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Upgrade design and analysis of the quench tank of the IFMIF-DONES lithium target system

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ABSTRACT

The IFMIF-DONES project aims to provide a neutron source that replicates the conditions expected in a fusion reactor, such as the future DEMO reactor. This facility will be utilized to test materials and conduct various scientific experiments. The selection process for materials involves rigorous testing and qualifying procedures to ensure their suitability. A high-power deuteron beam is used to create a neutron source by impinging on a liquid lithium-based target. In the Target Assembly (TAA), a free-surface high-speed lithium jet is generated under specific conditions to achieve the desired neutron flux for testing the materials. The lithium flow exiting from the TAA is collected in the Quench Tank (QT), which serves to reduce the flow velocity. After passing through the QT, the lithium is evacuated into the main lithium loop for further processing. To provide an updated design that takes into consideration the structural requirements and Remote Handling (RH) aspects a revision of the vessel's structure is needed. In this paper, a detailed analysis is performed to examine all the mechanical loads that occur during different operating conditions concerning the structural integrity of the Quench Tank.

1. Introduction

The International Fusion Materials Irradiation Facility - DEMO Oriented Neutron Source (IFMIF-DONES) [1] located in Granada aims to select materials that are sufficiently resistant to neutron irradiation and hence suitable for use as structural materials for future fusion reactors and additionally to advance on other scientific research areas (such as radio bio-pharmacy, physics, etc.). The material selection process is done via testing and qualifying materials by utilizing a neutron source created by a high-power 125 mA, 40MeV deuteron beam [2] that impinges on a liquid lithium-based target. A free-surface high-speed lithium jet is generated in the Target System (TSY Components included in the big red bracket in Fig. 1) [3] in the proper conditions, this delivers the desired neutron flux toward the testing materials placed behind it. The Test Cell (TC) houses the components of the (TSY) and the Test modules (TM). It serves as a vacuum vessel, and as the primary nuclear safety boundary. Being part of the Target System [4], the Quench Tank is located downstream of the Target Assembly (TAA) and fixed to the bottom of the TC [5] (Fig. 1). The Quench Tank (QT) serves two main functions: to slow the free-surface high-speed jet exiting from the TAA into a confined, low-velocity flow with adequate fluid-dynamic conditions to be injected into the main lithium loop; and to provide a buffer volume for the Lithium jet from above the Quench Tank. The QT vessel is designed to store approximately 500 kg of liquid lithium at 350 °C. A detailed analysis is crucial for ensuring the reliable operation of the TSY. This should consider all the loads and boundary conditions for the different working modes, including, but not exhaustive: thermal heat, seismic, vacuum, etc. Additionally, the design must meet other requirements and constraints, including facilitating remote handling, installation, and maintenance operations as well as fitting within the limited space inside the Test Cell (TC).

Currently, the Quench Tank needs to be revised by focusing on the aspects that were not investigated; therefore, this paper aims to complement the previous studies [6] adequately by providing an updated design of the outer structure.

Aiming to make an engineering analysis that focuses on the thermomechanical aspects while not affecting the hydrodynamical behavior inside the structure [7], a revision of the mechanical structure of the

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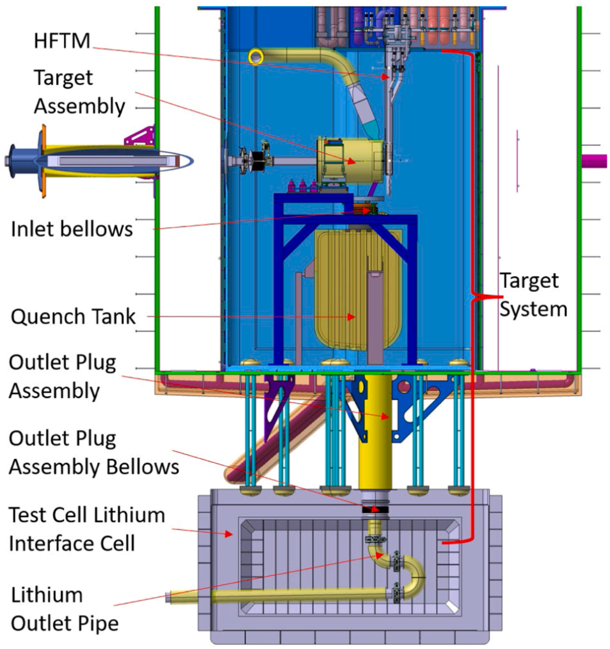

Fig. 1. Test Cell section view.

Quench Tank is made. This work shows several proposed modifications for the current design of the QT and thermo-mechanical performance. A design evaluation process is presented along with a short design selection phase, investigation of remote handling aspects, and consideration of space requirements. After that, a more suitable design is proposed and investigated in more detail.

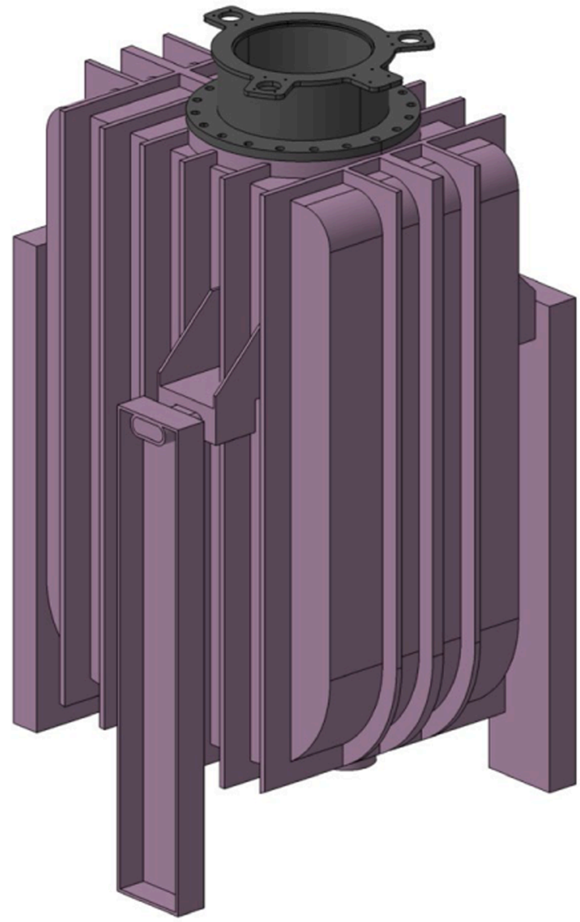

Fig. 2. Current QT.

2. Updated design of the QT

An image of the current QT can be seen below (Fig. 2), which features a robust rib structure conformed by vertical ribs. The fixation points of the legs were placed on the top half of the vessel, and the sliding supports could be assembled by aligning the QT to the legs and inserting the pins from the side.

The QT operates in an irradiation environment, located in the same confined area (TC) as the TAA, where the neutron beam is generated (Fig. 1). The QT could be potentially an activated component as it is part of the Lithium Loop. Although the QT is designed for the plant lifetime, Remote Handling (RH) [8] will be used in case of any malfunction or in case of failure due to other scenarios (such as a seismic event, a lithium leakage, etc.) due to the high activation level [9]. To minimize heat radiation by the QT and prevent the liquid Lithium from solidifying in case of any system shutdown or during the start-up, when filling up the loop a heating-insulating system is installed on the outside of the QT. Lastly, this system will be used during the "Warming up the loop" commissioning step. Unlike the QT, this heating-insulating system is planned to be maintained, therefore the ease of RH accessibility and installation is crucial. Due to the limited space inside the TC and being close to the TAS (Target Assembly Support), remote handling maintenance compatibility is essential to ensure that maintenance operations are possible at any occurring malfunction (Fig. 3).

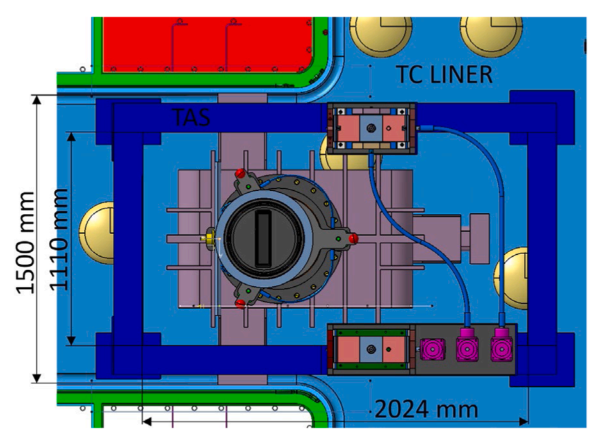

Fig. 3. QT Position inside the TC.

2.1. Main design scenarios and contributing loads

During operation, irradiation at full power operating mode puts the most significant heat load on the quench tank's outer structure. Another notable scenario happens during the startup procedure and every time after draining the Lithium and opening the Lithium loop. This is an impurity removal process that should be conducted under vacuum (QT), while the entire vessel is heated (called Baking) and the TC is at atmospheric pressure. The purpose of this procedure is to remove all the water molecules from the surfaces to be able to reach an ultra-high vacuum. Baking does not require to happen at operating temperature, but there is a commissioning step where the entire lithium loop is heated up to operating temperature under vacuum, so baking is considered implicitly in this step. This step is called Warming up the loop. The QT will go through several other operational modes, however only the most demanding ones have been listed here (Table 1). The eligibility of the proposed design needs to be verified by simulations to ensure structural integrity while subjected to different load cases.

Table 1
Design Scenarios and loads.

Design Scenario	Load Weight	Heat	Pressure
Irradiation	(SW) (LiW) (IW)	(350 °C) (HLL) (~1088 W/m^3) (HLI)	(LHP)
Warming up the loop	(SW)	350 °C (HLW)	−1 bar (vacuum) (PL)

SW:Self weight.
IW:heating-insulating system weight.
LiW:Lithium weight.
HLL:Lithium convective heat.
HLI:Nuclear heating (Heating due to irradiation).
HLW:Heat Load during Warming up.
LHP:Lithium hydrostatic pressure.
PL:Pressure load.
Seismic event: Floor Response Spectra (FRS) input superimposed on any load case above [10].

3. Analysis of solutions

Being in a sealed environment, ensuring the proper operation of the QT is very important, therefore the objectives of the design are driven by several considerations. The vessel plays an important role in an activated and heated Lithium loop, therefore focusing on a design that aids any possible maintenance operation by Remote handling is crucial (both on itself and on nearby components, like the TAA). Storing a high-temperature substance requires accommodation of the heat expansion of the vessel, moreover, to allow the heat expansion without interfering with the connected or nearby components of the Test Cell to protect the heating-insulating system, and the components themselves as well.

Aiming to produce a design that lasts for the plant's lifetime, and strongly considering the manufacturing procedures is a key point to ensure the production of a high-quality welded vessel. Lastly, the IFMIF-DONES facility is located in Granada, therefore the seismic events during the design process of the support structure should be taken into account.

3.1. Design objectives

- A design that can be installed and maintained in case of failure by RH operations.
- Redesigning the rib structure that allows the installation and maintenance of the insulation in case of any damage or malfunction
- Optimize the supporting structure, allowing thermal expansion and absorbing the seismic load.
- To analyze the Outlet Plug Assembly's behavior, and relation to the TC Liner, during operation
- To progress toward a manufacturing-oriented design

The supporting structure is of major importance since it ensures structural stability and impacts RH compatibility and RH maintenance procedures. Different versions have been analyzed considering all the objectives listed above to find a suitable design. During this evaluation, a 2-leg, a 3-leg, and a QT fixed to the target assembly support (TAS) versions were investigated (Fig. 4).

The 2-leg version is the most suitable solution from the RH and space requirement perspective. A 2-piece heating-insulating system can be applied without interfering with the TAS. However, the design is structurally unstable. The 3-Leg version aims to overcome the stability problem and still aims for the simplest possible heating-insulating system installation.

The idea behind the TAS-mounted version is to investigate an alternative solution that does not have a direct connection with the TC Liner.

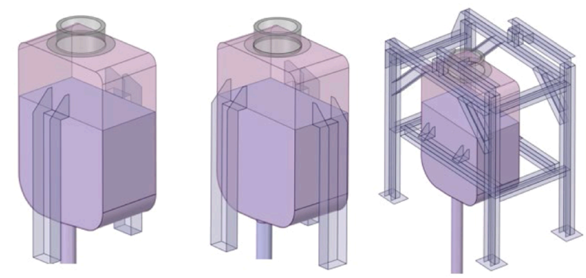

Fig. 4. 2-Leg,3-Leg, fixed QT to TAS.

3.2. Preliminary models

The analysis focuses on evaluating various support structure designs shown in Fig. 4. Simulations using the specific loading conditions associated with irradiation operations, as these conditions significantly impact the QT structure. To simplify the modeling process, the evaluation primarily addresses the supporting structures while neglecting the rib structures.

Modal analysis was performed to calculate the mode shapes and frequencies of the different supporting structures. For each design alternative, the first six vibration modes were analyzed.

In addition, data was utilized from another previously conducted simulation where two accelerograms were placed on either side of the High Flux Test Module (HFTM), where material specimens will be stored, and one accelerogram positioned on the TC Floor. These simulations aimed to determine the sensitive frequency ranges at the locations where the various supporting structures could potentially connect. By calculating the response spectra for these three points, the analysis identifies critical frequency intervals that may interfere with the mode shape frequencies of the support structures (Fig. 5).

It is essential to check if any modal frequencies of the support structures coincide with these sensitive frequency ranges. Such a frequency match could lead to resonance during a seismic event.

The Target Assembly Support (TAS) is connected to both the TC Floor and the HFTM through the Target Assembly (TAA), so both locations' frequency ranges must be considered. However, the 2-leg and 3-leg versions of the support structures do not have rigid connections to the Target Assembly and its support, making only the TC Floor response spectra relevant for these designs (Figs. 5 and 6). This analysis is crucial for ensuring the safety and stability of the structures in the event of seismic activity, particularly in radiation-affected environments where

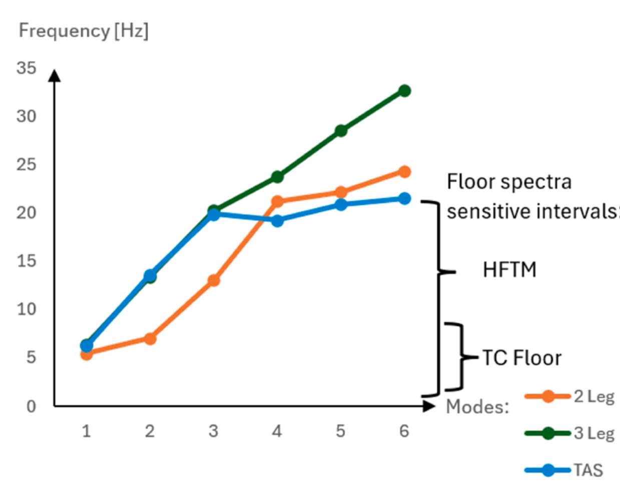

Fig. 5. Modal analysis evaluation.

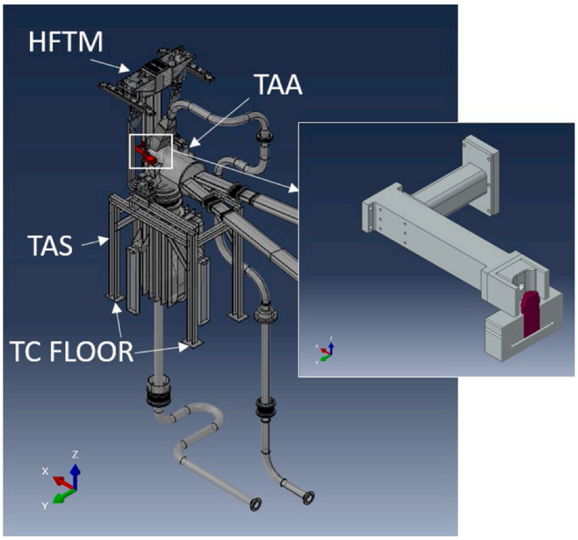

Fig. 6. Connections of the TSY.

resonance could compromise structural integrity.

Structural simulation results showed that the TAS-mounted version has the highest membrane and bending stresses at the support (Fig. 7) and the QT vessel's wall, moreover, this version has all 6 modes' frequencies in a sensitive interval (Fig. 5).

Regarding the other solutions, the modal analysis showed a dangerous tilting mode shape of the 2-leg version, so this solution must be eliminated. The 3-leg version provides enough structural stability while giving enough space for the necessary RH maintenance procedures. Finally, the stress map of the Irradiation operation (Fig. 8 *left)* design scenario shows two high-stress areas around the leg. Nevertheless, the values are overall suitable for further analysis of this structure. The high membrane and bending stresses that occur during warming up (Fig. 8 *right*) design scenario show that implementing a rib structure is necessary to withstand the vacuum load.

4. Detailed design

4.1. Quench tank vessel

The design process prioritized the outer structure. The internal dimensions of the QT have not been modified. Several analyses focusing on hydrodynamic performance have demonstrated a suitable hydrodynamic performance [11]. This confirms that the internal geometry effectively quenches the high lithium flow into a smoother and lower flow.

To evaluate the different rib structure ideas during the design process simulations with the loads corresponding to Warming up and Irradiation mentioned in Table 1 were conducted. By that, a final version was created which can be seen in Fig. 9. The proposed design features

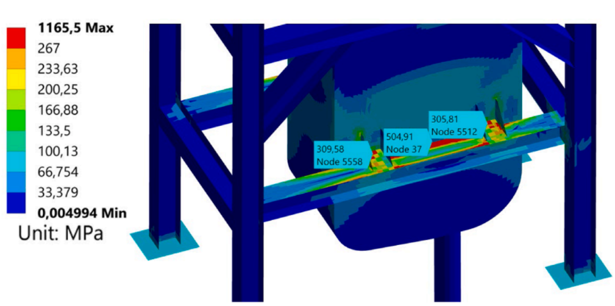

Fig. 7. TAS version stress plot.

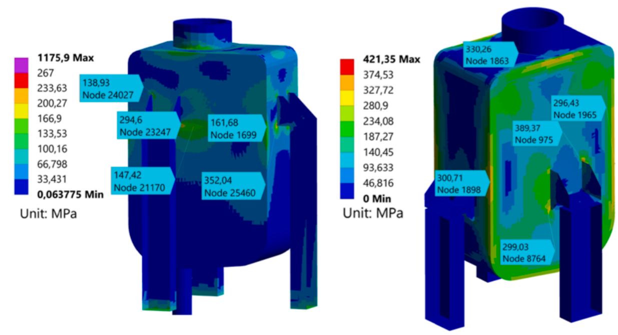

Fig. 8. 3-Leg version simulation results.

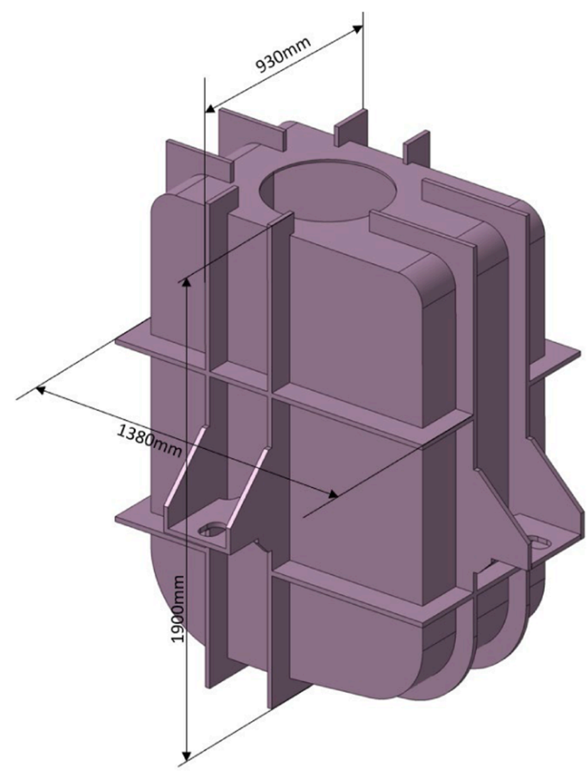

Fig. 9. Quench tank vessel size.

horizontal and vertical ribs to reinforce the outer structure, hence reducing membrane stress along the QT wall. Furthermore, horizontal ribs also ease the thermal insulation installation RH process (Fig. 10).

All the ribs are uniformly 20 mm thick and welded to the vessel's body. During the design process, pursuing a rib placement that can also serve as the connection point of the legs was also a key point. In this way, the welding connections can be minimized on the vessel's wall. The connection point of the legs was lowered to the stored Lithium's center of gravity to reduce the stress on the connection point of the legs in case of any seismic event.

During the design of the connections, the first objective was to present a design that allowed the heat expansion of the vessel. Secondly, the QT should be removable independently of the legs, easing the RH procedure in case of malfunction. The proposed connection solution consists of a conical positioning pin welded on the top of the legs that will position the QT, and a fixing cap will restrict the movement in the vertical direction. The oval-shaped holes on the vessel's connecting part will allow the structure to expand to a limit when it is at operating temperature (Fig. 11).

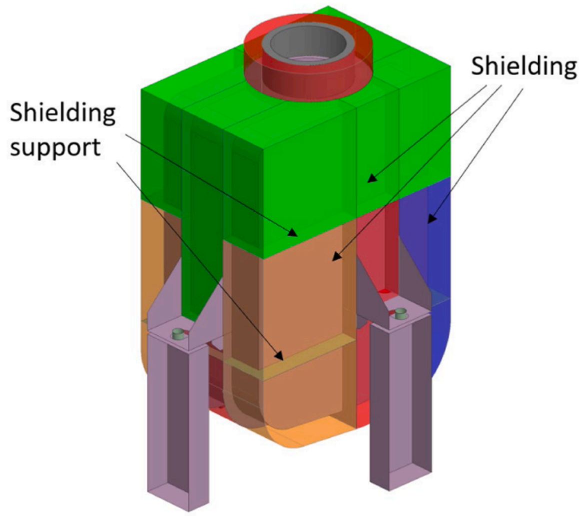

Fig. 10. Proposed QT *heating-insulating system* segmentation.

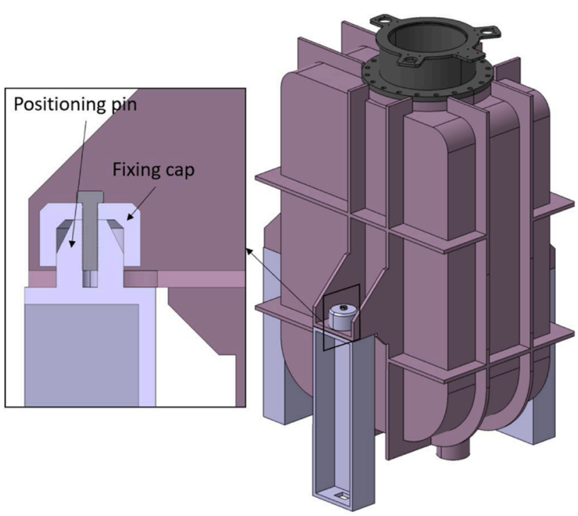

Fig. 11. Sliding support.

4.2. Outlet plug assembly (OPA)

The Outlet Plug Assembly accommodates the penetration of the Lithium outlet pipe from the QT, through the Test Cell floor, to the EMP (Electromagnetic Pump) allocated in the Lithium Loop Cell. The OPA consists of several layers, this includes the seamless pipe neutron shielding segments and thermal insulation with cladding.

Several optimization steps have been carried out in recent years, pursuing a cost-efficient solution and meeting the design requirements. According to the last design (see Fig. 12), the shielding consists of two parts of a stainless-steel seamless pipe (in essence a dog-leg), one is attached to the Lithium outlet pipe and the other to the TC Liner and they have a small overlap in the vertical direction against neutron streaming. The arrangement also accounts for manufacturing and assembly errors ensuring a minimum gap between the OPA surface and the TC Liner taking into consideration the heat expansion.

Pyrogel XT has been selected as a thermal insulation [12] of the lithium outlet pipe. On the top section of the pipe, it is around the shielding, and below, it only covers the Lithium pipe. On the thicker upper part due to the shielding, six layers, and on the lower part three layers of insulation should be installed. On top of the insulation layers, a thin (5 mm) metal cladding protects the insulation on the outlet pipe.

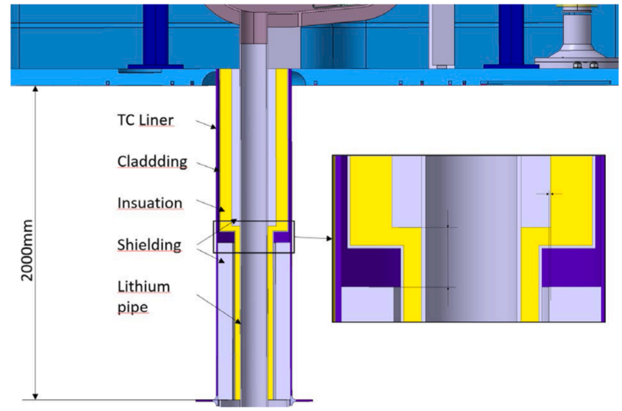

Fig. 12. Outlet plug assembly section.

4.3. Quench tank analysis

Several thermo-mechanical analyses of the Quench Tank and Lithium Pipes were conducted in the past [11]. This section revisits and refines those studies, using an updated ANSYS Finite Element model to optimize the design and ensure structural integrity under different scenarios.

In this analysis, shell elements are used for the numerical model of the final design, allowing the evaluation of primary membrane and bending stresses without the need for a stress classification method. Fatigue loads caused by the commissioning-operating cycle and seismic events are negligible as the load cycles are in the order of 100 cycles.

The inlet bellows and the OPA bellows' were modeled with springs. In both cases, one end of the spring is fixed, and the other is connected to the corresponding geometry (QT inlet flange and Lithium outlet pipe segment). The QT-leg connections allowed sliding movement in the X and Y directions denoted by the axis system and rotation about the positioning pin's axis. The end of the Lithium pipe is fixed by a cylindrical constraint that allows movement of the pipe along the X direction (Fig. 13).

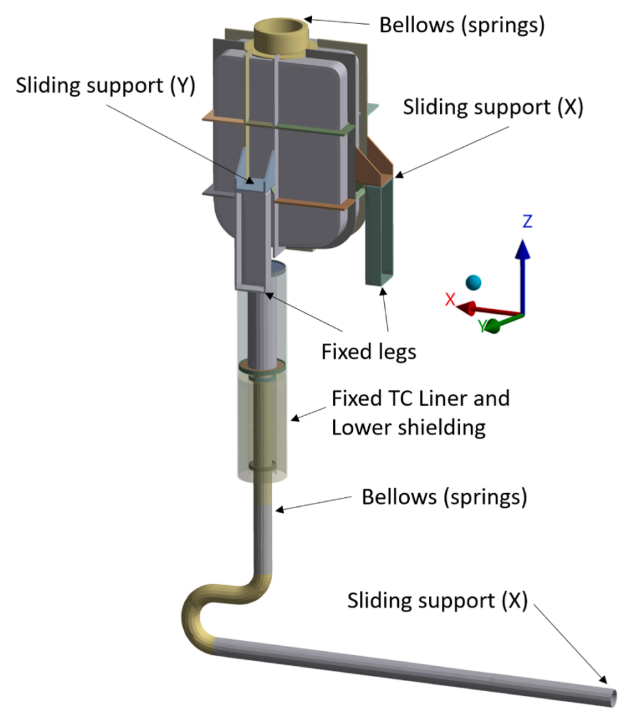

Fig. 13. QT Model.

A CFD simulation of the whole TC cavity including the TC liner and the components housed inside is ongoing (an updated investigation for two-beam case based on a previous calculation) [13]. An intermediate heat map of the QT has been extracted as input for this simulation. The heat map accounts for nuclear heating, Lithium convection heat load, and convection by connecting structural elements.

Using the imported heat map a steady-state thermal simulation was conducted to obtain heat loads for the new rib structure. (Fig. 14). Finally, the heat map is implemented on the structural model.

The lithium inside the QT and the outlet pipe were modeled with four point masses as a simplification (avoiding dynamic behavior), connected to the corresponding section of the structure. The heating-insulating system was applied to the Li pipe and the QT as distributed mass (Fig. 15) (as it does not contribute to structural stability).

In the case of the Warming up scenario, a uniform 350 °C temperature field is used as an input for the static structural model. The constraints are the same as for the normal operation, the lithium and the heat map were excluded from this model since the Warming up happens prior to filling up the Lithium loop. (Fig. 16).

4.4. Design requirements

The RCC-MRx is a widely used French code that describes design and construction rules for mechanical components of nuclear installations. Although the IFMIF-DONES is not considered a nuclear-graded facility, and therefore following the RCC-MRx design code is not mandatory, some aspects will be used during the design procedure as a guideline for evaluation. This code classifies damage mechanisms into two main types: P-type damage (Progressive-type damage) and S-type damage (Sudden-type damage). These classifications help in understanding how materials degrade under specific conditions.

In an irradiation environment, neutrons could, at moderate temperature, generate displacement of atoms and transmutation that could lead to changes in the material's properties. Earlier neutronics calculation [14]showed that the amount of irradiation damage for 20 years would lead to 2.4 dpa (two-beam case approximated by doubling the result for one beam case) at the top part of the QT which is the closest to the source. The RCC-MRx code states that irradiation is insignificant below 2.75 dpa and 375 °C for SS316L (RCC-MRx Table A3.1S.32). Lower parts of the QT experience even less irradiation. Operating at maximum 350 °C the structure is in the negligible creep region (below 450 °C for SS316L).

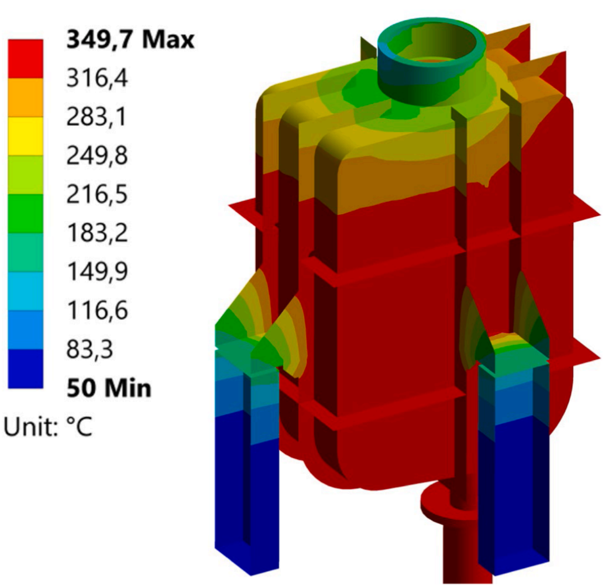

Fig. 14. QT Heat Map (Heat load of lithium and volumetric heat load from irradiation).

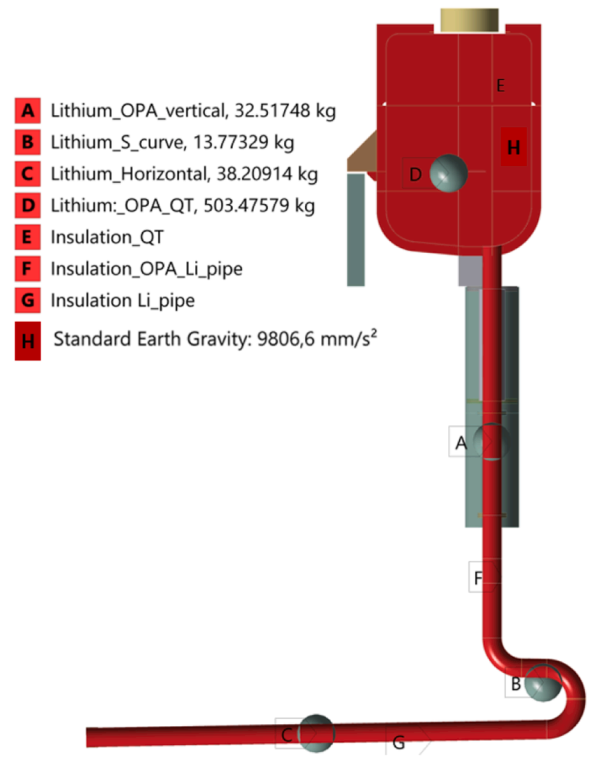

Fig. 15. Mass loads distribution in the model.

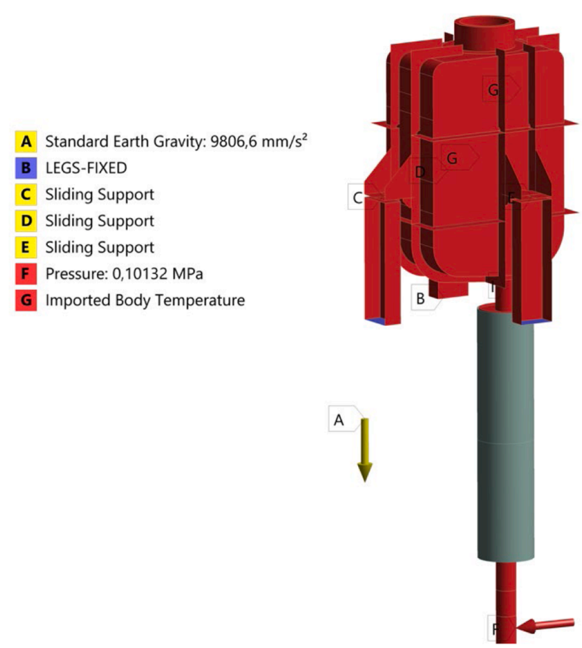

Fig. 16. Warming up simulation loads and constraints.

The material selection for the QT is Stainless Steel 316 L and the allowable stress (S_m) temperature dependence for SS316L solution annealed parts at 350 °C is 89 Mpa. Choosing Tungsten Inert Gas (TiG-method 141) welding, the corresponding welding factor for this welded joint using 19Cr12Ni2Mo as filler metal is $J_m = 1$ (RCC MRx table A9. GEN.11a). A geometry-dependent welding factor $J = 1$ was selected (RCC MRx RD3355.1a) based on the type of welding that connects the ribs and the leg mounts, (RD 3334.3a) and the ability to check the welds with volumetric examination.

4.4.1. Primary loads

Damages called "P-type damages" are those which could result from applying constantly increasing loads to a structure:

- excessive deformation
- plastic instability
- fracture

Elastic criteria for P-type damages are the following in case of negligible creep and negligible irradiation:

$$P_m \leq S_m; \ P_l \leq 1,5 * S_m; \ P_l + P_b \leq 1,5 * S_m$$

Where P_m, P_l, P_b and S_m are primary membrane stress, local membrane stress, bending stress, and allowable stress.

The primary loads consist of:

- Structural weight (SW)
- Insulation weight (IW)

4.4.2. Secondary loads – design scenarios

Damages called "S-type damages" are those which could only result by repeatedly applying loads:

- progressive deformation
- fatigue

Elastic criteria for S-type damage are the following in case of negligible creep and negligible irradiation:

$$P_l + P_b + \Delta Q \leq 3 * S_m$$

Where ΔQ is the secondary stress range.

The design scenarios consist of all primary loads and the corresponding secondary loads to each load case:

- Lithium weight (LiW)
- Hydrostatic pressure (HP)
- Heat load due to Lithium (HLL)
- Heat load due to irradiation (HLI)
- Pressure load during Warming up (PL)
- Heat Load during Warming up (HLW)

4.4.3. Irradiation operation – load case analysis

Results show that Primary loads do not cause significant stress in the structure (Fig. 17 and Fig. 18).

In the case of Irradiation operation, secondary membrane + bending stresses ($\boldsymbol{P_l + P_b}$) do not exceed the allowable stress (S_m) (Fig. 19).

After conducting simulations with the Irradiation operating conditions, the deformation Li pipe gap shows that the metal cladding of the thermal insulation is only 6–8 mm away from the TC Liner's walls (Fig. 20 left side). This gives the idea of protective rings, applied on the Lithium pipe. Investigating the deformation field of the vessel, results showed a maximum of 4.7 mm deformation at the single leg sliding connection, and a 7.15 mm deformation at the bellow connection, which is acceptable (Fig. 20 right side).

4.4.4. Warming up – load case analysis

Only the secondary load case has been investigated during the Warming up scenario as the primary loads are the same as for the Irradiation Operation. No area exceeded the allowable stress (S_m)(Fig. 21).

4.4.5. Primary and secondary stress comparison

For primary loads, the highest primary membrane stress is at a rib connection, and the highest membrane and bending stress is at the Li pipe-rib welded area so the selected welding factors should be included in the allowable stresses. For the secondary load cases, high-stress points occur in welding areas, so the factors are also included in Table 2.

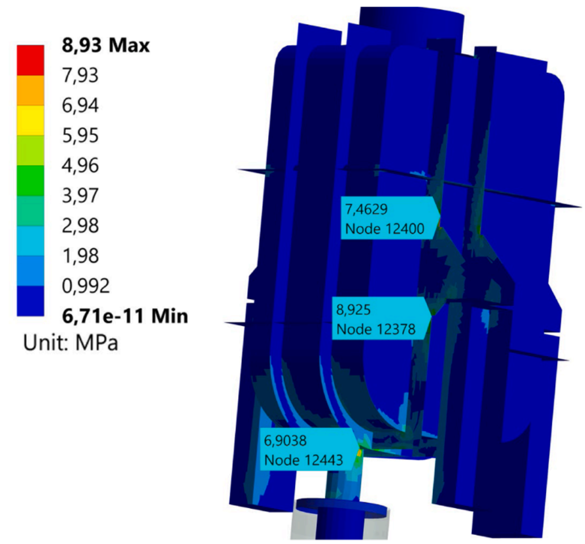

Fig. 17. Primary membrane stress ($\boldsymbol{P_m}$) due to Primary Loads (SW + IW).

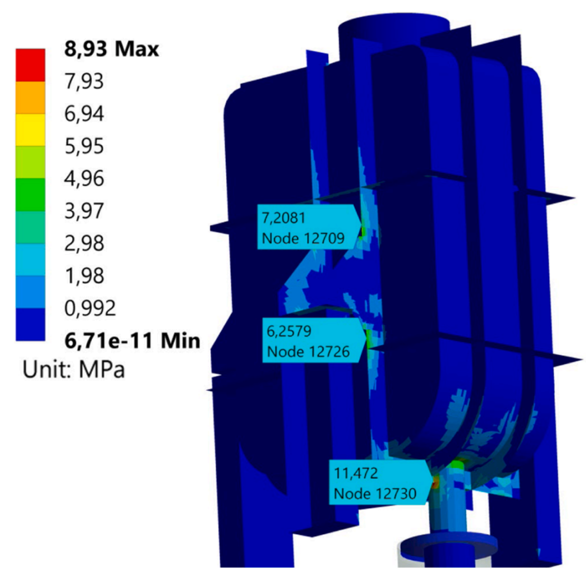

Fig. 18. Local membrane and bending stress ($\boldsymbol{P_l + P_b}$) due to Primary Loads (SW + IW).

5. Rib assembly proposal

An assembly order is presented for the updated rib structure, which also considers the implementation of a welding procedure (Fig. 22). The numbers corresponding to the colors represent the steps of the assembly. After the structure has been finished (Fig. 22 *left), it* should be welded to the quench tank's lower part with an already welded Li pipe section to the QT in an upside-down position, then it should be turned upwards so that the rest of the ribs can be finished at the top.

6. Conclusions

In this paper, a new design proposal was presented by considering different aspects of the QT structure such as structural integrity, RH compatibility and availability, and seismic stability. First, by evaluating

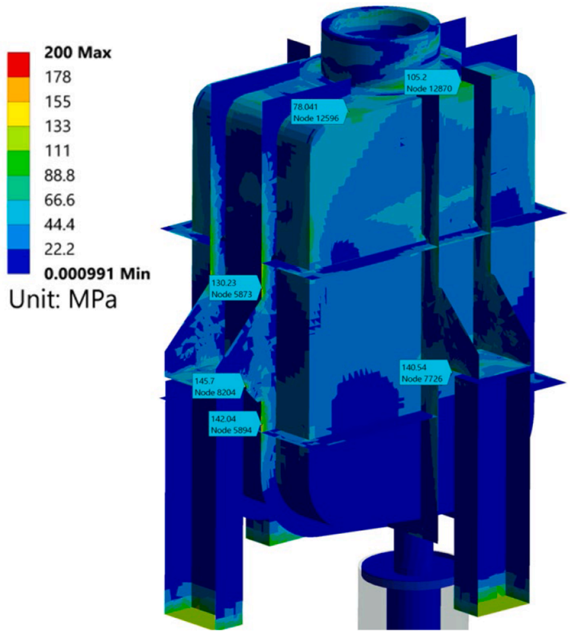

Fig. 19. Local membrane, bending stress and stress range ($P_l + P_b + \Delta Q$) range during Irradiation Operation due to secondary stresses (SW + IW + LiW + HP + HLL + HLI).

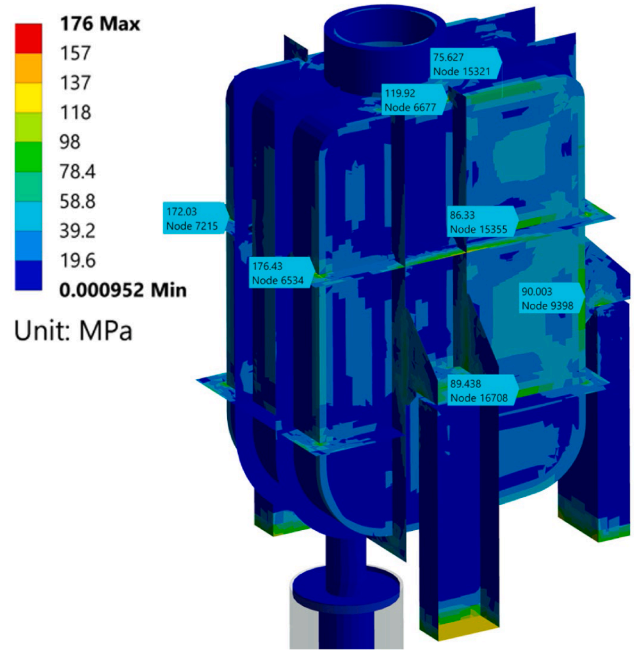

Fig. 21. Local membrane, bending stress and stress range during Warming up ($P_l + P_b + \Delta_Q$) (SW + PL + HLW).

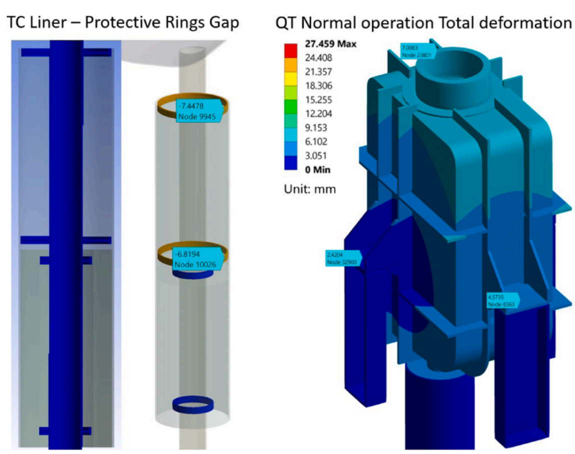

Fig. 20. TC Liner - Li pipe gap and QT deformation.

different support structures analyzing simplified models, and conducting simulations with them, a selection was made of the 3-leg version.

Second, a detailed 3-leg model was presented including the design ideas behind the proposed rib structure. Furthermore, the leg connection was designed to accommodate the heat expansion of the vessel during operation and to be compatible with RH installation. Then the selected support structure was evaluated with simulation models corresponding to each design scenario. In all cases, the stress did not exceed the allowable limits and thus the design is eligible.

7. Next steps

To investigate the proposed structure further and validate its eligibility, a detailed design and simulation should be made focusing on the connection areas. The first task would be the existing Leg-QT connection's current part design investigation and modification in favor of RH tool compatibility. Secondly, a Leg-TC Liner connection should be designed. Aiming to make a design that not only fixes the legs but also considers the positioning of them during installation on the TC Liner floor, will greatly support the RH operations. Following the proposed ideas about the connections, a Leg-QT and a Leg-TC Liner finite element solid sub-model should be created using the results of the QT shell model.

Furthermore, performing simulations including seismic loads can contribute to validating the mentioned seismic stability in the Conclusions paragraph. Considering the simulation results, RH compatibility could be advanced further with modifications of the rib structure that allow tr reduce the number of heating-insulating system segments on the QT vessel.

Table 2
QT weak points analysis.

Load Cases	P_m [MPa]	$P_l + P_b$ [MPa]	$P_l + P_b + \Delta Q$ [MPa]	S_m [MPa]
Primary	8.925	-	-	75.65
Primary	-	11.472	-	113.47
Irradiation Op. Secondary	-	-	145.7	226.95
Warming up Secondary	-	-	176.43	226.95

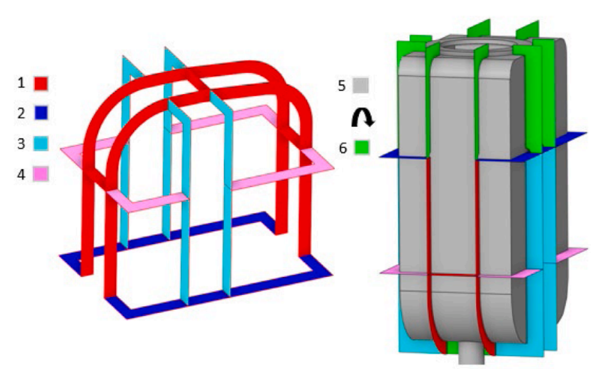

Fig. 22. Proposed Rib Assembly procedure.

CRediT authorship contribution statement

D. Ferenczy: Writing – original draft, Methodology. **A. Zsákai:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **T. Dézsi:** Validation, Methodology. **D. Oravecz:** Validation, Methodology, Conceptualization. **F.S. Nitti:** Validation, Supervision. **J. Maestre:** Writing – review & editing, Validation, Supervision, Formal analysis. **A. Ibarra:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Daniel Ferenczy reports financial support was provided by European Consortium for the Development of Fusion Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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