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Overview of design developments for Condensable Vapor Devices for ITER

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Abstract. The Condensable Vapor Devices (CVDs), which are part of the ITER Roughing Pump System (RPS), are designed to separate tritiated water content to protect downstream pumps and transfer the water to Tokamak Exhaust Processing (TEP) systems for further separation. CVDs operate on the principle that a cooling fluid, such as liquid nitrogen, cools the exhaust gas stream (process gas) from the Tokamak, allowing the water present in the process gas to condense and freeze, thereby trapping it in the CVDs. The CVDs once saturated with the ice are then regenerated to release the trapped water molecules, which are sent to the TEP. The present article will describe the technical requirements, challenges, and design progress made so far in the development of the CVDs.

1. Introduction

ITER, meaning “the way” in Latin, aims to achieve sustainable fusion energy through self-heating plasma with a gain ≥ 10. The United States is one of the seven members of this significant ITER project, which is in the advanced stages of construction in the south of France. The ITER project in the US is managed by Oak Ridge National Laboratory (ORNL) along with partner labs Princeton Plasma Physics Laboratory (PPPL) and Savannah River National Laboratory (SRNL). The United States is responsible for the in-kind supply of Central Solenoid, Tokamak Cooling Water Systems, Vacuum Systems, Tokamak Exhaust Processing (TEP) System, Diagnostic (US Share 14%), Pellet Injection and Disruption Mitigation, Steady State Electricity Network (US Share 75%), Ion Cyclotron Heating Transmission Lines, Toroidal Field Coil Conductor (US Share 8%) and Electron Cyclotron Heating Transmission lines.

The vacuum systems at ITER are vital to the project as they handle the evacuation and exhaust of the gases from the Tokamak machine. The Roughing Pump System (RPS), which is part of the vacuum system, consists of a series of roughing pumps, metal scroll, roots, and screw pumps for tritium compatibility, and provides a means to evacuate all gases or mixtures of gases originating from the Torus and Neutral Beam Cryogenic Pumps. These gases are then appropriately transferred to other systems such as the Tokamak Exhaust Processing (TEP), De-tritiation System (DS) or HVAC. These exhaust gases contain helium, isotopes of hydrogen and their combinations. Additionally, they contain water (H_2O) and its isotopes including heavy water (Deuterium Oxide, D_2O) and tritiated water (T_2O). The water in these streams could be from wall outgassing; plasma-wall interactions; water leak; impurity in the fuelling gas [1]. The schematic representation (extract) of Process Flow Diagram of RPS shows the broad scheme of CVDs and their connected systems in Figure 1 [2].

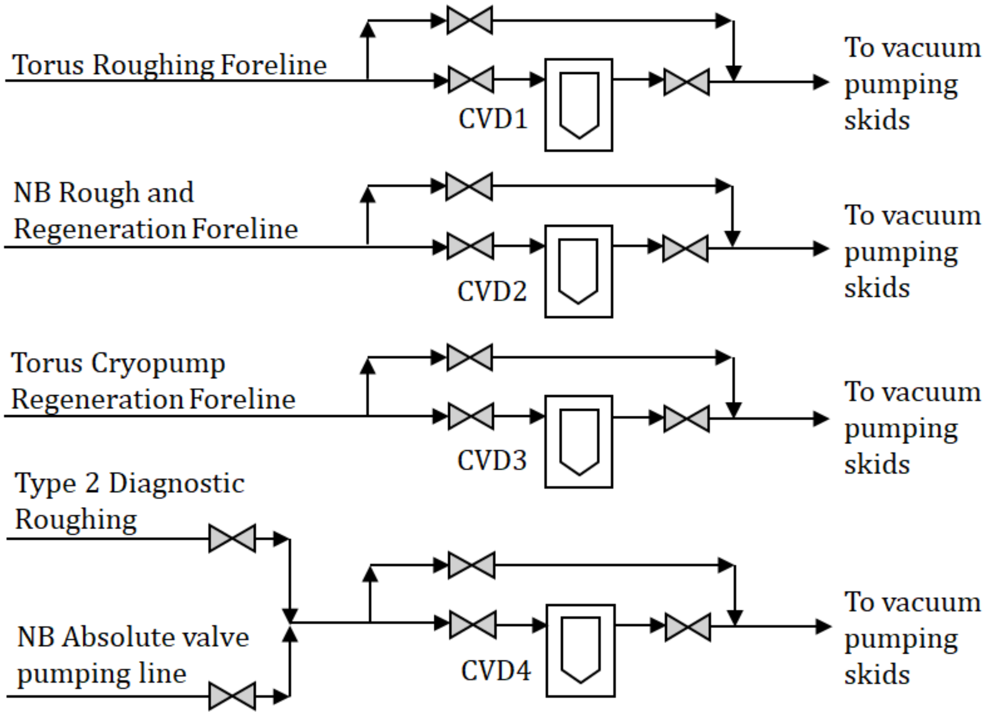

Figure 1. Extract of Process flow diagram of ITER Roughing Pump System showing the CVDs

1.1 System classifications

Several classification systems are implemented in ITER for categorizing the systems based on their function. The CVDs are classified as Safety Important Component (i.e., SIC-1), as they are required to bring to and maintain the ITER in safe state of operation. In terms of seismic classification, the CVDs are classified as SC1(SF), which means that the CVDs need to maintain their functionality and confinement without yielding of the construction materials during a seismic event.

The vacuum classification is associated with every vacuum component denoting its area of service on ITER. The CVDs, being double walled structures, are classified as Vacuum Quality Classification-1 (VQC-1) for the inner vessel as its connected to the torus high vacuum and VQC-3 for the outer vessel as its connected to the service vacuum system. This VQC classification imposes constraints derived from the ITER Vacuum Handbook [3] such as stringent leak rate and suitable material selection criteria. The inner vessel must meet the $1x10^{-10}$ Pa.m^3/s air equivalent rate for VQC-1 systems, whereas the outer vessel must meet the $1x10^{-9}$ Pa.m^3/s air equivalent rate for VQC-3 systems.

2. Technical requirements

The CVDs must fulfil several technical requirements to serve their required functionality. Some of the key requirements are elaborated in this section [4]. The CVDs shall have the capability to trap

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and confine ~100% water vapor (<1x10^{-4} Pa.m^3/s permitted at exit) by adequately cooling the gas using liquid nitrogen (LN_2). The CVDs shall be capable of trapping and storing of 5 kg of water, prior to carrying out any regeneration. Based on the conceptual design [5], it has been observed that the cold surface area of 10,000 cm^2 is necessary to trap 5 kg of water vapor. It is therefore necessary to provide a minimum of 10,000 cm^2 of cold surface within the CVDs. The CVDs shall be equipped with the heaters capable of warming the cold surfaces up to 393K (or 120°C) and the regeneration process shall be completed within 3 hours, in a controlled manner. These CVDs must be double contained to mitigate the Tritium leak risks. To avoid being the choking point for the process, the CVDs shall be designed with sufficient vacuum conductance. The Conductance (for air) shall be ≥ 4,000 Liters/second at 50 Pa when empty (i.e., no ice condition), and at 100 Pa when filled with 5 kg of ice.

In terms of mechanical design of the CVDs, the design pressure of the CVD vessels shall be 0.15 MPa (a) so that it is not categorized as Pressure Equipment. The CVDs shall be designed based construction code of EN13445 or ASME Section VIII Div. 2. The CVDs have been allotted the space reservation as 1 m x 1 m x 1.5 m and shall be enclosed within this allotted space. All the materials shall be chosen in accordance with the requirements of Vacuum Quality Class-1 (VQC-1) or VQC-3 based on the ITER Vacuum Handbook [3]. The materials used in CVD construction shall be traceable via EN 10204 Type 3.1 certificate and Commercially Off The Shelf (COTS) items provided with EN 10204 Type 2.1 certificates of conformance. The CVDs are in Room 23 of Building 14 inside the Tokamak Complex. This room will have temperatures within 18°C - 35°C,

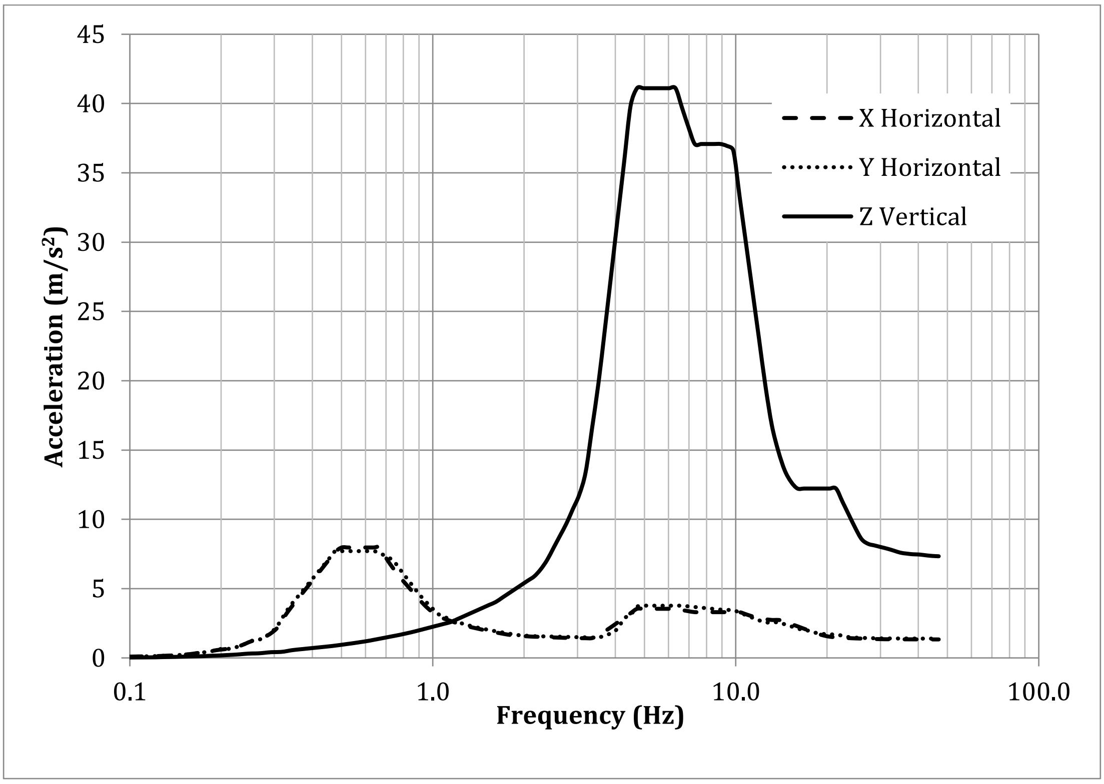

Figure 2. Floor Response Spectra (FRS) of the room 23, building 14 of Tokamak Complex at ITER for seismic design of the CVDs

with relative humidity in the range of 20%-60%. The floor response spectra to be considered for seismic design validation is provided in the Figure 2.

As the CVDs are subjected to a magnetic field up to 16 mT, all the sensors, Instrumentation & Control (I&C) equipment shall be compatible with this magnetic field. All instrumentation and heaters shall have 100% redundancy. The temperature sensors (RTDs) shall be installed to monitor cold and regeneration surfaces. The regeneration heater shall be capable of delivering ≥ 5 kW of power at 230-400V, 50 Hz, single phase. The heater sizing shall be confirmed during the detailed design phase, ensuring it fulfils the needs of the regeneration. These heaters shall be controlled based on regeneration surface temperatures. The pressure sensors shall be installed to monitor pressure of primary confinement of CVD trap. The cryogenic fill valve is used to control the flows of LN_2 to the CVDs and these valves are operated based on the LN_2 level inside the trap. The CVDs shall be equipped with the pressure safety switches inside primary CVD confinement interlocked with cryogenic fill valve with 0.11 MPa (abs) setpoint, to close the fill valve if needed.

3. Operating principle and conditions

The CVDs are designed to remove of vapor of water and its isotopes in the form of heavy water. (Deuterium Oxide, D_2O) and tritiated water (T_2O). This is achieved by cooling the exhaust gas stream, hereafter referred to as 'process gas', with the help of liquid nitrogen (LN_2). The LN_2 is flown inside the inner vessel of the CVDs through a series of pipes having extended surfaces in the form of fins. The process gas is flown over the cryogenically cooled surface and allowing it to get condensed and frozen on these cold surfaces. The amount of water trapped inside the CVDs is assessed using the moisture sensors located in the outlet streams of the CVDs. The overall flow scheme for the CVDs showing different gas flows is provided in the Figure 3.

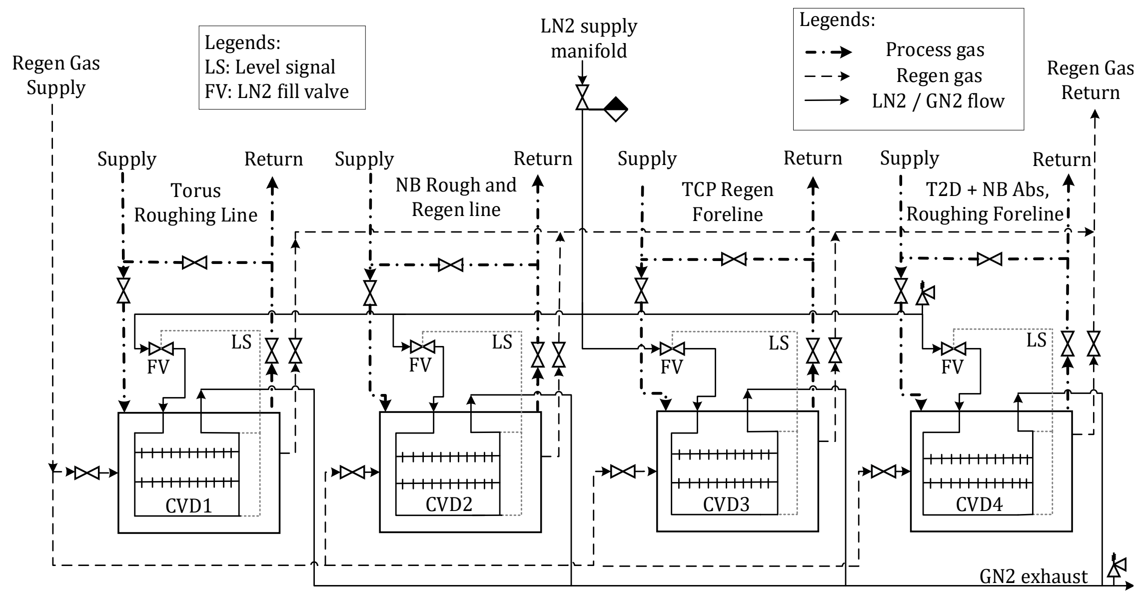

Figure 3. Overall flow scheme of the CVDs (only major flow paths shown, OVJ not shown)

The process gas is having a flow rate of ≤200 Pa.m³/s at room temperature (25%D_2, 25%T_2 and 50%DT) [5] enters the CVDs along with water (either in the form of D_2O, T_2O, DTO, H_2O) vapor flow rate of ≤ 1 Pa.m^3/s (typically much less). During the normal operation, the pressure inside trap can vary from 0.1 MPa to 1 Pa and maximum accidental pressure of 0.2 MPa. The purge gas is supplied at a flow rate of 200 Pa.m^3/s at room temperature and 0.09 MPa(a). The flow of regeneration gas is supplied and managed by Tokamak Exhaust Processing (TEP) side. This regeneration gas will be heated with the help of electric heaters and warm gas will be used to flush away the water vapor trapped inside the CVDs. As of now, the Argon is being considered as regeneration gas.

3.1 Liquid nitrogen needs
In order to ensure the trapping of the water content in the process gas of equivalent mass flow rate of 0.4 g/s, it is necessary to cool it down using the LN_2. In the current estimation, it is assumed that this process gas is cooled up to 80K, as a conservative approach. Additionally, the water content is cooled so that the ice is formed and get adhered to the cold surfaces inside the CVDs. This cooling requires the extraction of ~670W from the process gas, which results in ~3.5 g/s of flow based on the latent heat of LN_2.

4. Design development

CVDs have currently completed the preliminary design phase. This design phase includes the development of internal component arrangement, thermodynamic calculations, vacuum conductance estimations, preliminary selection of the I&C sensors and 3D model development based on these considerations. The preliminary 3D model fits within the space reservation

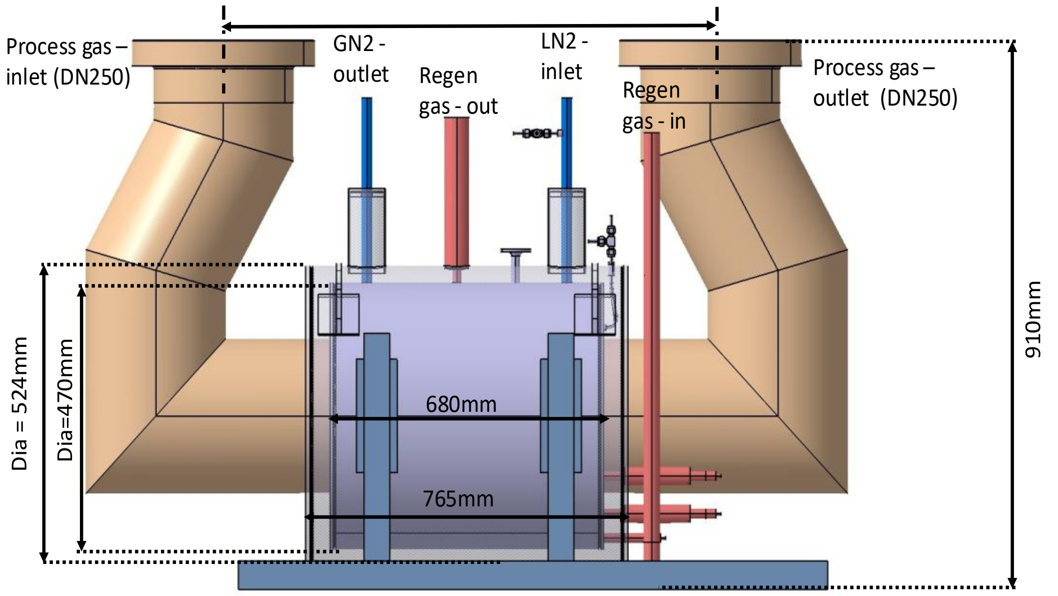

Figure 4. 3D model development of the CVDs

allocated for the CVDs. The major dimension of the CVDs is shown in Figure 4, whereas the Figure 5 shows the internal arrangement with a focus on the fins on the internal piping and regeneration heaters.

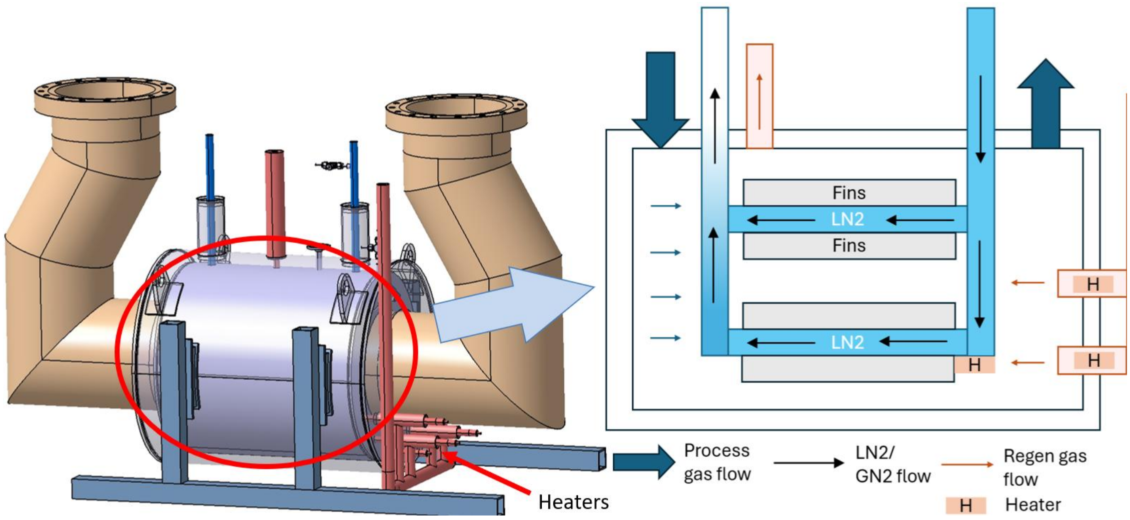

Figure 5. The internal arrangement of the CVDs

5. Challenges

As the CVDs are associated with several complex system characteristics such as Tritium facing components, presence of cryogens, magnetic field environment, etc., there are certain peculiar challenges being faced. These challenges include the following,

5.1 Design of safety protection system

In the unforeseen and accidental circumstances, there is a rare possibility of rupture of cryogenic piping inside the CVDs. This event may result in release of liquid nitrogen leading to generation of high-pressure gaseous nitrogen (GN_2) along with combination of Tritiated water and Tritium, if such rupture occurs inside the inner vessel. The mitigation strategy to overcome this challenge is being finalized.

5.2 Sensors and instrumentation compatible to magnetic fields

The I&C sensors and transmitters, such as pressure transmitters, level sensors, etc., are subjected to a magnetic field up to 16mT, as the CVDs are located inside room 23 of building 14. Currently, those I&C sensors are being considered for the CVDs, which have been validated for their capability to withstand such magnetic fields. These validated sensors have demonstrated their functionality in a magnetic field stronger than the actual field, applied across three planes. If needed, the qualification of other sensors may be carried out, to fulfil the magnetic field validation requirements.

5.3 Management of external interfaces

The external interfaces, including LN_2 supply and its return in the form of GN_2, are still under evolution. As the process parameters of these external interfaces are crucial for CVD design, these systems impact the design phase of CVDs. The maturity of these systems plays a crucial role in design development of the CVDs.

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6. Plan of works

Having completed the preliminary design phase, the work plan for the final design phase includes the following objectives,

- Finalize the 3D model and internal component arrangement
- Performance assessment from operational aspects
- Finalizing the safety scheme associated with the inner and outer vessels
- Design validation through various types of analyses such as,
    - Mechanical and thermal analyses
    - Seismic analyses
    - Regeneration process validation using Computational Fluid dynamic (CFD) analysis

7. Concluding remarks

The CVDs are essential for trapping water vapor for protecting the downstream vacuum pumps. The design of CVDs is being in-line with requirements defined in technical specifications. The preliminary design phase has resulted in the development of a 3D model, including the internal component arrangement. The next phase includes design validation which will be performed through various different analysis. In terms of schedule, the final design is expected to completed by end of this year.

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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