Force cooled quench tanks for the ITER cryogenic system

G Kouzmenko1, M Simon1, S Saulquin1, J Buskop2, T Voigt2, E Monneret2, D Grillot2, M Cursan2, D Pichot2, G Demar3

1Fusion for Energy. C/ Josep Pla 2, Torres Diagonal Litoral, 08019 Barcelona, Spain
2ITER Organization. Route de Vinon-sur-Verdon, 13067 St. Paul-lez-Durance, France
3Air Liquide Global E&C Solutions (France). 57 Avenue Carnot, 94500 Champigny-sur-Marne, France

Grigory.Kouzmenko@f4e.europa.eu

Abstract. The toroidal field magnets of ITER contain over 7 tons of helium. Most of the inventory is expelled from the magnets in case of a quench and it needs to be captured in external storage vessels (Quench Tanks). Force cooled technology with external gas circulation was chosen for these vessels in order to optimize their footprint, risks, and costs. This paper outlines the input data, assumptions, and studies performed in order to choose the most appropriate technology for the Quench Tanks. Further studies to demonstrate feasibility and ensure the required performance, as well as some peculiarities of the design and manufacturing of Quench Tanks are also described.

1. Introduction
The net helium inventory of the ITER cryogenic system amounts to about 24 metric tons. A substantial part of this inventory is concentrated in the coils of superconducting magnets which are intended to confine and shape plasma inside the tokamak [1]. During a possible accidental loss of superconducting state of the magnets (quench), most of the He inventory contained will be rapidly expanded and shall be promptly evacuated to prevent excessive pressure increase. Expelled He has to be captured and subsequently used for the re-cooling of magnets as He is quite an expensive commodity, to such an extent that global He supply problems are predicted by some researchers if its operational losses continue to be substantial [2]. Apart from capturing gas during a quench event, the Quench Tanks shall also be used for storing part of the He inventory during ITER system maintenance, when it is necessary to remove gas from the system and keep it in a storage for prolonged periods of time (months). During these storage periods most of the ITER cryoplant equipment is shut down and therefore Quench Tanks are to be able to operate in an autonomous mode.

Different technologies exist for capturing He gas rapidly exiting superconducting magnet systems ranging from conventional low pressure inflatable soft room temperature storage (gas bags), which are impractical for the given amount of He, to complex low temperature and high pressure vessels of a different design (Quench Tanks). All possible options were analyzed in preparation of ordering equipment to choose an optimal solution for capturing He gas from the ITER superconducting magnets.

This paper first outlines the design input data and assumptions for the Quench Tanks. The studies performed to choose the most appropriate design solution for the Quench Tanks are then presented. The chosen design and associated validation studies to demonstrate feasibility and ensure the required
performance are also described, as well as some of the peculiarities in design and manufacturing of the Quench Tanks.

2. Input data and assumptions
F4E, the European Joint Undertaking for ITER and the Development of Fusion Energy, is an organization created, in particular, to provide ITER with the European in-kind contribution, including equipment of LN2 Plant and Auxiliary Systems, and Quench Tanks as a part of it. Following the analysis of the overall He storage system performed by F4E [3] the next two major purposes for Quench Tanks were defined:

1) Capturing the large amount of cold He gas released from the system in the event of magnets' quench or fast energy discharge and storing it until it is recovered by He cryoplants.

2) Storing part of the total system inventory of He during the non-operational phases.

There are several possible scenarios for the quench of ITER superconducting magnets. One of the most severe of these scenarios chosen by the ITER magnets team represents the simultaneous quenching of all toroidal field magnets, which leads to the need to evacuate their inventory within 120 seconds. The total mass of He evacuated in these circumstances is about 7 tons with a peak flow estimated at over 100 kg/s and a fast cooling of the incoming He gas from room temperature down to ~20 K.

Operation of the ITER machine is planned in several stages with long shutdown periods in between the stages intended for upgrading the machine. During these shutdown periods the entire He inventory shall be removed from the ITER machine and distributed for storage between different elements of the storage equipment (liquid He tank, gaseous He tanks, and Quench Tanks) [4]. This sizing case was also studied and additional requirements on pressure and average temperature of the gas in the Quench Tanks during the storage mode were defined in order to meet the overall storage requirements.

The Quench Tanks were specified as double-walled, multi-layer or perlite insulated vessels with the inner vessel forced cooled to <86 K (average temperature) in the storage mode. The total volume of these vessels is 720 m³ in order to fulfill the requirements on capturing quench gas and storing inventory. The nominal operational pressure is 0.12 MPa-a in stand-by mode (i.e. ‘waiting for quench’) and up to 1.8 MPa-a in storage mode. The latter value is dictated by the operational pressure of ITER 80 K gaseous He circulation loops which are used to supply the inventory to be stored into Quench Tanks. The design pressure of the Quench Tanks is 2.0 MPa-g. Providing two identical tanks was found to be an optimal solution from the installation layout and transportation limitations points of view. Several additional requirements were also defined, including maximum allowable heat loads (to optimize operational costs), flow and allowable hydraulic resistance for the incoming gas and other parameters. Contract for the supply of LN2 Plant and Auxiliary Systems (including Quench Tanks) was awarded to Air Liquide E&C Solutions – ALE. The supplier was requested to justify the choice of equipment and propose adequate technical solution meeting all specified requirements.

3. Design considerations
F4E performed an extensive analysis of possible design options for the Quench Tanks in preparation for ordering equipment. All the options could be grouped into two categories: ‘warm’ design and design with active cooling foreseen. A brief summary of considered options and identified advantages and disadvantages is given in the section below. Following this analysis it was decided to exclude all ‘warm’ options and take active cooling as a baseline, allowing the equipment supplier to make a final choice of the technology based upon technical feasibility and cost optimization factors.

3.1. ‘Warm’ design
‘Warm’ design looks quite attractive as Quench Tanks are completely passive and simple in construction, requiring no thermal insulation. The main disadvantage of this simplicity is an increased volume and footprint comparing to the options with active cooling. Besides, cold gas enthalpy is
difficult or impossible to recover, which increases the operational costs. The following options were taken into initial consideration but disregarded following the analysis:

- Quench Tanks with measures taken to avoid local cooling of the wall (e.g. gas diffusers). Gas, entering Quench Tanks made out of carbon steel, can have temperature way below brittle transition. Therefore, even if the total available enthalpy of carbon steel is sufficient to reach a final equilibrium above the brittle transition temperature, special measures shall be foreseen for even distribution of cold gas around the vessel and avoiding ‘cold spots’. This approach was taken for the LHC cryogenic system at CERN [5]. However, the total mass and mass flow of cold gas to the Quench Tanks of the LHC system is much smaller (comparative to ITER) due to the large volume of a distributed quench line which can contain ~80% of the total magnets inventory in each sector without releasing gas to the Quench Tanks
- Quench Tanks manufactured from stainless steel. Although this option obviously eliminates the problem with a potential brittle fracture of tanks, it was disregarded based on the high cost of this solution
- Quench Tanks with external or built-in regenerators. Another method which helps to avoid brittle fracture of carbon steel is the use of external or built-in regenerators with a high heat capacity in order to warm incoming gas up to nearly room temperature. An additional advantage of this option is the possibility to partially recover cold gas enthalpy as gas can be returned to the system via regenerators. However, for the required mass flow of incoming gas, the expected frequency and unpredictability of the quench, the system of regenerators becomes too big, complex and expensive.

3.2. Active cooling

An alternative solution to the warm tanks is the use of cryogenic vessels, actively cooled to ~80 K. The common advantage of such type of solution is the reduced footprint and potential cost reduction due to a decrease in equipment size and savings on operational costs due to the recovery of gas enthalpy at 80 K level. The disadvantages are linked to the higher complexity of the equipment and the introduction of permanent operational costs due to active cooling.

Following the studies performed by ALE no directly applicable industrially-proven reference has been identified for actively cooled cryogenic tanks over 150 m³. Several technical solutions have been proposed and the use of an external cooling circuit (as described in section 3.2.3) is selected as the baseline solution.

3.2.1. Quench Tanks with inner pressure vessel cooled by independent cooling loop. This option foresees attaching an independent cooling loop to the inner pressure vessel either directly (e.g. by welding, brazing or placing a heat exchanger inside the inner pressure vessel) or via a thermal bridge. Liquid N2 (directly from ITER LN2 plant) or cold gaseous helium is supplied to this independent cooling loop in order to cool it down and keep the inner vessel and gas contained within it cold. Direct LN2 cooling option was discarded due to the high risk of LN2 freezing after a quench with subsequent uncontrolled expansion on warming up.

This solution was discarded due to risks associated with:

- Complexity of manufacturing and inspection operations during assembly
- Possible poor performance of the cooling loop leading to a temperature higher than 86 K in storage mode
- Risk of damaging the cooling loop during cool-down or operation which can cause leaks without any access for maintenance

3.2.2. Quench Tanks with independent LN2 cooled thermal shield. In this design option the vessel is built in a similar way to any LN2 shielded cryogenic storage. This allows avoiding the risk of LN2 freezing described above (as LN2 is not in direct contact with the inner pressure vessel), however it
substantially increases equipment complexity and cost and requires additional measures for initial vessel cooling down in preparation for operation.

This solution was discarded due to risks associated with:

- Necessity to support high inner vessel weight – dictated by the combination of large volume (360 m³) and high design pressure (2.1 MPa) – within the shield
- Weak thermal link between the shield and inner vessel which might lead to not meeting design specifications on the maximum allowable temperature during the operation
- Manufacturing complexity and lack of references of the solution for the given size and design pressure of the equipment
- Necessity of extensive follow-up of design and manufacturing

3.2.3. Quench Tanks with gaseous He circulation through the inner pressure vessel. The design of the Quench Tanks in this option is considerably simplified comparing to options 3.2.1 and 3.2.2. Gas is taken from the inner pressure vessel, cooled down by liquid N2 and returned to the inner vessel. This is done by means of an independent gas circulation loop. There is a risk of gas thermal stratification inside the inner vessel, which could substantially reduce effective storage capacity; therefore thorough thermal analysis of the solution is required.

4. Design of Quench Tanks and cooling loop

Following the industrial feasibility studies conclusion, two 360 m³ double walled perlite insulated vessels were ordered from an industrial tank supplier – Chart Ferox (Czech Republic). Design and procurement of the external circulating loop was provided by Air Liquide Advanced Technologies (France).

4.1. Quench Tanks

There were several potential issues to be solved during the design and manufacturing of the Quench Tanks. Two of the most important issues are:

- Guarantying a robust design of the vessel for all conditions, including quench with high gas flows entering the inner vessel, as well as for seismic events and other operational and accidental loads
- Minimizing heat loads onto the inner vessel, caused by supports, piping and gas in the incoming line

4.1.1. Robustness of the design. During the quench of ITER magnets very large quantities of gas enter into the inner vessels of the Quench Tanks within a short period of time. Maximum total mass flow of gas can be on order of 100 kg/s and the time in which all gas shall be collected inside the Quench Tanks is just about 2 minutes. Therefore, within this period of time, the pressure inside the inner vessels will change from atmospheric up to ~2 MPa, and the temperature of entering gas varies from nearly room temperature (due to the fact that long quench line between magnets and Quench Tanks does not have active cooling) to ~50 K or even lower. This induces stresses on the inner vessel.

Thus, apart from the usual verification of the Quench Tanks according to applicable design codes, additional extensive studies were performed by the manufacturer in order to demonstrate that this design is suitable for all unconventional operational demands. These studies included FEM steady-state seismic analysis, thermo-mechanical analysis for highly dynamic quench conditions for the vessels and piping, natural frequency analysis, mechanical verification of vacuum barriers, modal analysis of internal gas collector, etc. An example of the results of the thermo-mechanical analysis for the inner vessel and piping is given on the Figure 1. Previously calculated temperature and pressure profiles for the quench event were used in the analysis, so that stresses in typical sections (localized in areas of expected higher stress concentration) could be calculated in quasi-static states. The results demonstrate that stresses remain within acceptable limits in accordance with EN-13458 standard.
Figure 1. Example of maximal linearized secondary membrane + bending stress in typical inner vessel sections during quench event.

Combinations of all possible loads (pressure, seismic, wind, snow, etc.) were grouped into several categories (normal and accidental loads). Requirements and associated criteria are defined depending on the category into which an event falls. Additionally, all systems at ITER are classified differently depending on their relation to the core machine safety protection. Although cryoplant components at ITER (including the Quench Tanks) are generally not classified as safety relevant, some safety requirements were made applicable to the Quench Tanks. This led to a more stringent than usual seismic specification and the necessity to perform additional studies to demonstrate compliance with it. Special considerations were given also to a scenario of accidental rupture of the inner vessel or He inlet pipes and possibility to avoid consequential pressure build-up in the annular insulation space which might lead to a rupture of the outer vacuum casing.

4.1.2. Minimizing heat loads onto the inner vessel. Quench Tanks are double walled cryogenic vessels with vacuum perlite insulation. The contribution of insulation to the overall heat load mainly depends on the size of the annular gap between the inner and outer vessels, the level of vacuum in the insulation space, and the quality of the perlite filling (even perlite density to minimize or eliminate void spaces). The annular gap sizing is limited by the sizing of the outer vessel based on the manufacturer’s experience for vessels of similar design. A good vacuum in the insulation is achieved due to careful vacuum space preparation and consideration of vessel sizing in the design of the evacuation system. The quality of perlite filling is guaranteed by the manufacturer due to experience and use of special equipment and tools.

Requirements to the robustness of the design usually come into contradiction with the requirement on limiting heat loads to the inner vessel. The manufacturer completed a thermal performance analysis for the Quench Tanks and proposed specific design solutions for minimizing heat loads where possible. In particular, a specific design was proposed for the large diameter piping for the incoming quench gas so that heat loads by conduction and gas convection are minimized and contribute only
~3% to the overall heat load, whilst still keeping an acceptable hydraulic resistance. Occurrence of thermo-acoustic oscillations is prevented in the proposed design.

Due to the proprietary design of the supporting system using composite materials, its contribution to the overall heat load is also limited with fixed support contributing to 27% and remaining supports to 9% of the overall heat load. The heat load through the vacuum perlite insulation remains the largest contributor (61%) to the overall heat load, which remains within the specified value (1500 W per tank) including some margin.

4.2. Quench Tanks cooling loop

All equipment for circulation as well as interconnecting piping and valves are installed in a separate vacuum insulated cold box common for the two Quench Tanks. Active cooling is provided by means of a helium-LN2 thermosiphon heat exchanger (see Figure 2 for simplified PFD). Gas is extracted from the inner vessels by a cold circulator, cooled in a heat exchanger and returned into the Quench Tanks. A back-up circulator is installed to ensure availability of the system. In this way the overall Quench Tanks system requires only a supply of 20.4 g/s of liquid N2 (from a large operational storage tank available on-site), a small electrical supply (13.5 kW) and a very modest amount of cooling water (0.07 kg/s). Thus the system can remain fully autonomous for prolonged periods of storage time.

![Figure 2. Simplified PFD of QTs and circulators’ cold box.](image)

There were several potential issues to be solved during the design and manufacturing of the cooling loop, and in particular:

- Ensuring efficient operation for both storage and stand-by modes, as well as making the necessary provisions for transient operations, including cooling down and warming up
- Protection of the cooling loop equipment during a quench
- Minimizing gas stratification inside Quench Tanks

A brief description of the solutions adopted for the above issues is given below.

4.2.1. Operation in both storage and stand-by modes

One of the potential risks for the solution with GHe circulation is the necessity to operate the circulation loop in both stand-by (at near atmospheric
pressure) and storage (at ~1.8 MPa-a) modes. The system is equipped with cold circulators which are standardly manufactured by Air Liquide Advanced Technologies. The average temperature requirements are relaxed for the standby mode (~100 K) as opposed to the storage mode because during a quench, the average incoming gas temperature is actually much lower than 80 K. It was demonstrated by numerical calculations that for an initial inner vessel temperature in stand-by mode of 100 K, the resulting temperature of the tank after the quench is ~80 K. It is therefore possible to decrease the circulator mass flow in stand-by mode (at lower gas density). The circulators are equipped with magnetic bearings and variable frequency drives (VFD) allowing to change the rotational speed between storage and stand-by modes and cover the full operational pressure range (see Figure 3).

![Figure 3. Cold circulator working points on the operating map.](image)

4.2.2. Protection of cooling loop equipment during quench. The pressure inside the Quench Tanks increases rapidly during a quench. In order to protect circulators and other equipment inside the cold box, fast acting shut-off valves are activated on detection of a rapid pressure change.

4.2.3. Minimizing gas stratification inside Quench Tanks. Thermal stratification inside the inner vessels of Quench Tanks can occur due to a large volume of gas and considerable vessel dimensions. In case of stratification, the effective capacity of the Quench Tanks would be reduced due to a lower average gas density. To mitigate this risk, several studies using FEA technique were performed at different stages of the project. It was demonstrated that average gas temperature within the tank is $90 \pm 0.2$ K in the stand-by mode and $82.5 \pm 0.1$ K in the storage mode, which is well within the specified values (100 K and 86 K correspondingly).

5. Current state and future steps
The Quench Tanks were manufactured and factory tested by Chart Ferox in the Czech Republic. These vessels are 35 m long, have a diameter of 4.5 m and weigh approximately 160 tons each. The Quench Tanks were delivered to the ITER site at the end of 2016 (see Figure 4) by river / sea transport and then by a road convoy via a special itinerary for ITER equipment. The cold box for the external
circulation loop was manufactured and factory tested by Air Liquide Advanced Technologies and will be delivered on site by the end of summer 2017. Installation of the equipment is planned for 2018.

Figure 4. Quench Tanks after delivery to ITER site in Cadarache.

6. Conclusion
Following extensive design studies, actively cooled Quench Tanks with their associated external gaseous He circulation loop were designed and manufactured in full compliance with stringent ITER requirements. The adopted technology solution is optimized to reach optimal cost and efficiency as well as minimize associated risks and ensure the required robustness of the equipment.

7. References
[1]  Serio L 2010 Challenges for cryogenics at ITER, AIP Conf. Proc. 1218 p 651
[2]  Bradshaw A M and  Hamacher T 2013 Nuclear fusion and the helium supply problem, Fusion Eng. and Design 88 issue 9–10 pp 2694–97
[3]  Kouzmenko G, Simon M, Saulquin S, Buskop J, Voigt T, Monneret E, Grillot D, De La Forterie O, Pichot D and Cursan M 2016 Helium management concept for the ITER cryogenic system Proc. 1st IIR Int. Conf. of Cryogenics and Refrigeration Technology (Bucharest)
[4]  Monneret E, Benkheira L, Fauve E, Henry D, Voigt T, Badgujar S, Chang H-S, Vincent G, Forgeas A and Navion-Maillot N 2017 ITER cryoplant final design and construction IOP Conf. Series: Materials Science and Engineering 171
[5]  Chorowski M, Hilbert B, Serio L, Tavian L, Wagner U and van Weelderen R 1998 Helium recovery in the LHC cryogenic system following magnet resistive transitions, Adv. in Cryogenic Engineering 43 pp 467-74

Acknowledgments
As well as the main procurement contract with Air Liquide Global E&C Solutions (France) and its subcontractor Chart Ferox (Czech Republic), this work has been carried out thanks to a contract with SDMS Technologies (France).