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Overview of the Specialist Assessments Undertaken to Support the JET Safety Case Review

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ABSTRACT

The Joint European Torus (JET) operates using deuterium as a fuel but has also operated in D-T mode where the fusion reaction is fuelled by deuterium and tritium. To justify the safety of the experiments, safety reports are produced and approved. The Safety Case has recently undergone a periodic safety review and preparations are being made to undertake a tritium campaign in 2015. To provide information regarding the compatibility between reactor-grade plasma and the materials facing the plasma, an "ITER-like wall" was installed in JET comprising beryllium first wall tiles, solid tungsten and CFC tungsten coated tiles in the divertor region. In the prospect of the next D-T campaign with the new wall, the following areas of specialist assessment have been identified:

- Engineering Fit for Purpose assessment of Key Safety Related Equipment,
- Human Factor assessment of Key Safety Management Requirement,

This paper will present a status report of these assessments and the methodology applied. Along with the results of a Loss Of Coolant Accident (LOCA) analysis using the CEA developed thermal

1. INTRODUCTION AND BACKGROUND

The Joint European Torus (JET) is currently the largest operating tokamak in the world and the JET programme is a collective activity used by European fusion laboratories and managed by the European Fusion Development Agreement. JET was established with a long-term objective to create safe, environmentally sound prototype fusion reactors. To meet this objective, JET was designed to operate in D-T mode where the fusion reaction is fuelled by deuterium and tritium.

The first D-T Experiment (DTE1) was carried out in 1997. To justify the safety of DTE1, safety reports were produced to obtain approval for the experiments [1], the most significant being the JET Pre-Construction Safety Report (PCSR). The Safety Case has recently undergone a periodic safety review and a new version for 2011 D-D operations has been issued.

This has provided a new D-D specific sub-set of KSRE (Key Safety Related Equipment) and KSMR (Key Safety Management Requirement). Another review is ongoing for the next tritium campaign planned in 2015 which would provide a final set of KSRE/KSMR. Any protection system (engineered system or management rule) which is necessary to ensure that doses to workers or the public are below the Basic Safety Limit (BSL) is defined as a safety mechanism that is KSRE or KSMR. The BSL for determination is simplistically defined as a dose of 20mSv to a worker or 1 mSv to a member of the public. The KSMRs and KSREs are required to minimize, control or eliminate the major hazards on the plant. To justify D-T operations, the KSRE and KSMR need to be shown to be robust, to do this a Human Factor Assessment of KSMR and an Engineering Fitness for Purpose assessment of KSRE are required.

Because the JET Vacuum Vessel (VV) contains complex demineralised water coolant systems for plasma facing components and the divertor, the In-vessel LOCA (loss of coolant accident) has been identified as one of the worst accidental scenarios in each safety case reviews [2]. A LOCA analysis using the CEA developed thermal hydraulics code CATHARE 2 V25-2 has been conducted to update the analysis in the PCSR using "state of the art" software.

2. HUMAN FACTOR ANALYSIS OF KSMR

2.1 BACKGROUND

Table 1 defines the list of the KSMR identified for the DD campaign. For each listed KMSR, a human factor analysis has been conducted.

2.2 METHODOLOGY

The aim is to examine the effectiveness of the Management Requirement and to demonstrate that operator performance in the defined task(s) is acceptable and that plant equipment, task design, organization and environment are sufficient to assure that human error levels are ALARP and that the potential for operator error is minimized.

The typical issues considered during the assessment included the general ergonomics of the task environment, assessment of plant operations, management arrangements, competency and training of staff, emergency alarm handling, suitability of procedures to effectively support tasks and maintenance tasks.

The assessment involved appropriate staffs who are familiar with the situations being assessed. In all cases, staff were encouraged not to have a too 'success oriented' approach. Each report has been internally and independently peer reviewed and commented.

2.3 GENERAL RECOMMENDATIONS

The principal generic recommendation is that the KSMRs should be highlighted in the JET procedures in which they appear so that any modification to these documents would trigger a safety review. This recommendation became an improvement action in the D-D safety review.

Other recommendations included improvement of the tritium inventory awareness by undertaking a specific refresher training program and testing the response to RPI alarms prior to the start of a D-T campaign.

2.4 SPECIFIC RECOMMENDATIONS ON THE KSMR RELATED TO HYDROGEN ISOTOPES INVENTORY LIMIT ON THE CRYOPUMPS OF THE MACHINE

Since the installation of the ITER- like wall, the machine is now equipped with PFC (Plasma Facing Component) mainly made of beryllium. As opposed to the PCSR where the steam-graphite reaction has been ignored in LOCA analysis, the steam beryllium reaction is considered. The assessment of the control limiting the hydrogen inventory trapped on the cryopump panels in the machine during normal operation has been extensively reviewed.

The analysis concluded that the limits on hydrogen isotopes inventory should be reviewed to take into account the dependency of the LFL (Lower Flammability Limit) of hydrogen with temperature and pressure. A conservative approach was taken in evaluating that limit since data on LFL at high temperature and low pressure (relevant fusion devices conditions) are lacking [[3], [4]. The human factor analysis also highlighted the fact that the control of hydrogen on cryopanels should be done by measuring the total amount of gas injected through the gas injection modules – without involving any software calculation for the partitioning of the pulse gas inventory.

3. FITNESS FOR PURPOSE (FFP) OF KSRE

3.1 BACKGROUND

Within any Safety Case, there is a requirement to demonstrate that any and all engineered Structures, Systems or Components (SSCs) claimed as contributing to the achievement of safe operation are able to deliver those roles throughout the lifetime of that Safety Case.

Table 2 defines the list of the KSRE identified for the DD campaign excluding the ones related to non operational hazards.

For each listed KSRE, a fitness for purpose analysis has been conducted.

3.2 METHODOLOGY

The review was carried out in three stages.

Firstly, the KSRE is identified along with its safety functions. This stage also describes the performance requirements limits and conditions. The original standards used to design the KSRE are established. The methodology also provided the technical responsible officers with standards applicable for the KSRE FfP review listed in References [[5], [6]]. The margins available with respect to original design are evaluated, along with dependencies on other systems or operator interaction. This phase of the review also commonly involves plant walkdowns.

Secondly, KSRE current situation is described. The modifications since installation or last FfP are reviewed. The margins available are re-evaluated taking into account the modifications since installation. The ageing mechanisms are identified and taken into account. Reference [5] defines the notion of physical ageing of SSCs resulting in gradual deterioration of physical characteristics and also non-physical ageing (called obsolescence) when they become out of date in comparison with current knowledge, standards and technology. The appropriate consideration of operating experience feedback analysis should be given with respect to ageing. The feedback from the JET machine and others is also reviewed for this analysis. Operational feedback from other fusion devices has been gathered into reports mainly for safety and environmental assessments during the course of ITER engineering design activity [7]. Inspection regimes / results have also been studied. The machine inspection regime is defined in Reference [8]. This document defines for each KSRE the maintenance arrangements, interval and the tracking arrangements along with the responsible group. During the FfP analysis, the defined maintenance interval can be re-defined following the methodology in Reference [6] considering the equipment life stage (initial, maturity, ageing, and terminal).

The third stage deals with the future requirements in terms of operating conditions and effect on the safety function, inspection regimes, life limiting features and described recommendations or proposed modifications.

3.3 GENERAL RECOMMENDATIONS

The FfP reviews highlighted the importance of SSCs identification and control as an essential requirement for an effective program dedicated to the monitoring, prediction, detection and mitigation of plant systems degradation important to safety. The review found that the information describing these components is available however it should be collated in a single common asset register controlled for the machine. Similarly, the functional and physical configuration (design requirements and drawings) of JET are contained within disparate sources and should be brought into controlled design requirements documents. It is therefore proposed that the configurations of KSRE systems could be captured in a post Enhancement Program 2 shutdown baseline for JET and thereafter that configuration control is applied. With regards to maintenance, a great reliance is made on commissioning activities to performance test components. The extent of the use of systematic preventative maintenance should be reviewed to consider lifetime effects on components. It is recommended that a systematic analysis is undertaken on all of the KSRE to determine a targeted inspection program prior to the start of a D-T campaign.

3.4 SPECIFIC RECOMMENDATIONS

KSRE - Removable Shielding Elements and Biological Bulk Shielding. For D-T operation to take place, the shielding calculations for all the modifications carried out since 2003 (year of Trace Tritium Experiment) should be reviewed to ensure that the shielding calculations have taken loss of shielding and sky shine into account.

SRE (Safety Related Equipment) - Drain and Refill System (DRS) (1500Pa vessel pressure and in vessel water isolation). Up to now, the drain and refill has not been used very much and the components have not displayed many failures, if any at all. However, the current maintenance procedure consists of commissioning the plant using existing procedures. It is recommended that as a minimum the components, identified as being in Stage 3 “ageing” (see Reference [6]) of their equipment lifetime or being critical to the operation of the DRS, be disconnected and inspected thoroughly for signs of wear or damage. This includes pneumatic actuators and axial flow valves which are key components of the DRS.

4. SOME RESULTS OF SPECIFIC ENGINEERING ANALYSIS

4.1 BACKGROUND

On the JET machine, the drain and refill system is designed to drain and inhibit the refilling of the in-vessel cooling pipes of the machine after a LOCA due to a pipe break. The original calculations have been done analytically in 1996 and therefore involve some simplifications in the transient heat transfer mechanisms taken into account. As part of the FfP review for the DRS, it was proposed to analyze the accident of water ingress to the plasma vessel with thermal-hydraulic state-of-the-art CATHARE 2 V25_2.mod6.1 code and evaluate the pressure inside the VV as a function of time.

CATHARE is developed by CEA, EDF, AREVA NP and IRSN. It is a thermal hydraulic systems analysis code for all transients and postulated accidents in reactor systems, including both large and small-break LOCA as well as the full range of operational transients. The main hydraulic elements are pipes (1D), volumes (0D) and boundary conditions, connected to each other by junctions. Other sub-modules feature pumps, valves, sinks, sources and breaks. All CATHARE modules are based on a six-equation two-fluid model (mass, energy and momentum for each phase), with additional equations for non-condensable gases [9].

The first fusion related LOCA calculations [10] involved a benchmark to demonstrate the capabilities of the best estimate thermal hydraulic codes to simulate the main physical phenomena occurring during an in-vessel break transient. The pressurization of a volume at low initial pressure, the critical flow, counter pressure effect and relief into an expansion volume (ITER specific) had been calculated. The ITER engineering design activity to assess safety issues associated with LOCAs and loss-of-vacuum accidents (LOVAs) for the non-site specific safety report involved calculations using a modified version of the MELCOR code [11].

4.2 SIMULATION OF THE IN-VESSEL LOCA WITH CATHARE

The systems involved in the sequence are defined in figure 1.

The LOCA sequence is managed as follows on the machine (figure 1). When pressure switches on the VV measure PVV > 1500Pa, some valves close and cut the inlet/outlet flows of the CC. When leakage is confirmed by pressure drop test, the water in the CC is drained in the depressurized tank. When the pressure in VV > 2+04 Pa, the pumping circuit valves are opened. If the pressure in the VV is not reduced by the safety equipment then ultimately when Pvv > Patm + 4500 Pa, the bursting disc will burst. The in vessel water LOCA is a very unlikely event and has never happened in JET lifetime.

From a phenomenological point of view, when an in-vessel liquid water pipe breaks, the plasma disrupts and the CC liquid spreads in the vessel (a on figure 2). A fraction of the liquid water immediately flashes to vapor (b). Some droplets are created in suspension within the hot gas and exchange with it (c). Some water hits the VV walls, streams down and boils on it due to the elevated temperature of the walls (d). The remaining water then fills the bottom of the VV and boils on it (e).

The flashing at the break is well represented in a CATHARE model. The challenge of that modeling was to extend the saturation temperature as a function of pressure below the triple point. This was done by modification of the law initially implemented in the code.

The VV geometry is complex and as a consequence its filling sequence at the bottom is also complex. To simulate this, five “0D- VOLUME” elements have been described and connected. The water streaming down a wall and exchanging heat with it can’t be represented with a two-mesh wall of a “VOLUME” element. Specific CATHARE element (1D pipe) had to be added to the model to simulate that heat exchange. The droplet falling flow rate has been maximized in order to enhance heat transfer in the 1D pipe. The best model in CATHARE was obtained after many test runs. Any compromise in modeling was done by increasing conservatism of the peak pressure in the VV.

Similarly to the modelling approach considered for W7X LOCA [12], it was important to model the cooling circuit to assess the correct boundary conditions for the in vessel LOCA. The analysis involves “standard” CATHARE components and modelling. The pumping circuit is also modelled by “standard” CATHARE elements.All these circuits were explicitly coupled to run the final model.

4.3 MAIN RESULTS AND FURTHER DEVELOPMENTS

Figures 3 illustrates the pressure calculated in the VV, under initial conditions of injected water at mass flow rate and temperature at break similar to the ones taken in the PCSR analysis (temperature 30°C - QFig.4. Pressure in the VV as function of time for two sizes (large – small) break with safety related equipment 2+04 Pa by-pass valves operating or not.2.1kg/s up to PvvFig.4. Pressure in the VV as function of time for two sizes (large – small) break with safety related equipment 2+04 Pa by-pass valves operating or not.1500 Pa and Q = 1kg/s until 100kg of water discharged in the vessel). Only the VV and the pumping circuit are modelled. The pressure rises in the VV until the 1500Pa pressure signal is reached. The time to reach 1500Pa calculated with CATHARE is 7.95s and this compares well with the 7.6s calculated in the safety case. In the first seconds of the break event, the pressure is mainly controlled by flashing which was well evaluated by the PCSR hand calculations hence the good agreement between code model and hand calculations for the initial pressure evolution in the VV.

Some parametric analyses on the whole model have been run. Figure 4 illustrates the pressure evolution in the VV for different size of break and scenarios after the break has been opened at t = 1495s. The "large break" simulates the break on a main pipe of the CC (Ø = 67mm) and the "small break" one on a divertor base plate cooling pipe (Ø = 8mm). A failure in the pumping circuit by pass valves opening, after 2+04 Pa pressure has been reached in the VV, has been studied. For the two break sizes studied, there is a slope change at 2+04 Pa when the pumping line valves are opened. The pressure peak is damped by condensation in the pumping lines and this leads to pressure decrease after drain system managed to cut the flow and drain it into the depressurized tank. When the by-pass valves operate, whatever the size of the break, the VV pressure stays below bursting disc pressure. When the 2+04 Pa safety related equipment does not operate, the simulation shows an increase in pressure of the VV and the maximum pressure could reach bursting disc pressure.

Other parametric analysis both on physical (inlet/outlet temperature, failure of DRS to operate…) and modelling parameters are now being run. The final objectives of these analyses are to firstly assess the limits of the modelling and define validation requirements. The model designed to simulate the streaming water to wall heat exchange could be validated on existing ICE experiments [13]. Secondly the peak pressures in the vessel under different fault scenarios of the safety systems will be evaluated.

CONCLUSIONS AND FUTURE PROSPECTS

The human factor analysis of KSMR and fitness for purpose review of KSRE is an ongoing work which is currently in progress to include the management requirements and equipments defined for the next D-T campaign. This paper presented an overview of the methodology and main conclusions/ recommendations from these analyses. The importance of tritium awareness through review of procedures and training and the emphasis of preventative maintenance has been highlighted for the next D-T campaign.

The first results of the LOCA analysis for in vessel cooling circuit breach with the "state of the art" CATHARE code were presented. Parametric analysis on the physical and modeling parameters have to be conducted to draw final recommendations. The time evolution of the pressure in the vacuum vessel will be used as an input to the calculations of the beryllium-steam reactions to evaluate the impact of the beryllium wall on hydrogen deflagration.

ACKNOWLEDGMENTS

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Safety Requirement	Safety Function
Limit on Hydrogen Isotope Inventory on Cryopumps	To prevent a hydrogen deflagration in LOVA
Evacuation Procedures in the Event of an Radiation Protection Instrument (RPI) Alarm	To minimize operator exposure due to incorrect shielding configuration.
Pre-Operational Shielding Checks	To ensure that all shielding elements are in the correct position prior to pulsing.
Torus building Operational Areas Search	To ensure no-one remains in the Torus Hall prior to the restart of operations.
Interspaces must be pumped, purged and tested for tritium content	To minimize the internal dose to an Operator breaching a diagnostic interspace.
For work requiring full pressurized suit, the number of workers simultaneously drawing air from the breathing air supply system must be limited to 10.	To ensure that the breathing air system is not overloaded so that the full efficiency of the system is maintained.

Table 1: List of KSMR

Safety System	Safety Function Claimed
Area Gamma Monitors	To alert operators to any shielding deficiency and prevent pulsing
PSACS (Personnel Safety Access Control System)	Ensure pulse cannot be initiated until all shield doors and beams are closed and all removable shielding blocks are in place.
Shielding Doors, Beams and Removable Shielding Elements	Reduce operator doses outside a penetrations to as low as reasonably practicable.
Bulk Radiological Shield	Reduce the dose rate outside of the Torus hall to below 0.25 µSv / hour during all operational modes.
Torus Hall Emergency Stop Push Buttons	To allow an operator to prevent a pulse if trapped in the Torus hall.

Table 2: List of KSRE

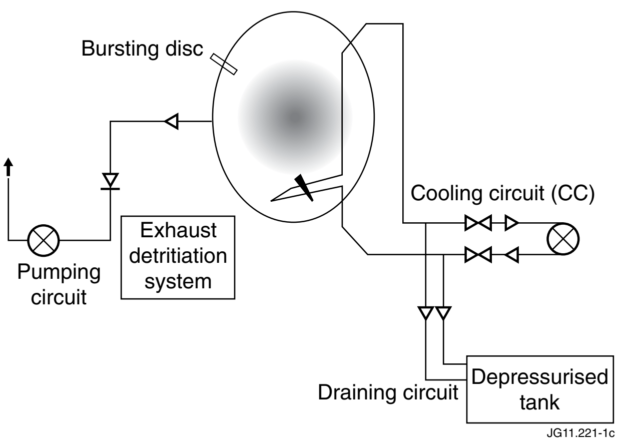

Figure 1: Description of circuits and components for the LOCA scenario.

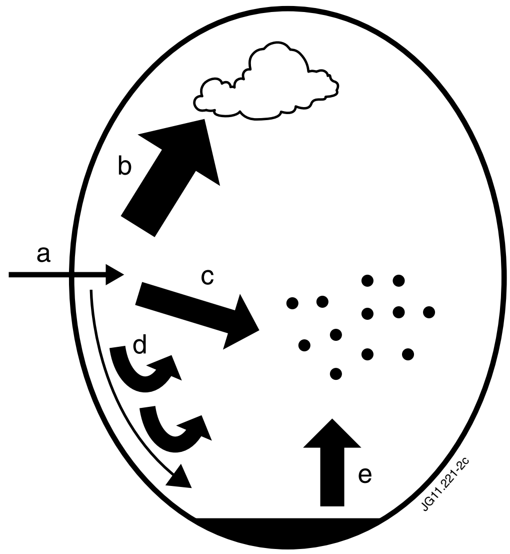

Figure 2: Mechanisms involved in phase transformation of the liquid water after break.

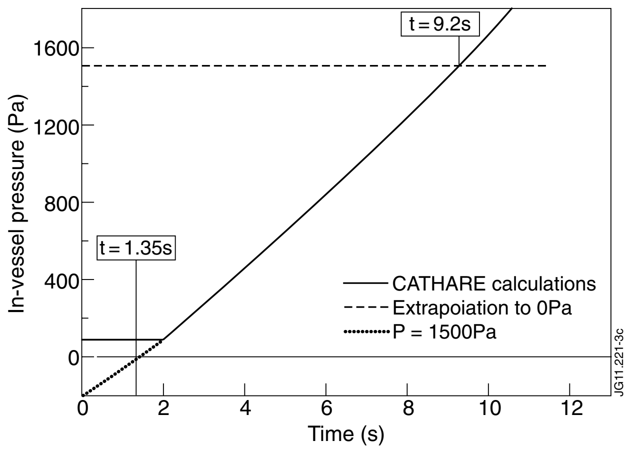

Figure 3: Pressure in the VV versus time (up to 1500 Pa– Qinjected at break=2.1kg/s - temperature = 30°C).

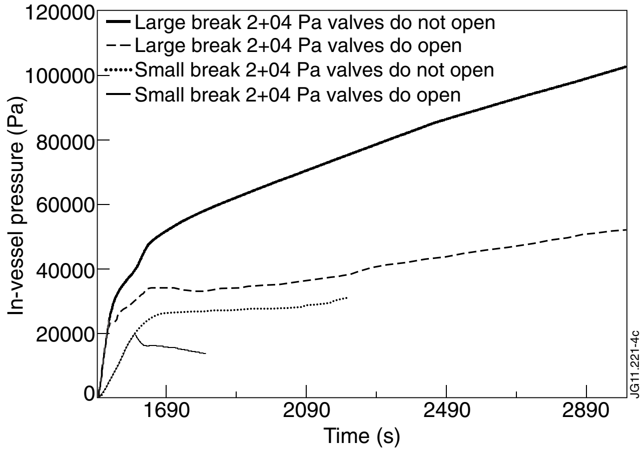

Figure 4: Pressure in the VV as function of time for two sizes (large – small) break with safety related equipment 2+04 Pa by-pass valves operating or not.