Benchmark calculation for spills of cryogenic He into the ITER VV used as basis for an experimental campaign by means of EVITA facility

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Abstract

Code validation activities have been promoted inside the EFDA (European Fusion Development Agreement) to test the capability of codes in simulating accident phenomena in fusion facilities and, specifically, in the ITER (International Thermonuclear Experimental Reactor) plant. This work concerns a benchmark between three different computer codes (CONSEN, MAGS and MELCOR) and one analytical model (ITER model) in simulating cryogenic helium leaking into a vacuum vessel (VV) which contains hot structures. The scope is the evaluation of the transient pressure inside the VV. The results will be used to design a vent duct (equivalent diameter, length and roughness) which allows helium pressure relief towards controlled volumes. A maximum pressure of 2.0e5 Pa inside the vacuum vessel is allowed during the accident transient. The reference geometry is a simplified scheme preserving the main features of the full scale ITER design. Based on the results of the simulations, a matrix of experiments will be proposed to validate the calculated results and to design the vent duct for the ITER VV. The experiments are planned to be performed in the EVITA facility, located in CEA Cadarache (France).

1. Scope of the study

The paper deals with tools, phenomena and experiments related to the ITER plant accident analyses.
The simulation computer codes used for accident analyses in the fusion frame are derived often from the fission field. The consequence is that they are not validated for some peculiar conditions in the fusion plants, as cryogenic temperatures or pressures near vacuum, for example.
The first scope of this work is to make a benchmark between different computer codes and one analytical model, for a cryogenic helium spill transient.
The second one is to tune the vent duct (cross section and length) of an experimental facility that must reproduce the ITER equivalent conditions in case of the same accident. The experiments will be carried out at the existing EVITA facility in the CEA (Commissariat à l'Energie Atomique) Cadarache research center.
The third scope is to fix a matrix of experiments that can be significant for the helium spill accident analyses in the facility and can give indications for the ITER behavior in similar cases.

2. Codes involved in the benchmark

The codes involved in the benchmark are ***CONSEN*** [1], ***MAGS*** [2], ***MELCOR*** [3] and one analytical model, called ***ITER Model*** in the following [4]. CONSEN and MAGS are two fast running codes developed by the Rome University "La Sapienza" in collaboration with ENEA (Italian National Agency for New Technolgies, Energy and Environment) the first one and by

FZK (Forschungszentrum Karlsruhe) the second one. MELCOR was initially developed at the Sandia National Laboratory (US) under the sponsorship of the USNRC (United States National Regulatory Commission) to assess reactor severe accident conditions. The current version was modified by INEEL (Idaho National Engineering and Environmental Laboratory) to adapt it to accident analyses for fusion plants. The ITER Model is described in [4].

3. Benchmark model and assumptions

A simple benchmark among the codes [5] has been prepared to simulate a scenario in which a spill of cryogenic helium happens into an area surrounded by hot structures. A compromise is made between simplicity and applicability to the ITER situation. To achieve this, the VV volume is the receiving volume for the He spill. It is modeled with its actual parameters as far as volume, in-vessel structures and temperatures are concerned. The cryogenic loop is modeled in a very simplified way. A realistic break size is modeled with a long pipe extending into the cryoplant and a large of supply of helium is assumed to drive the transient. Figure 1 shows the schematic of the proposed model and transient. It will be called in the following ITER-SM (Simplified Model).
All values are taken or derived from SADL-3.2.9 [6] or DDD-3.4 [7] or [8].

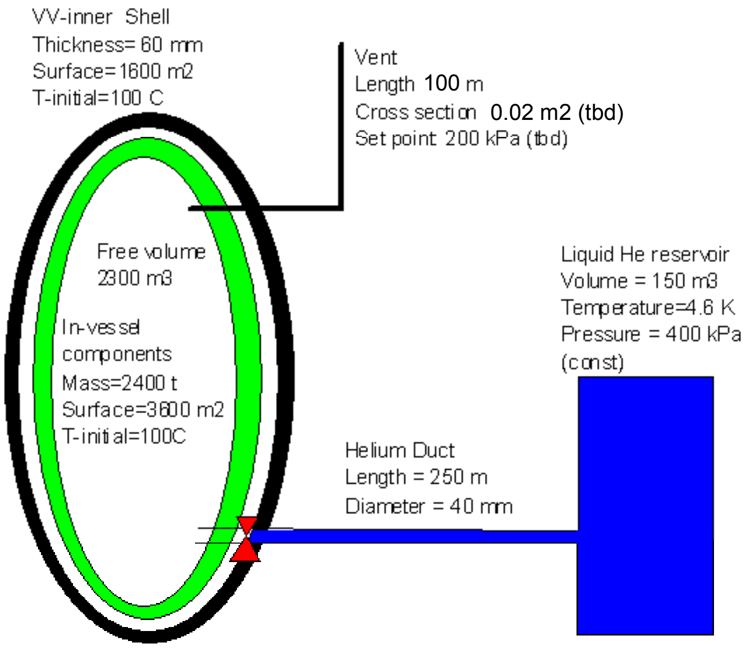


Fig. 1
Schematics of a simple model and scenario for a helium spill into the ITER VV (ITER-SM)

The in-vessel component is modeled as a separate block of material which provides thermal inertia; the heat transfer coefficient at the outer boundary of the VV to simulate (passive) cooling (or heating) due to the VV coolant is supposed equal to 15.4 W/m^2K and the external temperature is constant at 20°C.
During the transient the pressure in the liquid He reservoir is assumed to be constant.
The vent cross section is 0.02 m^2 and the pipe roughness should be taken as zero for the helium duct and 10^{-3} for the venting area.

The values defined as *tbd* in schematics (fig. 1) of the benchmark exercise (vent cross section and pressure set point for vent opening) can be modified if the analysis results will show critical conditions (pressurization > 200.0 kPa) or not sufficient margins for the fast depressurization of the vessel.

4. Benchmark results

The pressure trends during the helium discharge in the vacuum vessel are shown in the fig. 2 for the three codes and the analytical model used for the simulation.

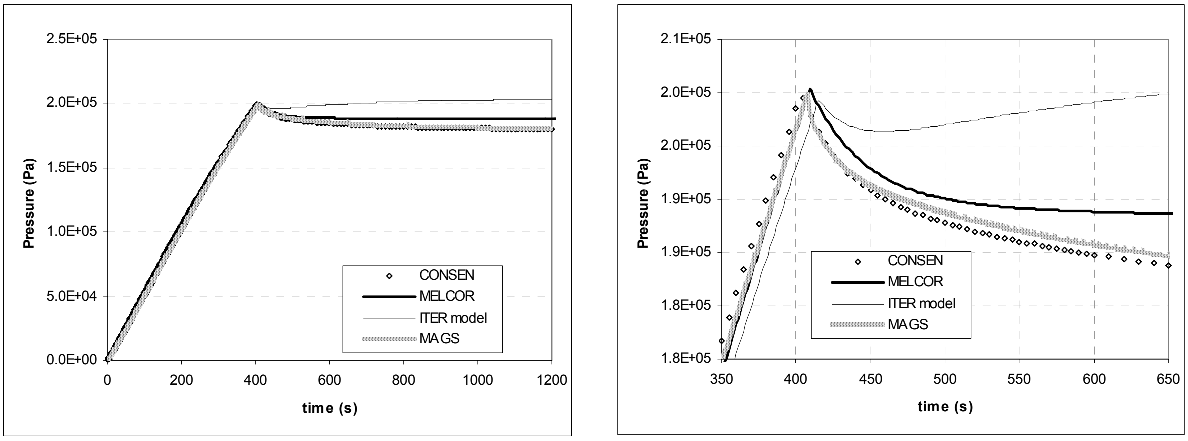


Fig. 2 – Simulated pressure in the vacuum vessel (scale enlarged in the right side)

The ramp up is quite similar in all the simulations and the VV design pressure (200.0 kPa) is reached in an interval of 10 s, between 405 and 415 s using the different codes. The fastest pressurization is in CONSEN, while the slowest is in ITER Model. Only ITER Model shows a further overpressurization, after the valve opening.

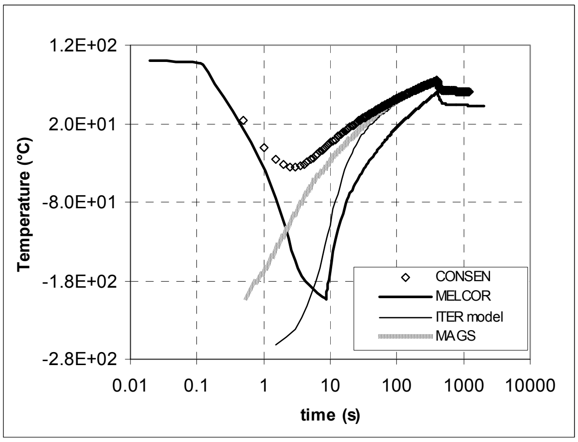


Fig. 3 – Vacuum vessel simulated temperature

On the contrary, the temperatures in the VV are not in agreement (fig. 3) in the different models: MAGS, MELCOR and ITER Model temperatures decrease of more than 300 °C from the initial temperature (100 °C) for the helium expansion in vacuum conditions. For CONSEN the range of decrease is about one half (150 °C). The discrepancies in the temperatures can be explained by the different ratio of liquid and gas in the helium flow. As a

consequence the heat exchange with the VV walls leads to different temperature evolution. The use of different libraries for the helium properties in cryogenic conditions should be negligible compared with the previous one. Different time steps or numerical algorithms used by the codes could also have an influence in this fast transient.
At any rate, being the transients very fast and the helium inventory low in the first phases of the transient, the temperature evolution is not effective for the pressure trend, as highlighted in the fig. 2.
As a conclusion of this first phase of the analysis it is possible to state that:
- for the formulated benchmark problem a relief area of 0.02 m^2 appears adequate to keep the VV pressure below 200.0 kPa in case of a helium spill from a large reservoir at 400.0 kPa back pressure and a break from a 40.0 mm pipe;
- the three codes and the analytical model give congruent and similar results for the pressurization in the short term. Then, all of them can be applied to analyse the accidents in which the expansion of cryogenic helium is involved. The overpressurization calculated by ITER Model in the long term must be proved experimentally. It stays below 200.0 kPa.

5. Experiment design

An experimental campaign will be set up for testing the helium behavior in condition similar to those existing in ITER during helium spill accidents.
The basic idea is to use the EVITA facility [9], already existing in CEA research center in Cadarache. The facility layout is outlined in fig. 4.

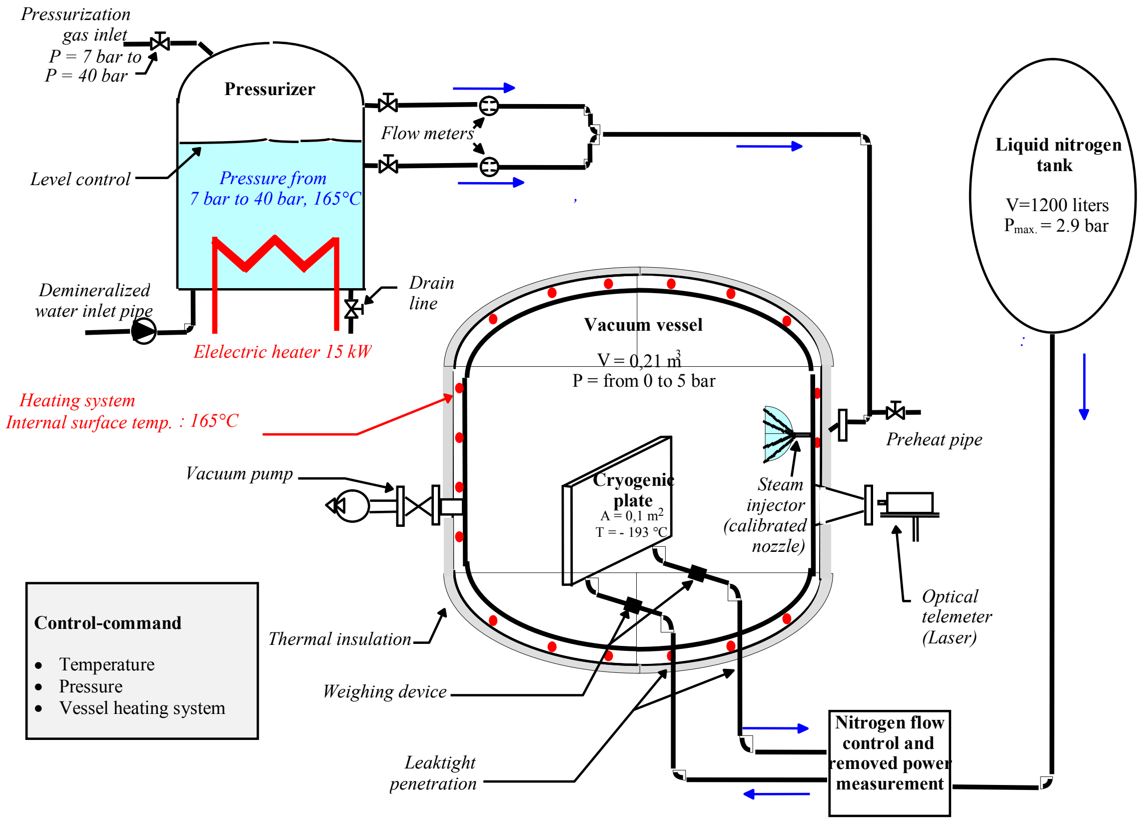


Fig. 4 – Layout of the EVITA experimental facility (CEA – Cadarache)

No scaling law for the ITER simplified model (ITER-SM) can be applied for EVITA because the dimensions are those of the existing facility. The ITER-SM volume is 10950 times the EVITA volume; the ITER-SM internal surfaces are 870 times the EVITA internal surfaces.
The ratio between the internal surface and the volume (S/V) is a significant parameter in the pressurization transients during which the expanding fluid heats up or cools down, according to the expansion volume conditions.
This ratio is:

$(S/V)_{ITER\text{-}SM} = 0.67\ (m^{-1})$
$(S/V)_{EVITA} = 8.7\ (m^{-1})$

that means the pressurization phenomena will be amplified in the experimental facility, due to the relative larger surface.
This is true also if we sum up the total surface of the First Wall/Blanket (FW/BL) walls together with the VV walls in the ITER-SM available for the heat exchange, because both the types of structures, that are at 150 and 110 °C respectively, can heat up the helium being. In this case, taking into account the FW/BL plus VV structure surfaces equal to 3600 m^2:

$(S/V)_{ITER\text{-}SM} = 2.2\ (m^{-1})$

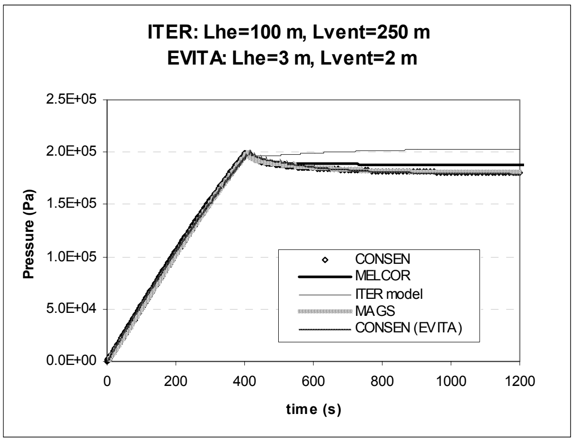
the ratio (S/V) is one quarter of the same ratio in EVITA.
In the table 1 it is possible to compare the ITER-SM dimensions with the corresponding ones in EVITA.

Table 1 – Comparison of ITER-SM and EVITA dimensions

Component	Feature	Units	ITER-SM	EVITA	Ratio
Vacuum Vessel	volume	m^3	2300	0.21	10952
	wall thickness	m	0.06	0.0037	16
	surface	m^2	1600	1.83	874
	weight	kg	748800	180	4160
	temperature	K	373.15	373.15	1
In vessel components (FW/BL)	weight	t	2400	-	-
	surface	m^2	3600	-	-
	temperature	K	373.15	-	-
Helium reservoir	volume	m^3	150	0.013	10952
	He mass	kg	19770	22.62	16
	temperature	K	4.6	4.6	1
	pressure	kPa	400	400	1

As a conclusion of the previous remarks no one scaling law will be taken into account, but we will focus on maintaining in EVITA the same initial values of helium pressure and temperature (P = 4.0e5 Pa, T = 4.6 K) of ITER-SM. The conditions for the ITER-SM VV walls such as that means a heat transfer coefficient equal to 15.4 W/m^2K at the outer boundary of the VV to simulate permanent (passive) cooling (or heating) due to the VV coolant, an external temperature of 20°C, and an initial internal wall temperature of 373.15 K will be retained too.
In the experiment the temperature conditions in the VV walls can be controlled using electric heaters.

The tuning of the inlet nozzle, the pipe length from the helium reservoir, the cross section and length of the venting duct would allow to obtain the same pressurization trend observed in the ITER-SM discussed above.
To reduce the evaporation effect due to the hot surfaces of the vacuum vessel it will be advisable to avoid the presence of heat structures like those in ITER-SM represent the FW/BL.
The ITER-SM maximum pressure is 200.0 kPa and EVITA should cope with the same stress. To be representative of the accident, the EVITA helium reservoir must have the same temperature and pressure conditions as the ITER-SM vacuum pumping coolant.
The results obtained from the study for the vent duct in ITER-SM have been used to plan the EVITA experiments. The modeling with the simulation codes for ITER-SM has been adapted to be representative of the EVITA dimensions and the conditions in absence of vent duct were the basis for the helium pipe calibration. For the EVITA simulation the CONSEN code has been used.
The results (fig. 5) show that the same ITER-SM pressurization trend could be obtained in EVITA facility if we use a pipe length of 3 m, with smooth walls (roughness equal to 0) between the helium reservoir and the VV a nozzle of $1.65 \cdot 10^{-7}$ m^2 (diameter $4.58 \cdot 10^{-4}$ m).



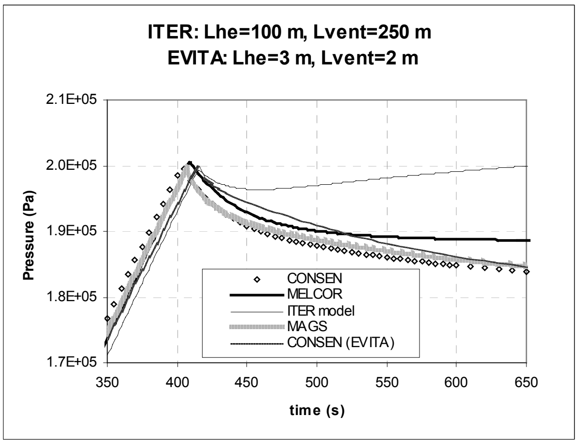


Fig. 5 - Simulated pressure in the vacuum vessel including CONSEN (EVITA) model (scale enlarged in the right side)

The length of the pipe and diameter and the size of the nozzle are a compromise between the possible length of a duct inside a laboratory and the calibration of a narrow nozzle. During the experimental phase the two parameters can be adjusted according to the availability of pipes and nozzles.
When the vent duct opens to avoid overpressure in the EVITA vacuum vessel tuning for the area of the duct was used to obtain the same pressurization trend as in ITER-SM.
A vent duct of 2 m length, having a cross section of $3.75 \cdot 10^{-6}$ m^2 (diameter $2.186 \cdot 10^{-3}$ m) should be able to maintain the pressure in the EVITA vacuum vessel below the design pressure of 200.0 kPa.
As anticipated by the discussion about the ratio S/V, the temperature in the experimental facility (fig. 6) will result higher than in ITER-SM due to the larger hot surfaces in relation to the volume available.

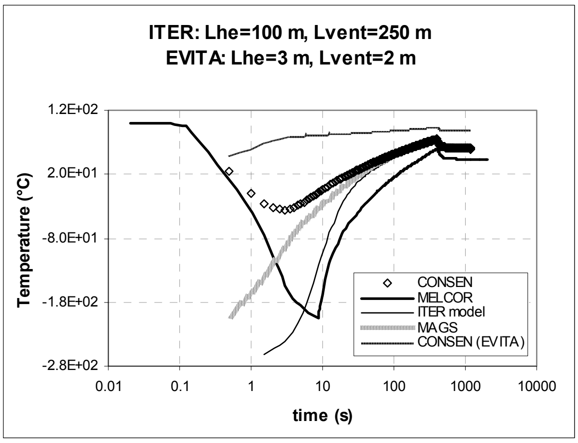


Fig. 6 - Simulated temperatures in the vacuum vessel including CONSEN (EVITA) model

6. Matrix of the experiments

In the table 2 a matrix of seven experiments to be performed in the EVITA facility is suggested in order to verify the sensitivity of the pressurization trend versus parameters like cross section (cases 1 and 2), roughness (cases 3 and 4) and length of the vent duct (cases 5 and 6). The reference case (case 0) is the one discussed in the previous paragraphs.

Table 2 – Matrix of the experiments

Case		**Vent area** [m^2]	**Eq. Diam.** [m]	**Vent duct length** [m]	**Vent duct relative roughness**	**Helium duct length** [m]	**Helium duct relative roughness**
BASE CASE ANALYZED							
0	ITER-SM	0.02	0.16	100	10.e-3	250	0
	EVITA	3.75e-6	2.19e-3	2	10.e-3	3	0
TO TEST THE SENSITIVITY ON THE VENT DUCT CROSS SECTION							
1	EVITA	2.81e-6	1.89e-3	2	10.e-3	3	0
2	EVITA	4.86e-6	2.49e-3	2	10.e-3	3	0
TO TEST THE SENSITIVITY ON THE DUCT ROUGHNESS							
3	EVITA	3.75e-6	2.19e-3	2	20.e-3	3	0
4	EVITA	3.75e-6	2.19e-3	2	30.e-3	3	0
TO TEST THE SENSITIVITY ON THE VENT DUCT LENGTH							
5	EVITA	3.75e-6	2.19e-3	1.5	10.e-3	3	0
6	EVITA	3.75e-6	2.19e-3	2.5	10.e-3	3	0

7. Conclusions

The loss of coolant accident involving the cryogenic pumps is one of the concern in the safety analyses for ITER experimental plant. An experiment to be performed for the helium spill is under evaluation in the existing facility EVITA in Cadarache (France). At this scope a benchmark between simulation codes and one analytical model has been prepared in order to compare the different results in the simulation of a helium spill transient, similar to ITER accident conditions. The results proved a reasonable agreement among the codes both in terms of pressure values and of transient timing.
Conditions similar to those existing in ITER have been simulated for the EVITA geometry with a helium duct length and diameter able to maintain the same pressure evolution studied for the ITER vacuum vessel. The approach was used also to derive the length and the diameter of the vent duct of EVITA. The geometrical dimensions that are able to avoid overpressurization in EVITA are:
Helium duct length = 3 m
Helium duct diameter = $4.58 \cdot 10^{-4}$ m
Vent duct length = 2 m
Vent duct diameter = $2.186 \cdot 10^{-3}$ m.
A test matrix including 7 different experiments is suggested in order to investigate different conditions, taking into account that in the real experiment the pressure drop reduces the pressurization velocity but the turbulence of the helium flowing in the vacuum vessel can increase the heat exchange between the helium and the walls. The range of the effects on the pressurization can be easily studied with the variations suggested for the cross sections, roughness and length in the vent duct.

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