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Development of High vacuum facility for baking and cool down experiments for SST-1 Tokamak components

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Abstract. SST-1 Tokamak, a steady state super-conducting device, is under refurbishment to demonstrate the plasma discharge for the duration of 1000 second. The major fabricated components of SST-1 like vacuum vessel, thermal shields, superconducting magnets etc have to be tested for their functional parameters. During machine operation, vacuum vessel will be baked at 150 °C, thermal shields will be operated at 85 K and magnet system will be operated at 4.5 K. All these components must have helium leak tightness under these conditions so far as the machine operation is concerned. In order to validate the helium leak tightness of these components, in-house high vacuum chamber is fabricated. This paper describes the analysis, design and fabrication of high vacuum chamber to demonstrate these functionalities. Also some results will be presented.

1. Introduction

SST-1 Tokamak is designed for 1000 sec long pulse hydrogen plasma discharge with 220 kA current [1, 2]. The main subsystems of SST-1 tokamak consist of vacuum chamber, magnet systems and LN_2 radiation shields as shown in the figure 1. Vacuum chamber of SST-1 has been divided into two parts such as vacuum vessel and cryostat. The vacuum vessel will be used for plasma confinement while the cryostat will be used to provide the operational environment for super-conducting coils. These super-conducting coils have to be cooled up to 4.5 K using super-critical helium gas and they will be charged at 10 kA current for longer time period. For this purpose, they have to be protected from heat radiation coming from room temperature cryostat surfaces and vacuum vessel surfaces maintained at 50 °C during entire campaign by using LN_2 radiation shields around them. The cryostat will be maintained at high vacuum $\leq 1.0 \times 10^{-5}$ mbar.

Nearly 162 numbers of 10 verities of different shape and size of bubble type of LN_2 thermal shields are used. These panels are cooled using Liquid Nitrogen (LN_2) maintained at 80 K uniform temperature at 6.0 bar (g) internal pressure. Since these panels will be operated for much longer time period at higher internal pressure, it is very essential to qualify all the weld joints of these panels for their leak tightness at room temperature (RT) and at their operational conditions. For plasma confinement, the main vacuum vessel will be maintained at ultra-high vacuum $\leq 1.0\times 10^{-9}$ mbar.

The complete SST-1 vacuum vessel structure consists of eight numbers of vessel modules (VM) and eight numbers of vessel sectors (VS). In order to achieve such ultra-high inside the chamber, it is very much essential to bake the vacuum vessel at 150 °C for longer duration to remove water vapor and other gases which are absorbed and adsorbed. Further during cool down phase and plasma operations, the vacuum chamber will be maintained at 50 °C under evacuated condition to avoid the cool down of vessel towards low temperature due to radiation loss. For baking purpose, rectangular channels (16 mm × 8 mm) of 2 mm thickness are welded on the inner surface of the vacuum vessel as per finite element analysis [3].The high pressure dry nitrogen gas at 4.5 bar (a) heated up to 250 °C is passed through these rectangular channels of the vacuum vessel for baking. Since a large amount of welding are exposed directly to the UHV portion and will be under high pressure at high temperature, the qualification of these welds in their operation conditions has to be established.

Before assembling these VM & VS into the system, the individual VM and VS are baked up to steady state temperature of 150 °C for eight (08) hours in a dedicated high vacuum (HV) baking facility developed in-house. After baking, the leak testing of VM and VS baking channels are carried out and qualified at the leak rate < 1.0×10^{-8} mbar l/s in vacuum mode and at < 1.0×10^{-6} mbar l/s in sniffer mode at 6.0 bar (g) helium gas pressure. Similarly LN_2 radiation shields are cool down to 85 K in the same chamber and integrated leak testing is carried out in sniffer mode using helium gas at a pressure of 7.5 bar (g) using RGA.

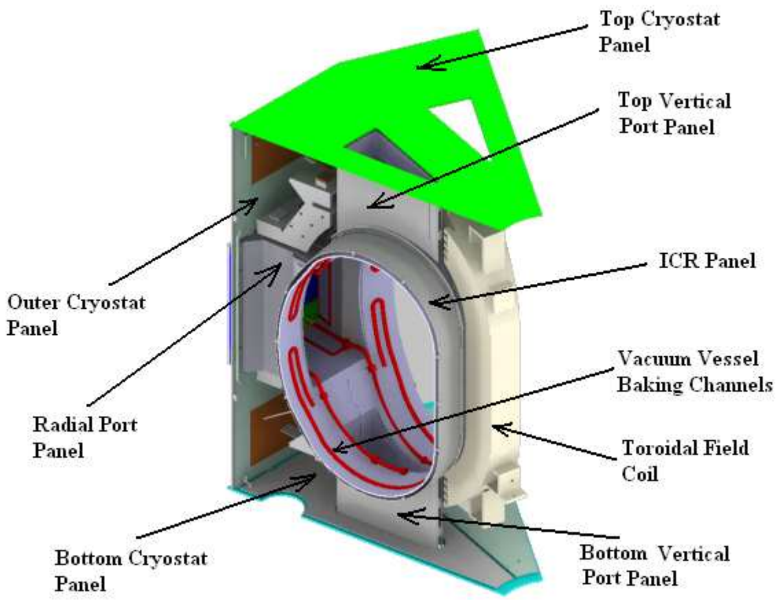


Figure 1. Schematics of SST-1 Tokamak with main sub-systems.

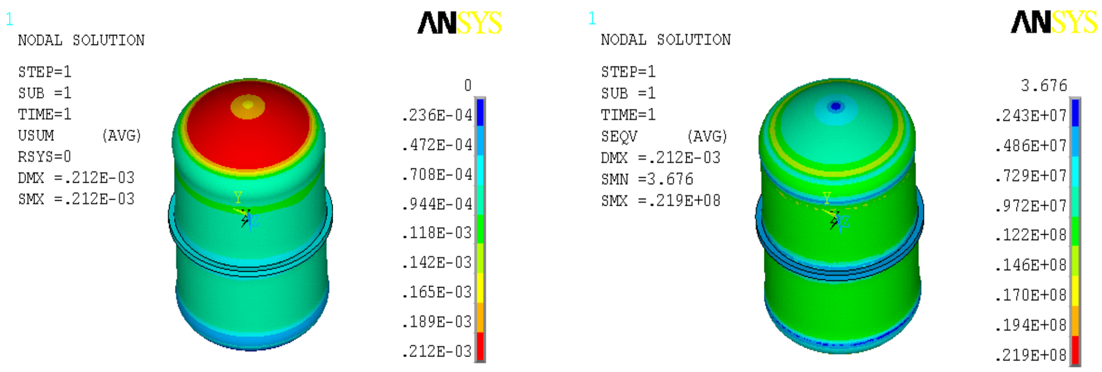
2. Design of high vacuum chamber

In order to accommodate VM and cryostat LN_2 shields (Dimensions: h = 2.5 m, w = 1.5 m) for their qualification along with additional structures necessary for their support, a dedicated chamber with a diameter of ϕ = 2.4 m, height of h = 3.45 m and wall thickness of t = 10.0 mm is designed and fabricated. The chamber is fabricated using SA 516 Gr-70 material, the out-gassing rate of which is 2.0×10^{-9} mbar l/s.cm^2 [4]. It is electro-plated with chrome to reduce the out-gassing rate to 1.0×10^{-9} mbar l/s.cm^2. The chamber is fabricated in two halves based on finite element analysis (FEA) using ANSYS software [5]. Model of this high vacuum chamber has been generated using CATIA software. The model is transferred to ANSYS through CATIA interface for the analysis considering the parameters as shown in the Table 1.

Table 1. Parameters considered for FEA analysis.

Analysis type	Structural
Element used	Solid 186
Material properties	
Density	7850 Kg/m^3
Young's modulus	190 GPa
Possion's ratio	0.27
Boundary conditions	
Inside surface pressure	1.0×10^{-5} Pa
Outside surface pressure	1.013×10^5 Pa
Displacement of lower elliptical end	x, y, z - displacements = 0

The element Solid 186 is a higher order 3-D solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom per node. The element supports plasticity, hyper-elasticity, creep, stress stiffening, large deflection, and large strain capabilities. Considering the above parameters of table 1, the deformation and von-mises stress results obtained after ANSYS analysis are shown in the figure 2. Analysis results show that maximum deformation of 0.2 mm and maximum stress of 21.9 MPa will be developed due to pressure difference which is less than the allowable tensile strength of 205MPa.



Deformation result Stress result

Figure 2. ANSYS results for deformation and stress values.

3. Experimental set-up and procedure

Due to larger dimension of the vacuum chamber, double O-ring configuration was utilized along with inter-space pumping in order to ensure the better leak tightness. Two numbers of 500 ISO-F flanges are provided on this chamber, out of which one is used for pumping purpose while other is used for human entry. Four numbers of 63 CF flanges are provided for connecting supply and return lines of VS and VM with hot nitrogen gas supply and return lines. Also two numbers of 300 class flanges are provided for connecting LN_2 supply and return lines for cool down of thermal shields as shown in the figure 3.

For rough pumping of the vacuum chamber, two numbers of rotary pumps are connected, each having a pumping speed of 35 m^3/hr. For high vacuum, one turbo-molecular pump of 5000 l/s pumping speed (N_2 equivalent) is connected to the chamber with effective pumping speed of 3550 l/s. Combined ionization gauge is used for the measurement of chamber vacuum. MKS make RGA is used to measure the partial pressure of different gases inside vacuum chamber.

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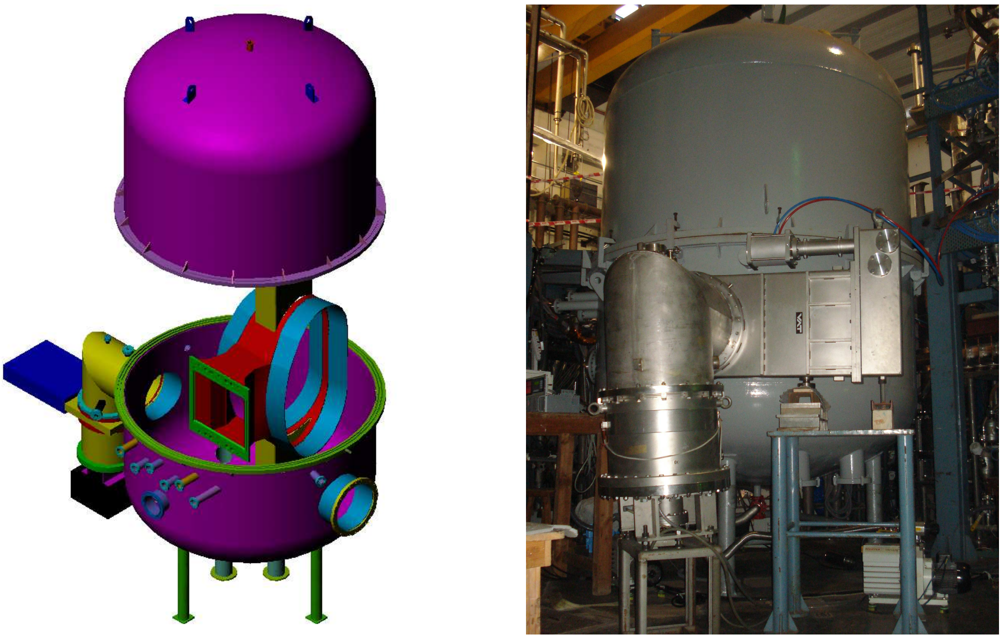

Figure 3. High vacuum chamber with vacuum accessories.

Before insertion of VM and VS into the chamber, the complete baking channel is leak tested for the acceptable leak rate. Twenty eight (28) numbers of K-type Kapton insulated thermocouples calibrated within the accuracy of ± 1 °C are mounted at the different locations of VM / VS using high temperature Ceramabond glue from M/s. Aremco which can withstand the temperature up to 500 °C. Temperature data are acquired through de-mountable type 36-pins feed-through using MASIBUS make DATA logger and stored using CITECT SCADA based software via RS-485 transfer protocol. After insertion of VM / VS, the chamber is closed and pump down to the pressure $< 1.0 \times 10^{-5}$ mbar and then baked for steady temperature of 150 °C for eight (08) hours by passing hot nitrogen gas at 250 °C with the ramp rate of 50 °C/hr. Then VM / VS is cooled down naturally and baking channels are leak tested.

Similarly, the thermal shields are leak tested in a component labels for the acceptable leak rate. Then these thermal shields are fixed with VM / VS and are kept inside this chamber with their common supply and return headers. A provision for inter-face between the vacuum side headers and the atmospheric side is provided with special type of connector. Also the provision for pressurizing the panels at room temperature and cold condition is provided using valve arrangement at supply end. Eleven numbers of Pt-102 temperature sensors are mounted to these panels at midpoint of each bobbles. Once again the entire configuration is leak tested in vacuum mode at the background $< 1.0 \times 10^{-8}$ mbar l/s and then tested in sniffer mode at the background $< 1.0 \times 10^{-6}$ mbar l/s with internal helium pressure of 8.0 bar (g). After qualification test, the vacuum chamber is pumped down to the vacuum $< 1.0 \times 10^{-5}$ mbar. QMA was switched ON and the panels are pressurized to 8.0 bar (g) with helium gas. Panels were kept under pressurized condition for few minutes and a QMA scan was taken. Leak tightness of the panel was confirmed by observing the Helium partial pressure in the QMA scan. Then, the panels were de-pressurized to atmosphere and Liquid nitrogen was passed through the panels to cool them up to 80 K. The same procedure was repeated after achieving 80 K temperature on panels to see the leak tightness at cold condition.

4. Experimental results

The test chamber vacuum during baking along with temperature profiles at different locations of one of the VM is shown in the figure 4. Also the thermocouples mounting locations at the radial port and vertical ports with saturated temperature values are shown in the figure 5.

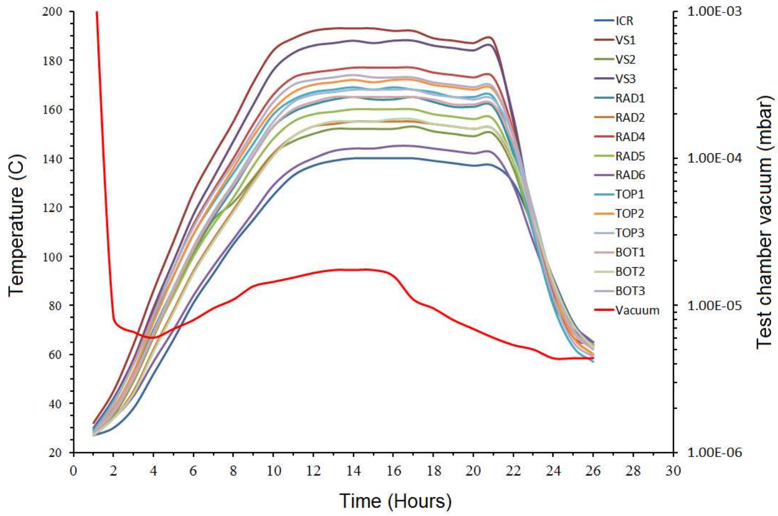

Figure 4. Test chamber pressure and temperature profiles of one of the VM.

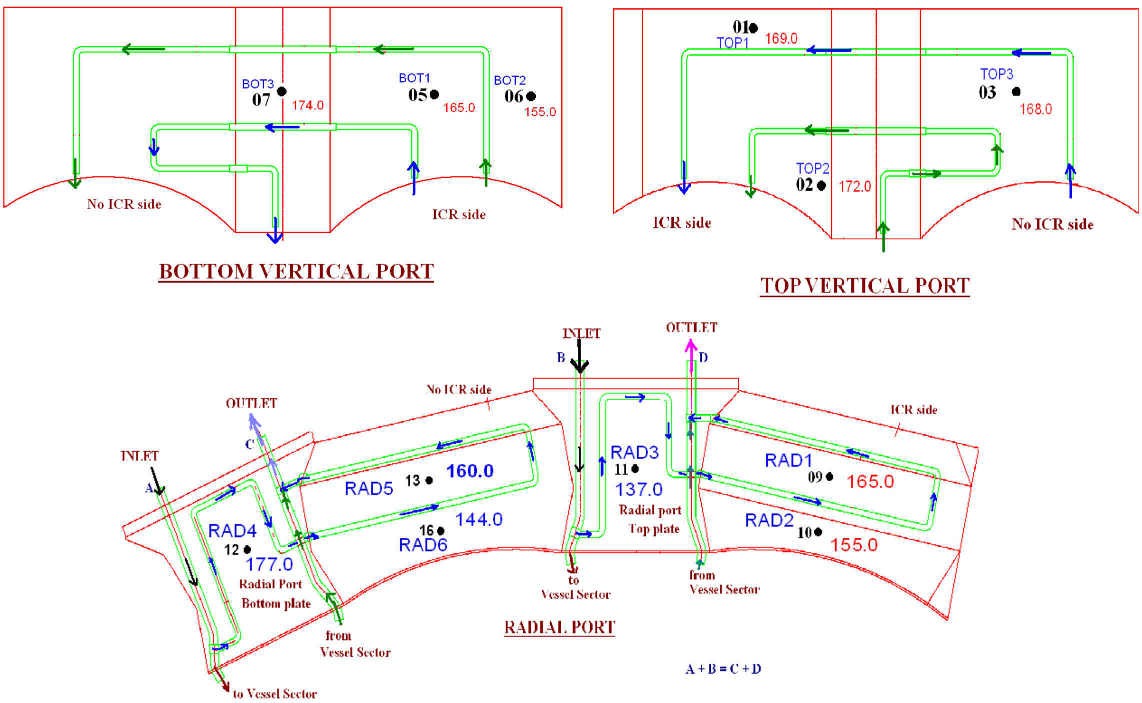

Figure 5. Temperature sensor locations of vertical and radial ports of one of the VM.

After baking and cool down, the leak testing of VM / VS baking channels is carried out. In few VM / VS, some leaks are detected ranging from 10^{-7} mbar l/s to 10^{-3} mbar l/s. These leaks are repaired and further leak tested and baked. This process is repeated till, the leaks are completely removed.

The cool down of thermal shields of two numbers of VS in series with time is shown in the figure 6. After achieving 80 K, QMA scan was taken as shown in the figure 7. This scan indicate no traces of helium gases confirming that there was no leak developed due to cool down. After integrated leak test, these panels are warmed up and again leak tested in integrated form. No leak found the background < 1.0×10^{-8} mbar l/s in vacuum mode and in the background < 1.0×10^{-6} mbar l/s with internal helium pressure of 8.0 bar (g) in sniffer mode.

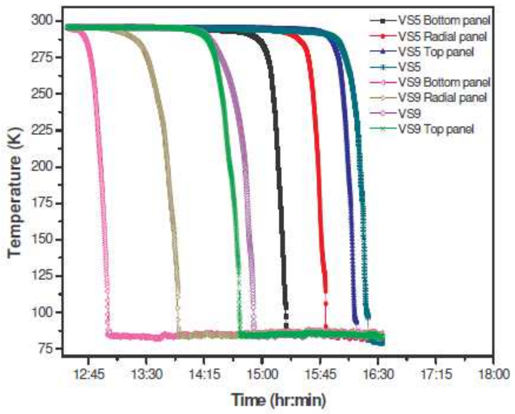

Figure 6. Vessel panels temperature with time.

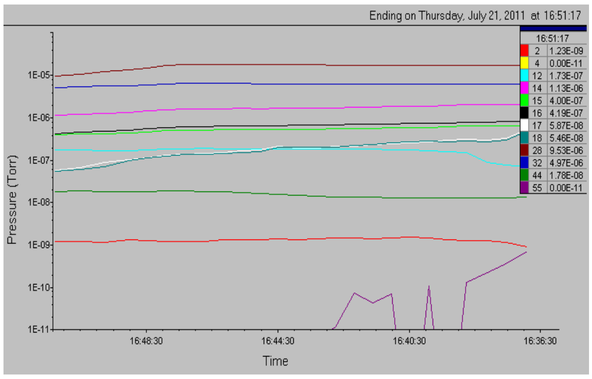

Figure 7. RGA Scan after cool down of shields.

5. Conclusion

The probability of leak development in the weld joints of VM /VS baking channels and in the thermal shields is significantly eliminated ensuring leak tightness of the system. Also their performances at their operating conditions are well established assuring their integration with SST-1 Tokamak.

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