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Application of Explosion Area Control Volume in MELCOR Code for Safety Analysis of Hydrogen and Dust Explosion Accident in ITER

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1. Introduction

Significance of nuclear safety and security cannot be overemphasized to protect public from any possible consequences due to nuclear accidents. A good deal of research in nuclear safety has been conducted especially after the Fukushima-Daiichi nuclear accident to ensure safety even after accident situations. Nuclear fusion power is said to be one of the most promising energy sources to generate large amount of energy with less radioactive waste or less radiological hazard due to nuclear accidents. However, the nuclear fusion device still confronts the tritium management tasks because they hold considerable amount of tritium for fusion reaction [1]. In so-called "Hypothetical events," the beyond the design basis accidents in nuclear fusion reactors, a radiological material release may occur. Therefore, safety analysis for hydrogen mitigation and management should be performed to demonstrate the ultimate safety margin of the design to evade from situations such as the Fukushima accident.

For ITER facility, accident analysis report (AAR) demonstrates the analysis of selected postulated accident scenarios holding the most challenging in terms of expected radiological consequences including beyond design basis accidents [2]. Nine of all 25 design basis accidents and eight of 12 hypothetical events have been identified in the AAR as the most severe events by taking radiological consequences into account [3]. MELCOR code was chosen as the code to perform ITER safety analysis due to its ability to model a broad spectrum of physical phenomena which may occur in severe accident circumstances [4]. However, since MELCOR does not have an explosion model, alternative method for modeling hydrogen and dust explosions in ITER needs to be devised. In this paper, the hydrogen and dust explosion in the ITER vacuum vessel accident analysis was performed by setting an explosion area using MELCOR code.

2. Accident Identification and Description

The hydrogen and dust explosion in the vacuum vessel (VV) accident is initiated with failure of the confinement barriers inside a penetration line between the vacuum vessel and a port cell, resulting in air ingress in the VV. The air ingress mobilizes the hydrogen and dust isotopes, forming hydrogen/air explosive mixture in the VV. Hydrogen explosion is assumed to trigger a dust explosion damaging the confinement of the ITER device. The rapid pressurization of the vacuum vessel up to 565kPa opens the bleed line from VV to suppression tank (ST). Pressurized VV also creates other penetration lines to port cell and NBI cell with the total flow area of 1 m^2 each. When the port cell and NBI cell pressure reach 120kPa, the pathway to the tokamak cooling water system (TCWS) and drain tank (DT) opens. The port cell and NBI cell confinement is damaged at pressure exceeding 160kPa and 200kPa respectively, resulting air flow into the gallery. In case of the gallery pressurized up to 105kPa, the gallery confinement is assumed to be damaged releasing radioactive material directly into the environment. Suppression tank vent system (ST-VS) and detritiation system (DS) is assumed to operate when reached the set point. Table I below explains the pressure sequence of the event.

Table I: Pressure Sequence of Hydrogen and Dust Explosion Accident

Event Sequence	Pressure Set Point
Failure of VV penetration line	-
Off-site power loss	-
Hydrogen/dust explosion	-
Bleed line valves to ST open	94kPa (VV)
Damage of VV confinement	565kPa (VV)
Pressure relieve way to TCWS	120kPa (Port/NBI)
Bleed lines valves to DT open	120kPa (Port)
Failure of port cell confinement	160kPa (Port)
Failure of NBI cell confinement	200kPa (NBI)
Failure of gallery confinement	105kPa (Gallery)

2. Methods of Analysis

MELCOR code version 1.8.6 was used to calculate the radioactive material release and transport for hydrogen and dust explosion accident. MELCOR code is capable of modeling reactor coolant thermal hydraulics, transport of fission products, aerosol dynamics and release of fission products to environment [5]. Modifications were made to model nuclear fusion devices such as aerosol transport module modifications for gas mixtures, HTO transport model, and so on. MELCOR can calculate combustion of gases in control volumes, yet the code does not hold an explosion model. Therefore, external control volume simulating the hydrogen explosion was attached on the left side of the vacuum vessel. Figure 1 shows the nodalization used for the calculation.

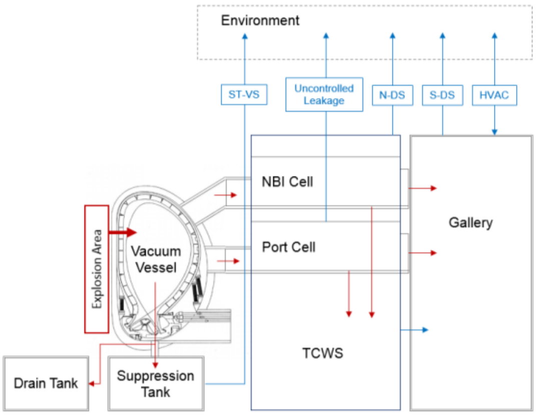

Fig. 1. Schematic of MELCOR model

The total free volume of the VV is 1715 m³, port cell is 200 m³, the free volume of NBI cell is 6755 m³, and the free volume of the gallery is 72000 m³. Additional 100 m² area volume is assumed as an explosion area where a rapid pressure increase during hydrogen and dust explosion is simulated. The free volume of VV itself is modeled as 1615m³ to make total of 1715 m³ by including the volume of explosion area. The pressure of the explosion area was defined through tabular function to make the highest pressure peak of the VV reach 565kPa. The temperature of the VV atmosphere was modeled by setting external energy source into the VV. Listed below is the assumptions made in the analysis:

- The VV pressure suppression system bleed lines open at reaching the defined set-points;
- ST-VS and normal detritiation system (N-DS) restore sub-atmospheric pressure inside VV;
- S-DS exhausts air in the gallery in order to maintain sub-atmospheric pressure after room isolation in case of contamination;
- Uncontrolled leak from the TCWS vault due to the differential pressure is defined as 80% to the gallery and 20% in the environment according to the surface area interfacing the gallery volume;
- Gallery is isolated when the concentration of tritium or dust in the gallery reaches set point;
- Off-site power is lost at the beginning of the event;
- The class III power is used to power the ST-VS, N-DS, and S-DS.

ST-VS exhausts air from suppression tank with filtering efficiency of 99.9% for dust and 99.0% for HTO. N-DS continuously exhausts air from port cell and S-DS exhausts air from gallery to maintain sub-atmospheric conditions. The S-DS is not activated initially, however, when the contamination of the gallery exceeds 0.2766kg-tritium/m³, the system is actuated with delay time of 5 minutes. The filtering efficiency of S-DS is assumed to be identical with the N-DS. The heating, ventilation and air condition (HVAC) system stops operating as the gallery is contaminated, with 30 seconds of delay time until complete isolation. Table II elaborates the initial conditions used in the calculation.

Table II: Pressure Sequence of Hydrogen and Dust Explosion Accident

Parameters	Values
Mobilized tritium in VV (HTO)	1kg
Mobilized tungsten dust	1005kg
Gallery HVAC ventilation rate	24 air-volume/day (no filtration)
Uncontrolled leakage rate (LR)	If P<300Pa, LR=Δ P/300Pa; If P>300Pa, LR=(Δ P/ Δ P_0)$^{0.5}$
ST-VS set point	ST pressure > 90kPa
ST-VS processing rate	150 m³/h (3 minutes delay)
ST-VS/N-DS filtering efficiency	99.0% for HTO 99.9% for dust
HVAC isolation set point	>0.2766kg-T/m³ in gallery (30 seconds delay)
S-DS processing rate	3000m³/h
S-DS filtering efficiency	99.0% for HTO 99.9% for dust

3. Results and Discussion

The peak pressure and temperature of the VV is set to be identical with the ITER AAR results for comparison.

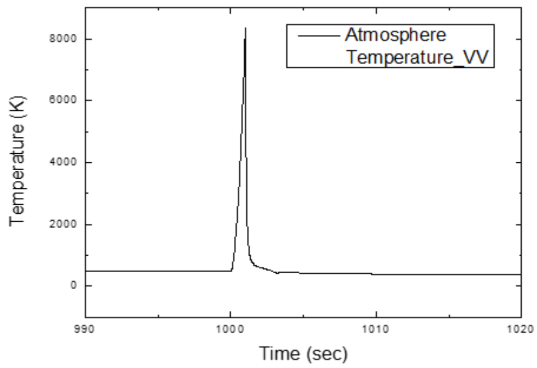

Fig. 2. Atmosphere temperature of vacuum vessel

The pressure of the vacuum vessel reached 565kPa due to the rapid pressure increase in the explosion area as modeled. Also, the peak temperature of the VV atmosphere is about 8300K due to the external temperature source into the VV.

The analysis showed overall accident scenario for explosion area model to follow similar scenario presented in the ITER AAR model. The fast pressurization of the vacuum vessel resulted the bleed line valve into the suppression tank and drain tank to open at 1.12 and 2.31 seconds after the explosion, respectively. The confinement of the port cell and NBI cell was intact resulting no air flow into the gallery.

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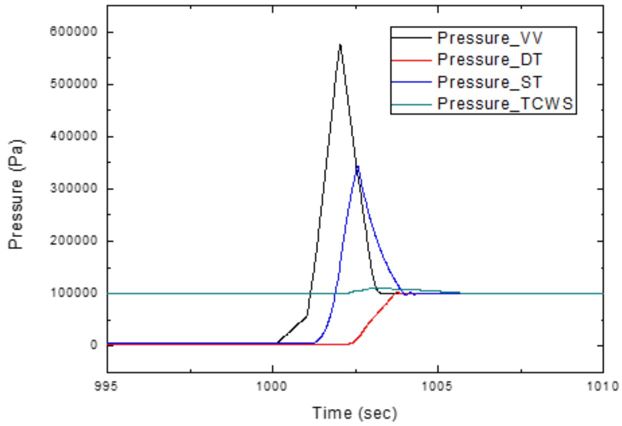
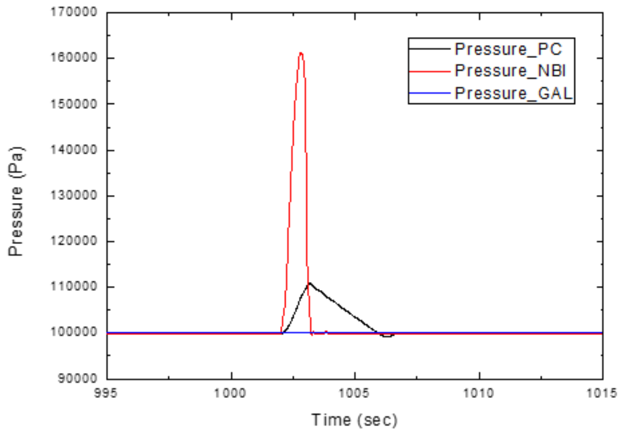


(a) Pressure of VV, DT, ST, and TCWS vault



(b) Pressure of port cell, NBI cell, and gallery

Fig. 3. Pressure transient of ITER explosion area analysis

The peak pressure of port/NBI cell and TCWS vault, however, were slightly different from the ITER AAR results. Maximum pressurization of the port cell, NBI cell, and TCWS vault presented in ITER AAR are 130kPa, 183kPa, and 108kPa, respectively. On the other hand, the peak pressure with the explosion area are 161.3kPa, 110.88kPa, and 110.99kPa reached at 2.82, 3.16, and 3.04 seconds after the explosion.

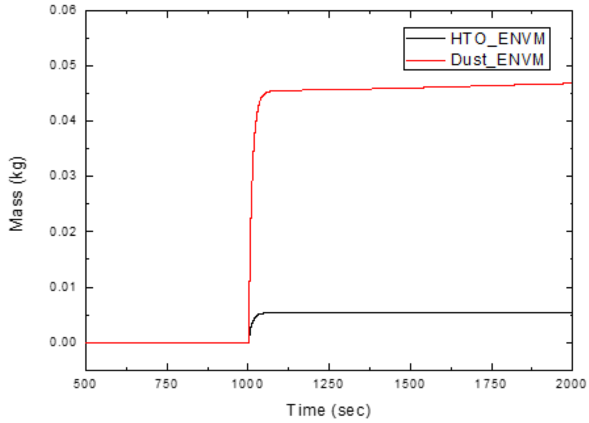


Fig. 4. Radioactive material quantity released into the environment

Analysis showed that most of the tritium and dust remained inside the vacuum vessel where about 5g of tritium and 45g of tungsten dust was release into the environment. Compared to the ITER AAR results of 9.035g of tritium and 4.67g of tungsten dust into the environment, transportation of tungsten dust into the environment was significantly high. Moreover, the aerosol distribution results for the explosion area model analsis was different from that of the ITER AAR results. AAR analysis resulted fast transportation of tritium and dust materials where most of the mobilized radioactive material were transferred into the port cell soon after the explosion..

On the contrary, as shown in figure 5 and 6, the aerosol distribution inside the vacuum vessel for the explosion area model was divided into 11 sections, which most of the aerosol remained in 4th section of the vacuum vessel.

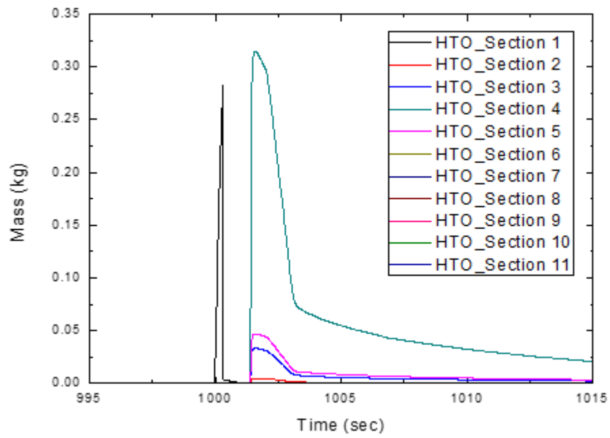


Fig. 5. Tritium distribution within the vacuum vessel

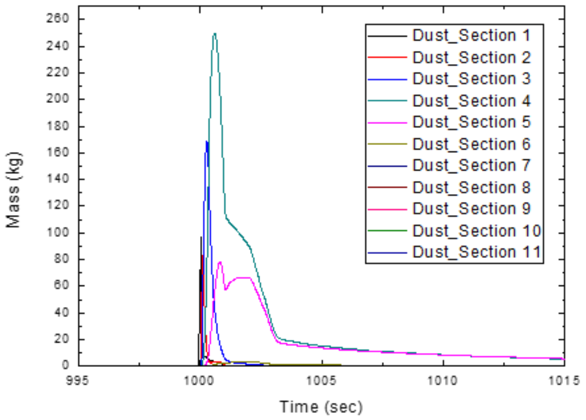


Fig. 6. Radioactive material distribution within the vacuum vessel

The air flow due to the hydrogen explosion was designed by giving intentional air flow pathway from the explosion area to the vacuum vessel. However, the designed air flow also caused backflow carrying considerable amount of aerosol back into the explosion area rather than being transported into the port cell through the penetration line. In other words, setting external explosion area resulted additional possible air flow inside the vacuum vessel which reduced the air flow into the port cell as presented in the AAR. This may have caused different aerosol release characteristics, but this results shows possible accident scenario depending on the explosion position in the vacuum vessel.

4. Conclusions and Further Work

Hydrogen and dust explosion in the ITER vacuum vessel using explosion area was modeled with MELCOR code. The vacuum vessel confinement was ruptured making a penetration line between vacuum vessel and port/NBI cell. The overall pressure transient of the accident was similar with the ITER accident analysis report (AAR) results, however, amount of tungsten dust release into the environment was significantly different. Also, most of the radioactive material flowed back into the explosion area at the moment of the explosion resulting most of the material remained inside the vacuum vessel. Further evaluation in modeling explosion air flow is required to simulate reliable aerosol transport behavior due to hydrogen explosion.

ACKNOWLEDGEMENTS

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