

In-Vessel LOCA Analysis for the PD stage of HCCP TBS

Hyung Gon Jin ^{a*}, Seong Dae Park ^a, Suk-Kwon Kim ^a, Jae-Sung Yoon ^a,
Dong Won Lee ^a, Chang Wook Shin ^a, Mu-Young Ahn ^b

^aKorea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon 34057, Korea

^bKorea Institute of Fusion Energy, 169-148 Gwahak-ro, Yuseong-gu, Daejeon 34133, Korea

*Corresponding author: jhg@kaeri.re.kr

*Keywords : safety analysis, nuclear fusion, HCCP TBS, in-vessel LOCA

1. Introduction

The Helium-Cooled Ceramic Pebble (HCCP) Test Blanket System (TBS) is being developed jointly by Korea and Europe for testing in ITER. In the in-vessel loss-of-coolant accident (LOCA), the first wall (FW) cooling channels of the test blanket module (TBM) rupture on the plasma-facing side and the 8 MPa helium of the TBM helium cooling system (HCS) is discharged directly into the vacuum vessel (VV). The event is a Category III design basis accident postulated within the Test Blanket system Safety Demonstration (TBSD) framework of ITER [2].

The rupture of the FW cooling channels can be postulated over a wide spectrum of break sizes. The present study, performed for the preliminary design (PD) stage of the HCCP TBS, addresses the bounding end of that spectrum: the simultaneous double-ended rupture (DER) of all twelve FW cooling channels. Following the TBSD TG-3 methodology [1], the case in which the active isolation is unavailable is analysed together with the case in which it operates as designed, so as to confirm that the VV pressure stays below the VV pressure suppression system (VVPSS) actuation set-point even for this bounding break and to quantify how much of that margin the active isolation provides.

2. Analysis Methodology

The analysis has been carried out with GAMMA-FR (General Analyzer for Multi-component and Multi-dimensional transient Application – Fusion Reactor), which is included in the list of tools approved for TBSD safety analyses [3]. The model reproduces the complete helium loop of the HCCP-TBM HCS based on the system P&ID, together with the TBM heat structures and the confinement volumes, and consists of 58 fluid blocks connected by 77 junctions. The first wall, the horizontal and vertical stiffening grids, the side cap, and the cooling plate are tracked as individual heat structures coupled to the coolant by convection and to one another by conduction and radiation.

The analysis follows the major considerations of the TBSD TG-3 methodology [1]. First, the current design configuration is used. Second, the fusion power shut-down system is not credited a priori; for an in-vessel LOCA, however, the plasma cannot physically be sustained once the coolant enters the VV, so a separate case without plasma termination is not required. Third, the consequence of the unavailability of active

functions is assessed, and it is this requirement that generates the second case of the present work, in which the safety-important-class (SIC) isolation valves (ISV) fail to close.

3. Analysis Conditions

The cross-sectional flow area of a single FW cooling channel is 197.5 mm². Under the DER assumption both severed ends discharge into the VV, so the simultaneous rupture of all twelve FW channels gives a break area of 4.74×10^{-3} m², which is the largest FW break that can be postulated for the TBM and therefore bounds the rupture spectrum. The main boundary conditions are listed in Table I.

Table I: Boundary conditions for the bounding in-vessel LOCA

Parameter	Value
Break area (12-channel DER)	4.74×10^{-3} m ²
He inventory / pressure / temperature	44 kg / 8 MPa / 300 °C
VV free volume with ports and extensions	1315 m ³
VVPSS bleed valve set-point	50 kPa in VV
High-pressure tank (HPT) pressure / volume	14 MPa / 0.4 m ³
HPT actuation set-point	HCS pressure < 7.95 MPa
SIC ISV closing time	3 s

An immediate plasma disruption is assumed to accompany the break: the discharge starts at $t = 0$ s, the HPT make-up actuates at $t \approx 0.1$ s, the plasma disruption is initiated at $t = 1$ s, the disruption thermal load ends and the SIC ISV starts to close at $t = 2$ s, and the ISV is fully closed at $t = 5$ s where the isolation is credited.

4. Results and Discussion

4.1 Vacuum vessel pressurization

Table II summarizes the two cases and Fig. 1 shows the corresponding VV pressure histories.

Table II: Results for the bounding 12-channel DER

SIC ISV	Peak VV pressure	He released into VV	Time to peak
ON	11.6 kPa	14 kg	≈ 5 s
OFF	35.3 kPa	43.9 kg	≈ 60 s

With the SIC ISV credited, the closure at $t = 5$ s truncates the discharge while the blowdown is still in progress: the VV pressure rises steeply for about five seconds and then remains at 11.6 kPa, and the helium released into the VV is limited to 14 kg out of the 44 kg HCS inventory. Without the active isolation, the discharge continues until the HCS and the VV equalize, the VV pressure approaches 35.3 kPa at about 60 s, and 43.9 kg of helium – essentially the entire HCS inventory – is transferred into the VV.

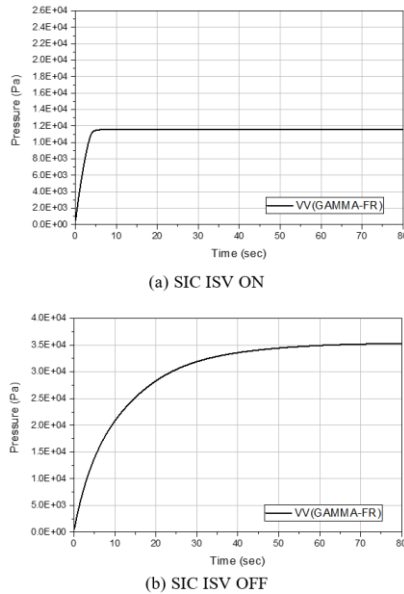


Fig. 1. VV pressure for the 12-channel double-ended rupture.

Both cases stay below the VVPSS bleed valve set-point of 50 kPa [5], so no venting through the suppression system is expected, and both are far below the 150 kPa VV pressure limit [4].

4.2 Thermal and radiological response

Fig. 2 shows the corresponding TBM structure temperatures. The disruption heat pulse raises the FW temperature to about 530 °C within one second. The escaping helium then cools the FW convectively to about 150 °C in the unisolated case, after which it recovers to about 320 °C at 1000 s as the stored and decay heat is redistributed. The HSG, VSG and side cap stay between about 360 and 550 °C, the highest of them being the HSG, while the CP reaches about 660 °C at $t \approx 400$ s and then decreases slowly. The long-term behaviour is governed by radiative redistribution inside the TBM rather than by the break size or the ISV state.

As the discharged coolant is helium, no metal-steam reaction is credited for this TBS-only event. The dominant source term is the tritium carried by the coolant, of the order of 0.6 mg [6]. Since the VV pressure stays below the VVPSS set-point in both cases, no venting path towards the surrounding rooms is opened through the VVPSS, and the release to the environment is negligible for this TBS-only event.

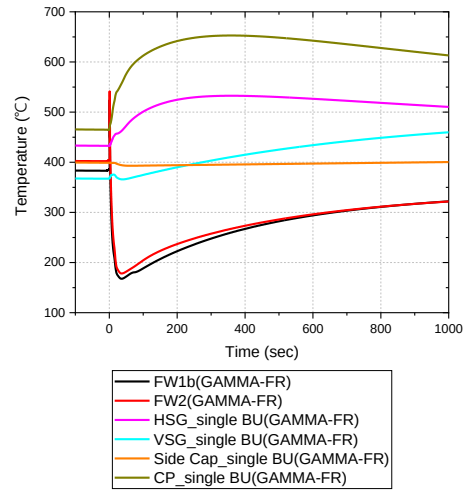


Fig. 2. TBM structure temperatures without isolation.

5. Conclusions

The bounding in-vessel LOCA of the HCCP TBS – the simultaneous double-ended rupture of all twelve FW cooling channels – has been analysed with GAMMA-FR for the PD stage design following the TBSD TG-3 methodology. Even for this bounding break the VV pressure remains at 11.6 kPa when the SIC ISV is credited and at 35.3 kPa when the active isolation is assumed unavailable, both below the 50 kPa VVPSS set-point and well below the 150 kPa limit for Category III events. The active isolation is the dominant contributor to that margin, since its loss triples both the peak pressure and the helium released, whereas the asymptotic pressure itself is set by the HCS-to-VV equalization. Further work will address the break flow history, the sensitivity to the ISV closing time and the VV free-volume assumption.

Acknowledgments

This work was supported by the R&D Program through the Korea Institute of Fusion Energy (KFE) funded by the Ministry of Science and ICT of the Republic of Korea (KFE-IN2603).

REFERENCES

- [1] TBSD TG-03 – Methodology, ITER_D_DA68K9, v1.1, ITER Organization.
- [2] TBSD TG-03 – Postulated Initiating Events, ITER_D_EHCVHR, v1.1, ITER Organization.
- [3] TBSD TG-03 – List of tools, ITER_D_DMDFH4, v1.1, ITER Organization.
- [4] Accident analysis safety rules, ITER_D_9CGERR, v1.6, ITER Organization.
- [5] SADL preparatory section: VVPSS, ITER_D_2X4XUQ, v2.0, ITER Organization.
- [6] HCCP-TBS Tritium Analysis (THETA-FR), ITER_D_AB5QMZ, v1.0, ITER Organization.