximum allowed operating temperature for HTS devices is longer for the GHe if the cold mass of the system is larger than 3.1 kg.

6. References

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