Journal of Physics:
Conference Series

Preliminary thermal-hydraulic deterministic safety analysis of an in-vessel LOCA for the DTT facility

To cite this article: G. Grippo *et al* 2024 *J. Phys.: Conf. Ser.* **2685** 012060

Preliminary thermal-hydraulic deterministic safety analysis of an in-vessel LOCA for the DTT facility

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Abstract. The DTT (Divertor Tokamak Test) facility is a new experimental tokamak under development by an Italian consortium in cooperation with several high-standard European laboratories. The ENEA division FSN-SICNUC is involved in the project for carrying out deterministic safety analysis of postulated accidents. In the first year of activity, it has been analyzed an In-Vessel LOCA (IVLOCA) scenario. The IVLOCA scenario selected is caused by a break in the divertor's cassette cooling tubes with the consequent release of coolant inside the Vacuum Vessel (VV). The best estimate thermal-hydraulic system code TRACE, developed by USNRC, was selected to conduct the preliminary thermal-hydraulic analysis of this accident. DTT is currently under design, so not all the data are frozen. Therefore, based on some engineering assumptions and scaling considerations from similar facilities, the nodalization of DTT VV was developed using the three-dimensional TRACE component "VESSEL". Then, a sensitivity analysis was carried out to simulate the break and the consequent water injection in the VV. This was done to compare the system behavior and test different nodalization approaches. Subsequently, the data of the DTT divertor cooling system were used to run additional simulations. The results allow to compare different nodalization approaches and to have a preliminary estimate of the pressure peak and temperature behavior in the VV for an IVLOCA. Finally, a first uncertainty analysis was carried out using the DAKOTA toolkit, coupled with TRACE code in SNAP. Two uncertain input parameters were selected: the rupture area of a cooling divertor tube and the temperature of the divertor coolant. The uncertainty analysis allows having a wider spectrum of system behavior and a preliminary insight on the dispersion of the VV pressure, selected as figure of merit. This paper aims to show the results of this preliminary analysis, characterizing the phenomena that occurred during the selected transient.

1. Introduction

The DTT (Divertor Tokamak Test) facility is a new Italian 6T, 5.5 MA superconducting tokamak [1]. The aim of the DTT project is to test different divertor configurations and possible solutions for future design. The performance extrapolation of different divertor configurations, based on the physical knowledge obtained thanks to ITER experience, is sufficiently reliable for the implementation of a solution on DEMO. Considering that some plant data have not yet been fully defined, this paper presents a preliminary deterministic safety analysis of a postulated accident in a nuclear fusion reactor such as DTT. Among the possible accidents, the first scenario that has been considered is the In-vessel LOCA [2]. Initially, the postulated initiating events (PIE), which can cause this scenario, have been evaluated: LFV1 (Large First Wall rupture) [3] and LDV1 (In-Vessel LOCA caused by a divertor cassette large rupture) [3]. In this work, it has been selected the LDV1 case; in particular, it has been performed the simulation of a break of the divertor primary cooling circuit, assuming a rupture of the tube apparatus inside the divertor component itself [4].

Therefore, the purpose of this study is to conduct a preliminary thermal-hydraulic analysis of in-vessel LOCA accident, performed with the best estimate thermal-hydraulic system code TRAC/RELAP Advanced Computational Engine (TRACE) developed by USNRC [5,6]. The adopted nodalizations were developed through the Symbolic Nuclear Analysis Package (SNAP) [14,15].

2. Input development

The development of the DTT model for the TRACE code is based on the available geometric and thermohydraulic design data. Considering that the plant is currently under design, some data, necessary to develop the model and qualitatively evaluate the results, are not already present in the current collection of data, summarized in the Safety Data List (SADL) [7]. Therefore, in order to develop this preliminary analysis and test the TRACE model, some data have been extrapolated from the existing experimental Integrated ICE facility [4,8], where the in-vessel LOCA has been investigated. The Integrated ICE facility, built at the Japan Atomic Energy Research Institute (JAERI), is used for the characterization of two-phase flow during an Ingress of Coolant Event (ICE) in fusion reactors; in particular, it simulates a plasma facing component tube rupture. The facility is geometrically scaled 1:1600 from the ITER-FEAT design with prototypical fluid conditions [4]. ICE has a pressure suppression system (Suppression Tank, ST) connected with the VV through a Relief Pipe (RP). The suppression system is activated by a magnetic valve (MV), installed on the RP [8].The Integrated ICE facility is equipped with three injection nozzles, from a boiler to the Plasma Chamber (PC), to simulate the rupture of the coolant piping and the consequent water injection in the PC. The chosen ICE experiment, considered to test the DTT model, is case 4, in which 2 out of 3 nozzles are in function: the main thermal-hydraulic parameters of the test are summarized in Table 1 [8].

Table 1. ICE case 4 main thermohydraulic parameters [8]

Parameter	Unit	Value
Initial wall temperature (PC, VV)	*K*	503.15
Initial wall pressure (PC, VV)	*bar*	0.01
Water temperature injected from the boiler	*K*	423.15
Boiler pressure	*bar*	20
Injection time	*s*	45

2.1. Geometrical and thermohydraulic data

Since some in-vessel components' geometrical data are currently under design, the most important parameters on which the TRACE nodalization is based are the plasma side VV volume and, consequently, single torus geometrical quantities [1,7,9,10].

Regarding the thermal-hydraulic data of DTT, the considered ones are reported in **Table 2** [11].

Table 2. DTT thermohydraulic parameters [7,9]

Quantity	Unit	Value
Vacuum Vessel nominal pressure	*Pa*	5.0E-06
Divertor cooling fluid temperature	*°C*	30 - 130
Divertor cooling water volume	m^3	30

2.2. Vacuum Vessel modelling

In order to develop the VV model, it was used the 3D TRACE component “VESSEL” [5,6]. The nodalization has been created (Figure 1) to fit the first radius of the grid with the internal one of the VV structure, while the last radius of the grid with the most external one of the VV. Seven radial rings have been created in total. In relation to the axial 3D nodalization, ten axial levels have been used, distributed with higher density on the top and on the bottom of the VV to find a compromise between the geometric detail and the calculation time. In addition, the coolant injection to simulate the rupture of the divertor cassette occurs at the bottom of the PC [4]. Regarding the azimuthal coordinate, four azimuthal sectors have been defined. The flow area fractions and the volume fractions have been settled to define the internal geometry of the VV and replicate the characteristic “D shape”; in particular, the volume fraction has been settled to zero where the cell was not comprehensive of a VV volume portion as well as the flow area fraction for the boundary [5,6]. About the geometrical data of the PC and the plasma facing components, it has been done a volume scaling from the Integrated ICE facility data [8]. To simulate the PC, the TRACE model flow areas have been settled to define the VV internal region representative of the DTT PC; in addition, the cell R4A4 (radial mesh 4, axial mesh 4) has a non-zero lower axial flow area (Figure 2), to simulate the PC area in which is assumed the divertor. In fact, the nodalization has been done to recreate the position in which is located the divertor and, consequently, where the rupture of the coolant piping takes place.

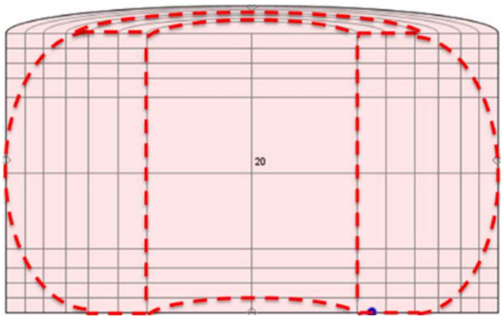

Figure 1. Scheme of VV TRACE nodalization developed through SNAP

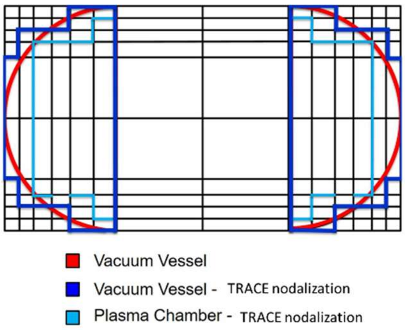

Figure 2. PC and VV discretization in the TRACE 3D vessel nodalization

2.3. System injection – Sensitivity analysis

After the development of the TRACE VV and PC nodalization (Figure 1, Figure 2), it was needed to properly simulate the water inlet due to the rupture of the divertor cooling tubes. To simulate the release of coolant inside the VV, several injection models were created, initially using the Integrated ICE thermal-hydraulic data (Table 1) to evaluate the code results.

Fill model – Mass flow ramp

The adoption of the TRACE FILL injection [5,6] allows the definition of the mass flow rate and the thermal-hydraulic boundary conditions. For this model, the ICE experimental injection curve [8] is settled by the FILL component, properly scaled from the ICE data.

BREAK model

The TRACE BREAK component [5,6] is normally used to settle the boundary thermal-hydraulic conditions specifying the inlet/outlet fluid temperature and pressure. The BREAK is connected to a valve to reproduce the same ICE injection time (45 s) [8]. The difference between the current model and the previous one is that the boundary condition implemented is the BREAK constant pressure instead of the injection mass flow rate (Table 1). The valve that provides the BREAK connection to the VV has a hydraulic diameter that represents the rupture of the coolant pipe, properly scaled from the Integrated ICE data considering the presence of two active nozzles in the test (ICE case 4 [8]). The obtained value has been applied to all the models derived from the Integrated ICE facility with an injection valve.

BREAK model – Pressure ramp

The BREAK component allows also the setting of a time-dependent pressure trend. Therefore, it has been created a model in which is implemented the ICE injection pressure curve [8].

Accumulator model

The water volume inside the divertor cooling circuit is a very important data for the simulation of an IVLOCA (Table 2). Therefore, it has been created also a model with a volume containing the actual amount of cooling water. It does not act as a FILL and BREAK components but simulates the water injection inside the VV without specific predefined behaviours. To fulfil the requirements, it has been used the TRACE PIPE component [5,6] modelled considering the divertor cooling water volume data (Table 2). Initially it has been created a pipe full of liquid water with the ICE boiler thermal-hydraulic conditions. The moment in which the connecting valve opens, both VV and the pipe (Injection Tank, IT) are subject to a strong pressure difference. During the water discharge from the IT to the VV, the pressure equalizes causing the stop of the flow through the valve. To simulate the discharge of a larger water mass in the VV, it has been adopted, for the IT, the accumulator configuration: 75% of the total volume occupied by the coolant and 25% of the total volume filled with non-condensable gases [12]. In thus way during the water discharge the non-condensable gasses expand permitting the fluid flow.

2.3.1. Results of the injection sensitivity analysis

One of the aims of this work is to verify if DTT plant needs a pression suppression system. Since the presented results are referred to preliminary analysis, the target of this study is to make some qualitative and phenomenological consideration on the DTT behaviors in transient conditions and all the data are presented in adimensional form. When the design data of the DTT will be consolidate quantitative evaluation on the pressure peak will be done. Figure 3 to Figure 5 show the results of the sensitivity analysis on the different injection options considered. The pressurized water flashes at the entrance of the VV at lower pressure and enters in contact with the hotter walls of the VV, increasing the VV pressure (Figure 3). Figure 4 shows the pressure peak occurring at the end of the injection phase, the accumulator model has the lower peak. The entrance of pressurized cold water in the VV brings to a sudden drop of the temperatures in the VV atmosphere (Figure 5), that then rises again, following the saturation value. After the initial pressure peak at the end of the injection the pressure rises. Considering the results of this analysis on the various injection options, for the DTT simulation it has been decided to use the accumulator model (Figure 6). This option has been selected since the accumulator model provides the more conservative results, with the final highest PC pressure. In addition, this option simulates the water injection inside the VV without specific pre-imposed code component behaviours (e.g. fixed pressure or mass flow rate).

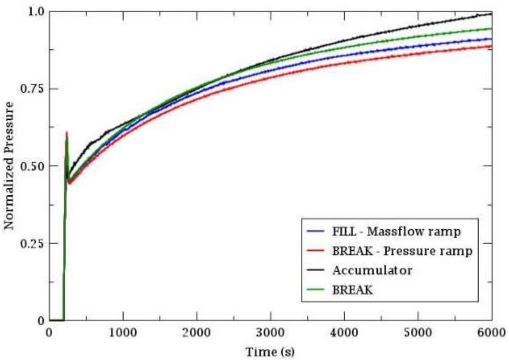

Figure 3. Injection sensitivity analysis, VV pressure

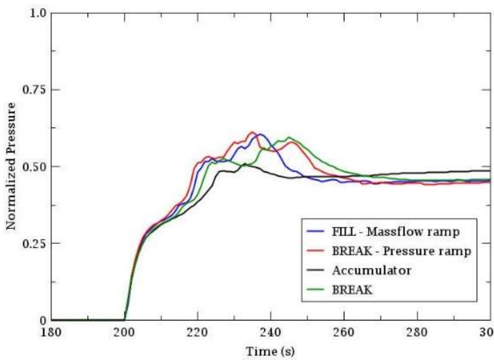

Figure 4. Injection sensitivity analysis, initial VV pressure peak

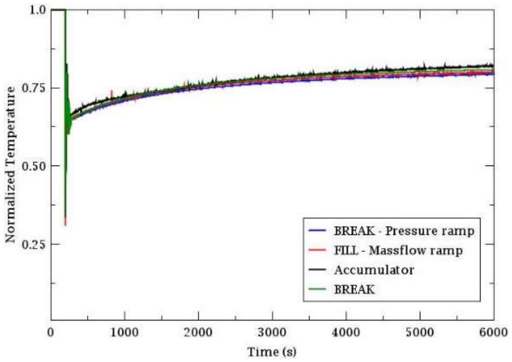

Figure 5. Injection sensitivity analysis, VV temperature

2.4. DTT model

To simulate the DTT conditions, only the thermal-hydraulic data have been changed since the IT has been modelled considering the water volume of the DTT divertor cooling system (Table 2). The pressure present in the Safety Data List [7] could be implemented since TRACE code does not allow systems simulation with pressure below $1e^{-3}\ Pa$ [6,13]. Therefore, as first approximation, it has been settled the initial pressure condition of the ICE facility (Table 1). For the cooling system thermal-hydraulic data, it has been considered the highest temperature case (Table 2): 403.15 K. Regarding the injection valve, it remains opened after the start of transient and the pressure difference between the VV and the IT regulates the mass flow and the amount of injected coolant. The valve flow area has been set to simulate the complete rupture of a cooling divertor pipe.

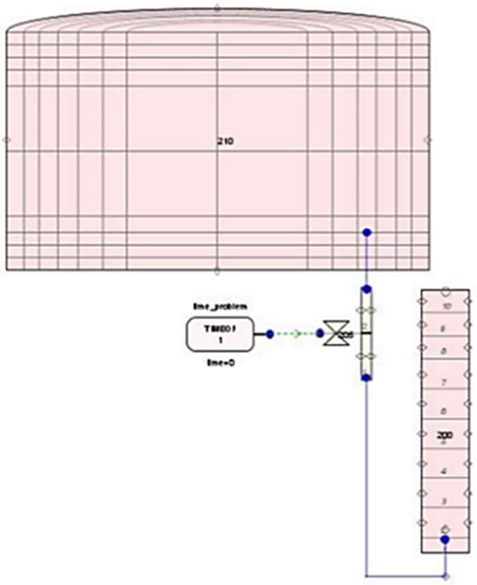

Figure 6. DTT nodalization developed through SNAP

3. Results

The simulations performed with ICE conditions have been used to test different options for the coolant liquid entrance in the VV and observe the behaviour predicted by the TRACE code. Considering the obtained results, it has been selected for the DTT model the PIPE component (Figure 6) modelled as an accumulator (IT).

Figure 7 shows the VV pressure behaviour along the simulation. At the beginning of the transient, when the valve opens, the VV pressure rises rapidly up to 500 s; then, there is a slower increase of the pressure up to the final maximum value. Figure 8 shows the pressure equalization between the VV and the IT after the opening of the connection valve. The IT pressure sharply decreases at the break opening and the equalization is reached at around 400 s; then, the two pressure trends are the same with a slight increase in the remaining part of the transient (Figure 8).

Regarding the VV temperature, at the beginning of the test, when the valve opens, the inlet of the coolant from the IT to the hotter VV environment causes a sudden decrease of the VV (Figure 9). Then the temperature slightly increases following the saturation value.

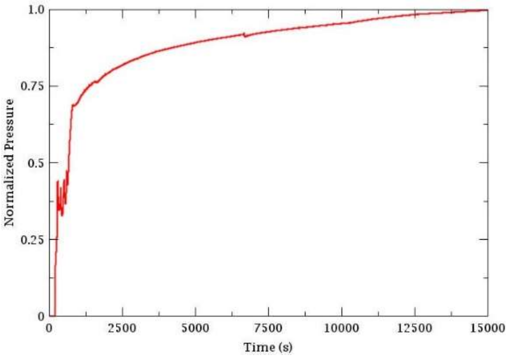

Figure 7. DTT nodalization results, VV pressure

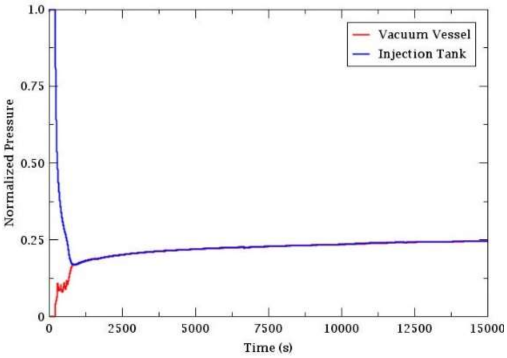

Figure 8. DTT nodalization results, accumulator model VV and IT pressure equalization

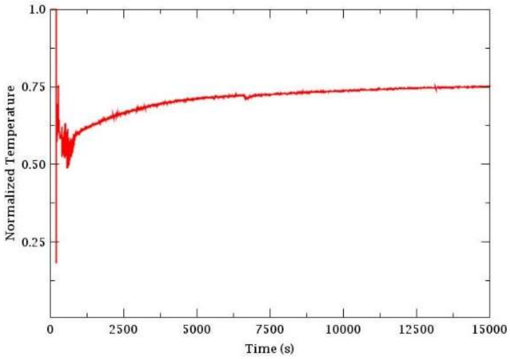

Figure 9. DTT nodalization results, VV temperature

3.1. *Uncertainty analysis*

Since some data of the DTT facility are still under design, an Uncertainty Analysis (UA) has been performed applying the probabilistic propagation of input uncertainties method. The UA has been carried out with the Design Analysis Kit for Optimization and Terascale Application (DAKOTA) toolkit, coupled with TRACE code in SNAP [14,15]. More information on DAKOTA can be found in references [16,17]. In the first instance, two Figures Of Merit (FOM) have been selected: the VV pressure and the VV temperature. Subsequently, two uncertain input parameters have been chosen: the divertor cooling pipe rupture area and water temperature.

Table 3. Uncertainty analysis input parameters

Parameter	Min value	Max Value	Distribution
Pipe break flow area [m^2]	4.05366e-4	2.02683e-3	Uniform
DIV Cooling temperature [K]	303.15	403.15	Uniform

Table 3 shows the assumed variation range of both uncertain input parameters with a uniform distribution. Regarding the pipe rupture area, the maximum value corresponds to the complete break of the pipe (100% pipe flow area), while the minimum is equal to 20% pipe's total flow area. Considering the described range, it represents a large spectrum that covers different possible rupture in the system. Related to the divertor coolant temperature, it is presented in the Safety Data List as a range [7], therefore the UA has been performed using this range. In order to perform the UA, the probabilistic propagation of input uncertainties method has been used; considering 2 FOM, a probability content and a confidence level of 95%, 93 calculations have been required for the one-sided tolerance interval [17].

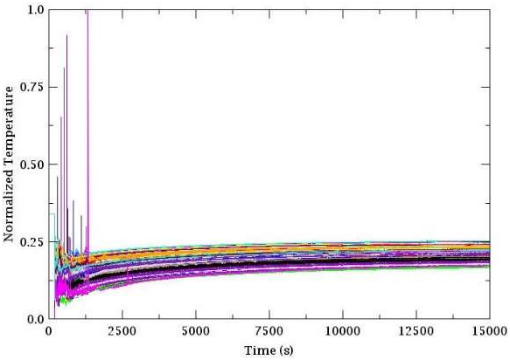

Figure 10. Uncertainty analysis results, VV temperature

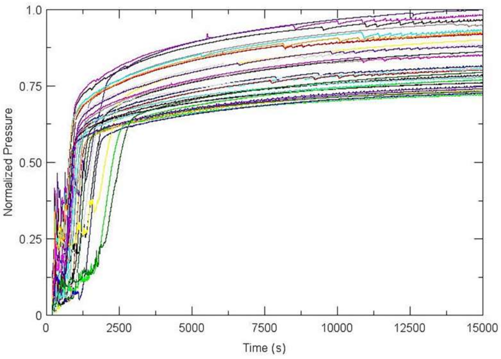

Figure 11. Uncertainty analysis results, VV pressure

To characterize the correlation between the uncertain input parameters and the FOMs, in the present work it has been considered the Pearson coefficient and the Spearman coefficient. The Pearson correlation coefficient, calculated between an input and an output variable, represents the linear correlation between the two variables (Table 4), while the Spearman one represents the monotonic correlation [8,16].

Table 4. Correlation coefficients results

	VV Temperature		***VV Pressure***	
	Pearson	*Spearman*	*Pearson*	*Spearman*
Pipe break flow area	-0.31	-0.39	0.67	0.96
DIV Cooling temperature	-0.02	0.07	0.01	-0.02

At the beginning of simulation, the VV pressure (Figure 11) rapidly increases, with a results dispersion width reaching around 0.75 (normalized pressure); then, at the end of the simulation, there is a results dispersion between around 0.75 and 1.0. Observing the correlation coefficients for the VV pressure FOM (Table 4), the pipe break flow area presents a positive correlation, while the divertor cooling water temperature is very low. In particular, the rupture area presents a significant correlation coefficient (i.e. >0.5) while the cooling temperature has a low correlation (<0.2) according to the threshold values used in [8]. Considering the VV temperature (Figure 10), some simulations show initially high peak values; then, the results dispersion width is almost constant with final values which range between around 0.125 and 0.25 (normalized temperature). The correlation coefficients (Table 4) are both negative for the pipe break flow area (moderate correlation according to the threshold values used in [8]) while the correlation is low for the divertor cooling temperature.

4. Conclusions

In previous activities of the authors, the thermal-hydraulic best estimate system code TRACE has been validated for fusion applications against the data developed in the Integrated ICE facility. Starting from that base, this work presents a preliminary analysis of an accident in the DTT facility caused by a break in the divertor cooling circuit, with consequently release of coolant inside the VV. The analysis was carried out with the TRACE code, adopting a 3D modeling of the VV and PC. The obtained results provide, in first approximation, the trend of pressure and temperature in VV during the accident. Then an uncertainty analysis was performed with the probabilistic propagation of input uncertainty method varying two input parameters, which were uncertain in the reference calculation. However, as mentioned above, these results are to be considered preliminary because some data of the facility are still under design. In future studies, the model will be updated considering: the divertor cooling circuit with updated geometrical dimensions following the finalized design, and several systems concerning the facility (e.g First Wall cooling circuit,…) exploring different scenarios and transients; finally, the input deck assumption will be substituted with all the final thermal hydraulic data in order to reduce the uncertainty on the results (specifically to the VV pressure peak at the beginning of the transient).

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