T.2: Cryogenic aspects of testing super-conducting RF cavities

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1. Introduction

Superconducting Radio Frequency (SCRF) cavities are main building blocks of all advanced accelerators. In view of the upcoming future projects on accelerators, work has been taken up at RRCAT for the development of SCRF cavities. These cavities operate at liquid helium temperature (4.2K). Their performance gets increased many fold if they are operated at 2K. Infrastructure is being set-up at RRCAT for fabrication, processing and charactering of these cavities in-house.

To hold liquid helium of required quantity a special container called "cryostat" is used. Often it is also called pooled type vertical cryostat. This cryostat is basically a double walled container. The inner container, in which liquid helium is filled, is thermally insulated using multi layer insulation from the ambient. The gap between the inner container and outer container is evacuated to offer high quality thermal insulation using multi layer insulation. A portable container used for storage of liquid helium is called a Dewar, named after the inventor of the double walled vacuum insulated container Sir James Dewar. System complete with vertical cryostat, its related RF system and cryogenic auxiliaries constitute the Vertical Test Stand (VTS). Details regarding cryostat design can be found in earlier issue of news letter Volume 25, Issue 2, 2012 [1] and elsewhere [2]. Engineering design is jointly developed by RRCAT, Indore and Fermi National Accelerator Laboratory, USA. In this article only the cryogenics aspects of testing SCRF cavities in VTS is covered. Fig.T.2.1 shows the VTS setup at RRCAT during one of the test runs [8].

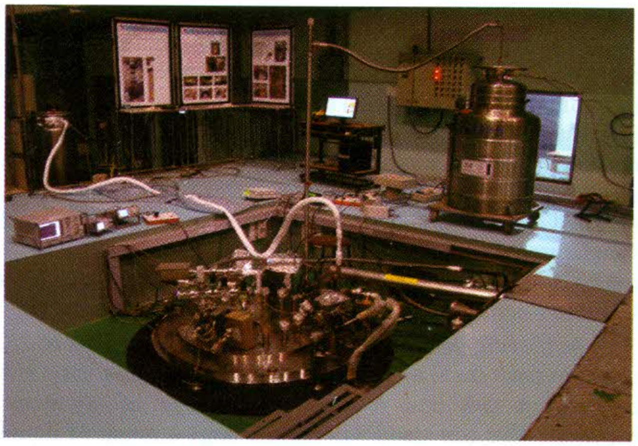


Fig. T.2.1: View of Vertical Test Stand.

The inner vessel or the liquid helium vessel has an inside diameter of 92.25 cm and has a overall height of 486.03 cm. Initially, cryostat is filled with liquid helium, having a Normal Boiling Point of 4.2K (NBP: boiling point at atmospheric pressure). Transfer of liquid helium requires special skills. This is due to very unusual properties of liquid helium, one of them is its very low latent heat, which is only 21 J/g as compared to 2,260J/g in case of water. During transfer of liquid helium from a Dewar to the cryostat, not all the liquid helium collects as liquid in the cryostat. Instead only a part of it is collected, which strongly depends upon the transfer conditions such as the pressure difference used for transferring and temperature inside the cryostat. The transfer losses (also called flash-off losses) can become as high as 50% or more. This means only half of the liquid being transferred will be collected in the cryostat and the remaining half of the liquid escapes as vapor. Temperature of the collected liquid is further reduced to 2K by reducing the pressure inside the cryostat to 31 mbar. At 31 mbar the helium boils at 2K. The refrigeration for cooling comes from the evaporation of liquid helium. This cryostat has been designed to support thermal load up to 300 W at 2K and will be used to evaluate cavity processing methods and procedures. This will also form the pre-qualification test for the cavity. Once the cavity qualifies testing procedure in the VTS, then it will be further worked upon and its other components such as tuner and helium vessel will be attached to it. Finally, the cavity in its final configuration, also called a "dressed cavity" will be tested in another continuous flow type cryostat in horizontal test stand (HTS). In HTS the dressed cavity is tested under identical conditions as it will see during operation in the cryomodule, except beam. After the cavity qualifies in HTS, it is assembled in the cryomodule, which is a part of accelerator section. Each test in the VTS requires large amount of liquid helium (LHe). Initial estimates show that one 9-cell 1.3 MHz cavity test will require about 4,500 liters of liquid helium for complete cycle. This includes cool down of helium vessel and other parts, such as components of insert, SCRF cavities etc. from ambient temperature (300K) to 2 K, and liquid required for maintaining the bath temperature at 2 K, during the testing period.

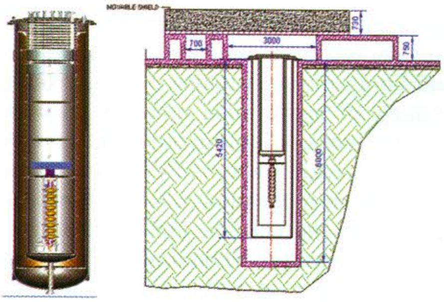


Fig. T.2.2: Cutaway view of the cryostat and its positioning inside the pit.

For operating the VTS at full test configuration as designed i.e. six 9-cells cavities, it will require about 10,000 liters of liquid helium [4]. In this, significant fraction of total LHe usage is spent for cooling down the thermal mass of six numbers of 9-cell niobium cavities, in addition to helium vessel and test insert. Suitable infrastructure has been installed to recover helium gas during cool down and maintaining the cryostat at 2K temperature during the cavity testing. Fig.T.2.2 shows the cutaway view of the cryostat with 1.3 GHz 9-cell SCRF cavity and its location inside the pit [3].

Achieving and maintaining a stable temperature of 2K in the cryostat for testing SCRF cavities on regular basis is a challenging task and require broad range of cryogenic expertise. This test stand will handle large amount of liquid helium on continues basis. To handle liquid helium in such a large scale, it requires good understanding of helium cryogenics and needs many in-house technological as well process developments. It is well known that volume of one liter of liquid helium results into 748 liters of gas when warmed to room temperature (NTP). Therefore, an appropriately designed infrastructure is required to handle such large amount of helium gas which is generated during the operation of this Vertical Test Stand.

Boiling point of Liquid helium is 4.2 K (Normal Boiling Point). For testing the cavities, first the cryostat is filled with liquid helium. Its temperature is further reduced to 2K by reducing the pressure inside the cryostat to 31 mbar. At 31mbar the helium boils at 2K. Suitable vacuum pumps operating at room temperature are used to create this vacuum. These pumps should be leak tight for helium gas, so that no helium escapes to atmosphere. Normally, for prolonged operational life of mechanical pumps, oil lubrication is used. Small amount of oil always gets carried with the helium gas. To make the helium gas reusable, these oil traces needs to be removed from the gas before appropriate storage. Therefore, an efficient oil removal system has to be developed to meet this requirement. A oil removal system has been developed and is in use. Helium gas recovered through this system is being re-liquefied, confirming the efficient removal of all impurities.

Whole new set of cryogenic infrastructure is required to support the operational requirements of VTS. This includes in-house design and development of helium purifiers, liquid helium and liquid nitrogen transfer lines, procurement and commissioning of appropriate ambient vacuum pumping systems etc. Helium gas coming out of the cryostat is below 50K. This gas will require about 25kW of electrical heating to warm it up to room temperature, before it enters the above vacuum pumps. In present case ambient heat is utilized for warming up the helium gas. Therefore, piping system to warm the 2K helium vapor to near ambient temperature was designed in such a way that it offers the required heat transfer condition. The pipe sizing should also take care of pressure drop requirements. Larger pressure drop will hinders with achieving the resultant temperature of 2K.Sizing as well selection of appropriate safety devices and its associated piping alongwith its lay-out is also an important issue for safe operation.

Finally, all these equipments have to operate in a closed cycle manner, without any sub-atmospheric leak in to the helium circuit. For smooth operation of the cryostat in a production like manner, it should be integrated to helium cryogenic plant.

This article will elaborate the commissioning goals, different system design and operational requirements, issues and intricacies to make VTS operational.

2. Commissioning Goals and Challenges

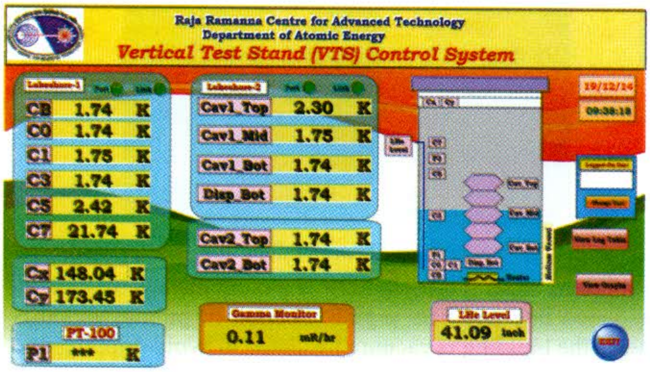
The commissioning and operation of VTS cryostat should be considered as a first major large scale cryogenic activity at RRCAT. VTS operation requires handling of complex and challenging sub-atmospheric operation. Therefore, careful planning and good amount of work are required during the whole commissioning and operational work of VTS. The VTS cryogenic commissioning was planned in three stages. These three phases of VTS cryogenic commissioning are described below.

Phase-I

In this phase, attention was mainly focused on the cryogenic testing of different subsystems used in VTS. This phase, basically restricted to initial testing and filling of VTS cryostat with liquid helium at 4.2K. This test has established basic cryogenic operational procedures like cryostat cold leak test, purging and contaminations check-outs, cool down, filling and warm-up procedures. During this phase of commissioning various instrumentations and devices located inside and outside VTS were verified. These included temperature sensors, liquid level indicators, control valves etc. Static heat load at 4.2K was measured to validate the heat in-leak by observing drop in liquid level or boil-off and also from the amount of helium gas collected. This is an important step to verify the sizing of 2K pumps. As sizing of these pumps should be sufficient to handle this static heat load plus the dynamic heat load.

Phase-II

After accomplishing the task defined in Phase I successfully, VTS was operated under sub-atmospheric mode. Cryostat was pumped to 31 mbar (23 torr), corresponding to 2K temperature, using an ambient pumping system. The design of pumping line and its ability to handle the helium flow in dynamic condition was assessed. Flow handling capacity of VTS piping system and capacity of 2K pumping was verified. Pumping line control valve characteristics are to be worked out to achieve stable 2K operation. In this phase of operation, written procedures for achieving 2K were refined and revised wherever necessary. Thermal performance of the cryostat at 2K was assessed by measuring static heat load. Filling time of Dewar was also optimized. To bench mark VTS, superconducting RF cavity, fabricated in India, processed and characterized at FNAL, was tested. The RF system used in VTS was developed by PHMS, RRCAT [5]. The cavity reproduced same results as achieved at FNAL [8]. Work has been completed till phase II. Fig.T.2.3 shows the temperatures at different locations inside the cryostat during the testing of SCRF cavity. In this, the liquid helium bath is at 1.74K and the super fluid liquid helium level is 104 cm (41 inch). Volume wise this corresponds to about 850 litres. To reach this state about 1,600 liters of 4K helium is required at start, inside the cryostat. And to collect this amount of liquid helium inside the cryostat about 3,000 liters of 4K liquid helium is transferred inside the cryostat. To monitor these parameters, Graphical User Interfaces (GUI) has been developed by Accelerator Control Section.


Raja Ramanna Centre for Advanced Technology
Department of Atomic Energy
Vertical Test Stand (VTS) Control System

Lakeshore-1
CB 1.74 K
C0 1.74 K
C1 1.75 K
C3 1.74 K
C5 2.42 K
C7 21.74 K

Cx 148.04 K
Cy 173.45 K

PT-100
P1 *** K

Lakeshore-2
Cav1_Top 2.30 K
Cav1_Mid 1.75 K
Cav1_Bot 1.74 K
Disp_Bot 1.74 K
Cav2_Top 1.74 K
Cav2_Bot 1.74 K

Gamma Monitor
0.11 mR/hr

LHe Level
41.09 inch

19/12/14
09:38:18

Fig. T.2.3: Snapshot of Graphical User Interfaces (GUI) developed by Accelerator Control Section.

Phase III

Based on the experience of Phase I and Phase II, written procedures for leak testing, contamination checking, cool-down, filling, pump-down and backfill operations would be finalized during this phase of commissioning. Therefore, this phase of commissioning would be mainly dedicated to establishing different accurate cryogenic procedures and attempt would be made to analyze and optimize the procedures to minimize liquid helium consumption. Towards the completion of this phase, VTS will be run with possible automated operation. Also at the end of phase III VTS will be integrated to the cryo-plant for regular cavity testing.

3. Ambient Sub-atmospheric Pumping System

Vertical Test Stand (VTS) has to be operated at 2K for testing the Superconducting Radio Frequency (SCRF) cavities. Fig. T.2.4 shows the saturation pressure of helium corresponding to the temperature.

Normally, operation at 1.8K is preferred to take advantage of up-hill nature of the specific heat curve for super fluid helium. This offers better temperature stability, as the specific heat of super fluid helium increases with increase in temperature in this range.

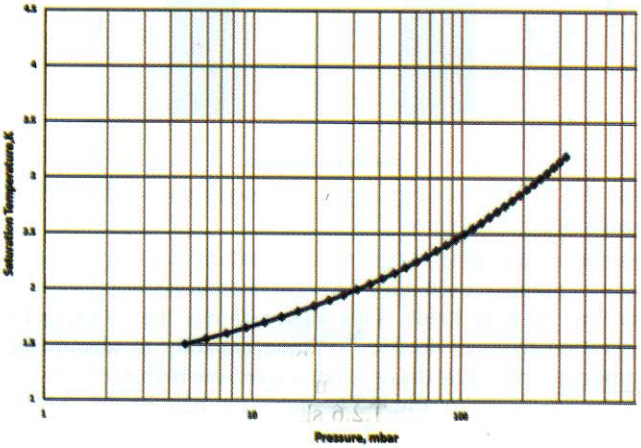


Fig. T.2.4: Saturation pressure corresponding to VTS operating temperature.

For operation at 1.8K the pressure inside the cryostat should be 16 mbar. This means, VTS has to operate continuously under sub-atmospheric condition during the testing of SCRF cavities at 2 Kelvin or lower. To operate under sub-atmospheric condition, the most stringent requirement is for avoiding atmospheric leaks. We have used pumping system procured from a local vendor. During its installation, suitable modifications were carried out in-house, to use it for helium gas pumping. It is also necessary to maintain stable operation of the test stand within required temperature limits. Ultimate operational aim of VTS is to sustain 250 W dynamic load, at 2 Kelvin while testing the SCRF cavities. This load is in addition to the static heat load which is due to atmospheric heat in-leaks depending on its design. This heat load will generate more than 14 g/s mass flow of helium gas during testing of cavities. If due to any reason more heat input takes place. It will evaporate more liquid and the pressure inside the cryostat will rise. This will result in under-cool condition of the liquid. Therefore, further heat input will result in increasing the liquid temperature. This continues temperature drift will also drift the resonant frequency of the cavity, which is not a desirable condition. For maintaining stable 2K temperature during the entire testing period the pumping system should be able to handle this gas flow rate. The pump down capacity of the pumping system depends on the inlet pressure. Therefore, pumping requirements are significantly different for 1.8K VTS operations as compared to the 2K. Pressure drop in pipelines will further reduce the pressure at pump inlet. The same pumping system will handle different heat loads at different temperatures. Fig. T.2.5 shows the

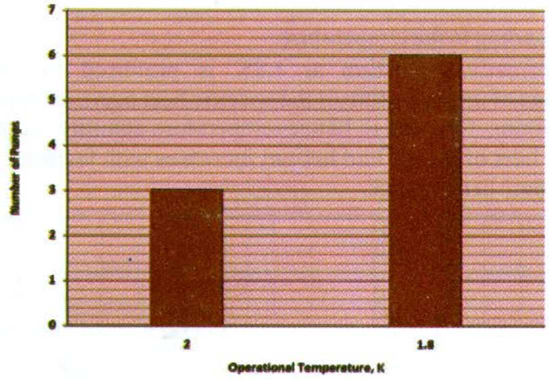


Fig. T.2.5: Number of pumping systems required for 250 W heat loads at 2 Kelvin and 1.8 Kelvin.

number of pumping systems (combination of fore pump and booster pump) required for different operational temperatures for 250 W heat loads. This figure shows that 1.8K VTS operation requires double pumping capacity to absorb the same amount of heat dissipation into helium bath as compared to the 2Koperation. Fig.T.2.6 shows the heat load handling capacity as a function of bath temperature. Three pumping systems of booster capacity of 4000 m^3/hr are assumed in the calculations. Assumed pressure drop between cryostat and pump inlet is 4 mbar.

It also shows that for given pumping capacity the heat load handling capacity is a strong function of bath temperature.

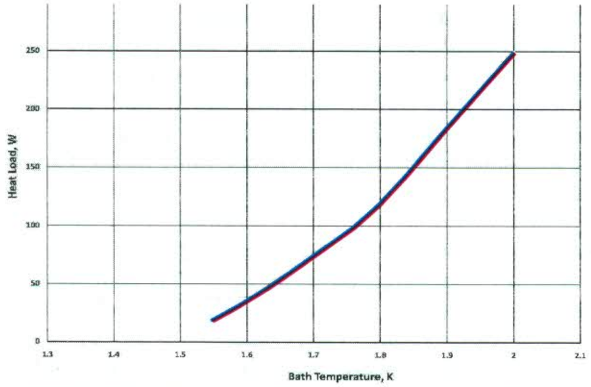


Fig. T.2.6: Heat load handling capacity for different bath temperatures.

4. Cryogenic Integration and Operational Issues

Vertical Test Stand (VTS) will operate in a closed loop. Fig. T.2.7 shows the simplified process flow scheme. Initial commissioning of this facility is aimed to test single cell cavity. In long run VTS has to test the multi-cell cavity which will demand more reliable and safe operation of VTS. For testing of multi-cell cavities, large amount of liquid helium will be required to be transferred in the VTS. Also continuous supply of liquid nitrogen will be needed for cooling the thermal shields.

Another operational issue is the sub-atmospheric handling of gas during VTS operation. There is always a chance of contamination of helium through pumping system, safety valves and other instruments installed in the circuit. Therefore, it is important to continuously monitor the purity of recovered helium gas. Locating the source of contamination, in such a large systemoperating at sub-atmospheric conditions, is a highly skilled job.

Among the integration issues, VTS has to be connected with an appropriate pipe sizing to warm the 2K vapor to near ambient temperature and also ability to handle dynamic load conditions. This piping lay-out is a combination of vacuum insulated line and bare piping. Section of piping, which is inside the building is vacuum insulated to avoid dripping due to moisture condensation, and outside the building it is bare for heating the cold gas from ambient heat. The design criticalities of this piping lay-out is to warm the helium gas to near ambient temperature at pump inlet through natural convection with minimum pressure drop. Fig.T.2.8 shows the temperature profile of helium gas along the pipe length for different size of bare pipes [6].

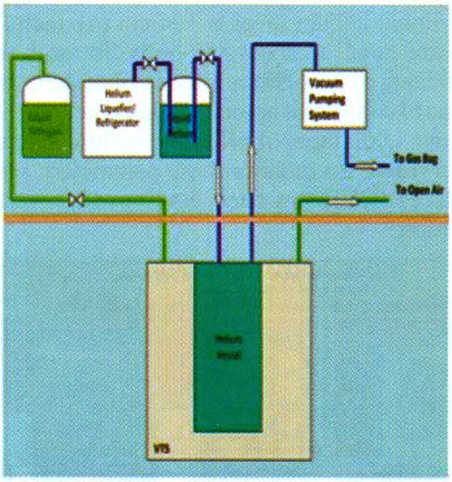


Fig. T.2.7: Simplified process flow scheme for VTS.

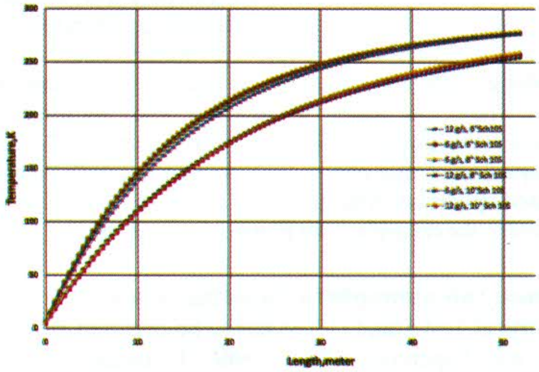


Fig. T.2.8: Temperature profiles of helium gas along the pipe length for different size of bare pipes.

Significant efforts were required to learn the VTS operation effectively. Therefore, regular and reliable VTS operation required broad range of capabilities and technological developments. Such as developing and establishing different operational procedures, different safety issues, large gas management issues and development of helium purification system. It also needed efficient transfer lines for handling the cryogens from remote locations.

4.1. Liquid Helium Requirement for Testing Single Cell Cavity

Table 1 gives the VTS cryostat helium vessel dimensions. Liquid helium holding capacity of VTS cryostat is 2,800 liters. Assuming 50% flash-off rate for achieving 2K, the vessel will remain only half filled when 2K is reached i.e. only 1,400 liters of 2K liquid will be available. Accumulation of this amount of 2K liquid will be sufficient for the complete test. It will not require any refill of cryostat during pump down. However, for testing a single cell cavity 680 liters of 2K liquid is required. Assuming 50% flash-off rate for achieving 2K, 1360 liters of 4.2K liquid helium at the start will be required for achieving the required level. Tests carried out shows that approximately 150 liters of liquid helium was used for cooling the cryostat and its auxiliaries, before the first drop of liquid helium started collecting in to the vessel, when the helium vessel was already pre-cooled with liquid nitrogen.

Therefore, total about 1,500 liters of liquid helium is required for testing a single cell cavity. These values match with the tests carried out.

Table 1: Dimension of VTS Helium Vessel

Helium vessel inner diameter	923 mm
Total depth of helium vessel	4860 mm
Liquid holding capacity below pumping line	2797 Liter

4.2. Helium Recovery during Achieving and Maintaining 2 K

Transfer of liquid helium from storage Dewar to the cryostat is also an important exercise. Due the typical properties of liquid helium only a part is collected as liquid in the cryostat during transfer, and the remaining converts in to vapor. This fraction which is not collected as liquid is called "Flash-off losses". During transfer of liquid helium to the cryostat initially liquid helium is used for cooling down of helium vessel to 4.5 K. After the cool down about 50% of liquid helium get flashed-off, and further liquid helium will be flashed during achieving 2K. Complete gas being coming out of the cryostat has to be recovered by the recovery system. This gas is first collected into two bags of 20 Cubic meter each. A Helium gas recovery compressor of cap 210 m^3/ hr is used to compress this recovered helium gas to high pressure cylinder cascades. This compressor is sized to compress helium gas generated by the VTS cryostat during full test with 250W thermal load at 2K continuously. Continuous active pumping by recovery compressor from the recovery gas bags to pressurized buffer cylinders is essential. When cryostat is operating at 120 mbar it will take approximately 6 minutes to fill each bag. At lower pressure, when the cryostat is operating at 53mbar,the bag fill time will be approximately doubled i.e. 12 minutes. This estimate is just to give the feeling of critical conditions demanding full alertness during VTS operation.

4.3. Temperature Rise Scenario in case of Power Dissipation

It should be noted here that temperature must be measured within 50 mK accuracy and bath temperature should be maintained stable within 100 mK during the period of Q_o v/s E_{acc} test and stabilizing temperature time should be minimum [7].

The bath temperature stability largely depends on the accumulated 2K liquid helium mass in helium vessel and specific heat of liquid helium at operating pressure and temperature. Fig. T.2.9 shows the specific heat of liquid helium as a function of temperature. Specific heat is relatively constant for the 100 mK temperature span at average operating pressure of 35 mbar. Fig. T.2.10 shows the time required for temperature excursion of 100 mK for different heat load for 680 liter 2K liquid helium bath. With a heat input of 50 W into 680 liter of 2K liquid, it will take about 20 minutes for a temperature rise of 100 mK.

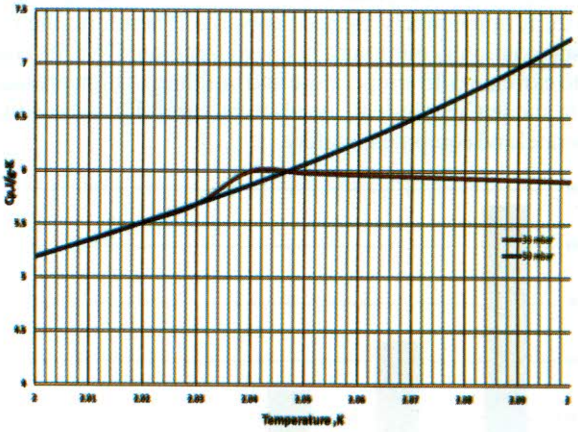


Fig. T.2.9: Specific heat of liquid helium as a function of temperature.

Similarly, Fig.T.2.11 shows time required for temperature rise of 100 mK for different quantities of 2K liquid helium, when 50 W power is dissipated into helium bath. With same heat input the time required for temperature rise of 100mK reduces significantly with change in liquid helium quantity in the cryostat. It will take about 3 minutes, for a rise of 100mK if the liquid remained is only 100 liters.

This will lead to bath temperature instability which is not a desirable feature for testing cavities.

5. Cryogenic Operational Safety Issues

Large amount of liquid helium is handled to cool the cryostat from room temperature to 2 Kelvin and to maintain it for testing of SCRF cavity. Although, helium gas is inert gas and is not harmful to the extent that in deep sea diving helium gas is mixed with breathing gas for inhalation. This is done to mitigate the problem of oxygen getting dissolved in blood under high pressure produced by water. Also being lighter than air it immediately escapes upwards. Therefore, the risk of asphyxiation is minimum in a well ventilated lab. Its risks due to extreme cold temperature and building of high pressure due to sudden heat in-leak, needs to be carefully assessed for personnel and equipments safety.

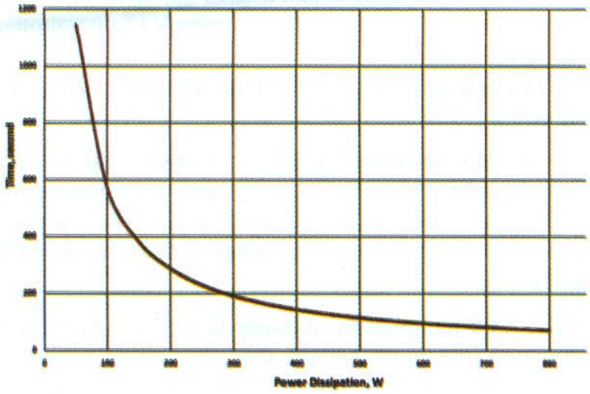


Fig. T.2.10: Time required for temperature excursion of 100 mK for various heat loads into 680 liter of 2 K liquid helium bath.

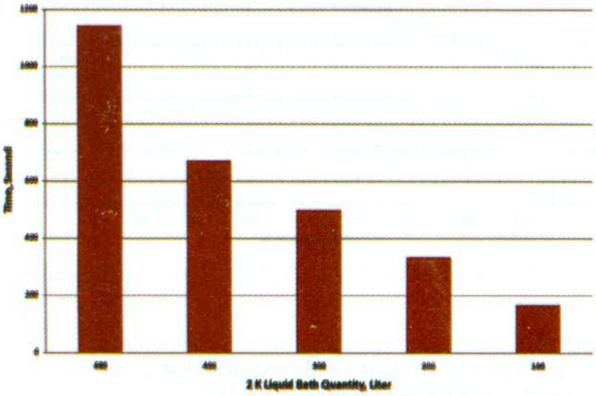


Fig. T.2.11: Time required for 100 mK temperature excursion for different 2 K liquid helium capacity for 50 W power dissipation into helium bath.

6. Conclusions

This article elaborates different commissioning and operational aspects of VTS. The full VTS commissioning and reliable operation at 2K is a challenging task. It requires a careful planning and sophisticated technical expertise, along with system level understanding in large scale cryogenic set-up. Successful commissioning of VTS has generated the broad range of valuable capabilities and sub-atmospheric operational experience. State-of-the-art full commissioning and reliable operation of VTS 2K cryostat has established RRCAT unique capability, first time in the country.

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