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Study of Additional Suppression System Effect in Accident Analysis of Nuclear Fusion DEMO Reactor

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1. Introduction

Hydrogen explosion is one of the most dangerous accident phenomena in fusion reactor operation. In a fusion reactor, deuterium and tritium are used as the fuel inside plasma chamber. And also, non-ingnorable amount of hydrogen can exist in a condensed state around the cryo-pump during normal operation. Under accident conditions like loss of coolant accident or plasma disruption, Temperature increase of the cryo-pump is used to mobilize large amounts of tritium in the vacuum vessel. At the same time, when plasma termination due to air ingress happens, the activated dust on the surfaces can be mobilized. Enough oxygen exists within the vacuum vessel when a vacuum boundary rupture is happened. Those mobilized tritium and dust aerosol with enough oxygen can make explosion inside the vacuum vessel that damages the containment building. This kind of explosion can damage the containment building even though the explosion happens within the vacuum vessel. In this study, hydrogen and dust explosion accidents of the International Thermonuclear Experimental Reactor (ITER) were applied to the design of a Korean fusion demonstration reactor to conduct a preliminary safety analysis. And the effect of suppression system for DEMO reactor is conducted. MELCOR [1] software was used to simulate. As a result, the aerosol distribution and its release route are calculated and the final amount of aerosol released to the environment was compared to the release guidelines.

2. Methods and Results

In this section, to model the nuclear fusion demonstration reactor, the design parameter of primary heat transfer system and secondary confinements.

2.1 Korean DEMO reactor modeling using MELCOR

Korean DEMO fusion reactor design is not determined [2], [3] but most design parameter are based on the ITER design. Modeling Korean DEMO fusion reactor has two parts. One is primary heat transfer system which contains Vacuum vessel, first wall, blanket, in/out manifolds, hot leg/cold leg, main pumps, pressurizer and steam generator. DEMO will use 4 loops of pressurized water like pressurized water reactor (fission). And the other is volumes of confinement building. Those volumes will be the path of aerosol to the environment. If those volume are pressurized due to some reason like heating from decay heat, hydrogen explosion transient or loss of coolant accident. To reduce pressure inside those volumes, suppression systems operate during accidents. Vacuum vessel suppression system, detritiation system and HVAC isolation system are referred from ITER safety systems.

Table I shows the conditions for the primary heat transfer system. This Korean DEMO reactor generates about 2.2 GWth inside and surface of blanket. Blanket design is referred from [4], [5].

Table I: PHTS design parameters

Parameters	Value
Number of loops	4 loops (1 steam generator and 1 pressurizer each)
Operation pressure	15 MPa
Coolant mass flow rate per each loop	3800 kg/s
Inlet temperature to the blanket system	520 K
Outlet temperature to the blanket system	622 K
Total heat generation inside blanket per each loop	468.5 MW
First wall plasma heat	103.25 MW
Coolant volume per each loop	260 m^3

Table II shows the conditions for the confinement volume. Most of the designs are referred from ITER and the ratio between DEMO and ITER vacuum vessel. The vacuum vessel volume is 2028.4 m^3. This value comes from the ration of blanket system between ITER and Korean fusion DEMO reactor. And other volumes like Port cell, NBI cell, Gallery is referred from ITER. Each pressure design limits are 565 kPa for VV, 160 kPa for Port cell and 200 kPa for NBI cell. Leakage rate is proportional to the square of pressure difference between two volumes.

Table II: Korean DEMO reactor confinement building parameter

Parameters	Value
Vacuum vessel volume	2028.4 m^3
Port cell volume	810 m^3
NBI cell volume	74.17 m^3
Gallery volume	26701.97 m^3
Vacuum vessel design limit of pressure	565 kPa To : Port cell, NBI cell
Port cell design limit of pressure	160 kPa To : gallery
NBI cell design limit of pressure	200 kPa To : gallery
Port/NBI cell Uncontrolled leakage to gallery	$\sqrt{\frac{\lvert P_1 - P_2 \rvert}{300\ Pa} \cdot \frac{Volume}{24 \cdot 3600}}$ $\lvert P_1 - P_2 \rvert < 300\ Pa$ and $\frac{\lvert P_1 - P_2 \rvert}{300\ Pa} \cdot \frac{Volume}{24 \cdot 3600}$ $\lvert P_1 - P_2 \rvert \geq 300\ Pa$
Gallery design pressure	105 kPa

Table III shows the basic safety systems inside DEMO reactor. Volume and parameters are referred from ITER RPrS [6], [7]

Table III: Korean DEMO reactor basic safety system

Vacuum vessel suppression system	Volume: 2246 m^3 (water volume: 1055 m^3) (Rupture disk: Δ P = 94 kPa) (Bleed line: Δ P = 200 kPa)
ST-VS	Open bleed valve = 1 s Opening pressure = 94 kPa Processing rate = 150 m^3/h
HVAC isolation system	Opening valve: 30 sec delay Isolation criteria: 1.844 g HTO/m^3 Processing rate: 1 gallery volume per day = 0.31 m^3/s
Detritiation system	Opening valve: 300 sec delay Operation criteria: 0.2766gT/m^3 = 1.844 gHTO/m^3 Processing rate = 150 m^3/h

2.2 Accident cases and suppression system

In this accident analysis, hydrogen explosion with loss of coolant accident is used to study the effect of suppression tank. The accident scenario is referred from RPrS. In the RPrS, two accidents are independent to each other and are not considered to happen in the same time. Scenario shows in Table IV. Before 1000 seconds, the whole system maintains the steady state. In 1000 seconds, hydrogen explosion with boundary rupture is happened. LOCA, coolant pipe break comes from the impact of plasma disruption when the explosion comes. In this study, the various detritiation system processing rate is considered and compared with the amount of radioactive dust release and pressure transient inside gallery.

Table IV: Accident scenario and simulation case study

Accident scenario	~ 1000 sec	Steady state operation
	1000 sec	Hydrogen explosion with boundary rupture
	1000 sec ~	Loss of coolant accident (0.1 sec opening time) Break area = 0.00104 m^2
Case study	Detritiation system processing rate	
Case 1.	Rate = 150 m^3/h (base)	
Case 3.	Rate = 350 m^3/h	
Case 3.	Rate = 450 m3/h	

3. Results and conclusions

Figure 1 shows the pressure transient results of single explosion accident with LOCA accident. As shown below, the explosion volume makes temperature and pressure inside itself and the valve between explosion volume and vacuum vessel opens to deliver the explosive pressure. The peak explosive pressure reaches up to 600 kPa inside explosion volume and vacuum vessel.

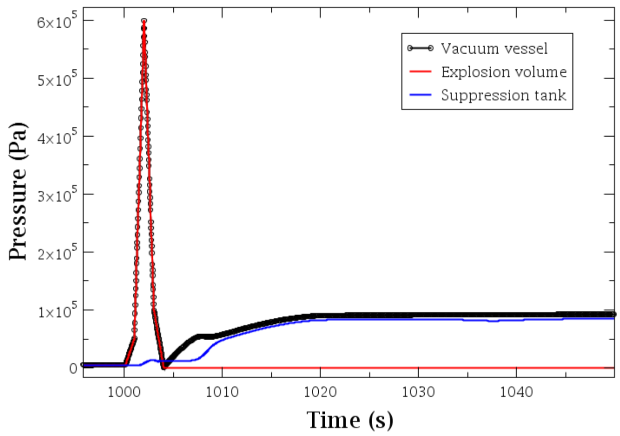

Fig. 1. Pressure transient results of single explosion accident with LOCA accident

Figure 2 shows the filtered dust mass through detritiation system from gallery. Dust produced inside the vacuum vessel will move to outside (environment) with pressure difference. 3 cases. Case 1 is base case and case 2 shows twice more processing rate and case 3 shows 3 times more processing rate. The results in figure 2 shows not promising. Table V shows the data of processing rate and maximum filtered dust amount.

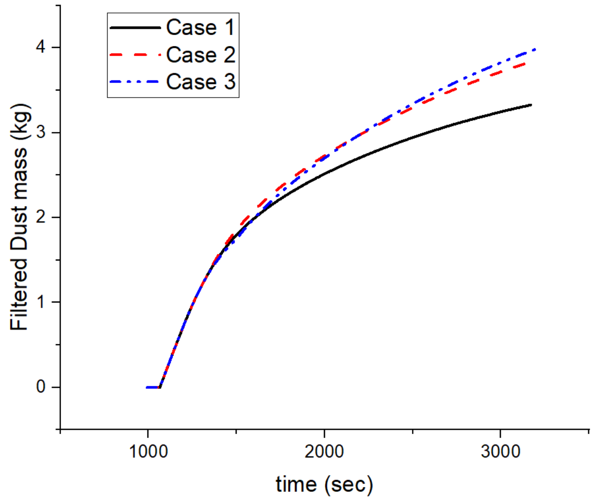

Fig. 2. Filtered dust mass through detritiation system between environment and gallery volume.

Table V: Processing rate and filtered dust mass

Case	Processing rate	Filtered dust max
Case 1.	150 m^3/h (base)	3.3269 kg
Case 2.	350 m^3/h	3.8432 kg (16 % enhance)
Case 3.	450 m3/h	3.9799 kg (20 % enhance)

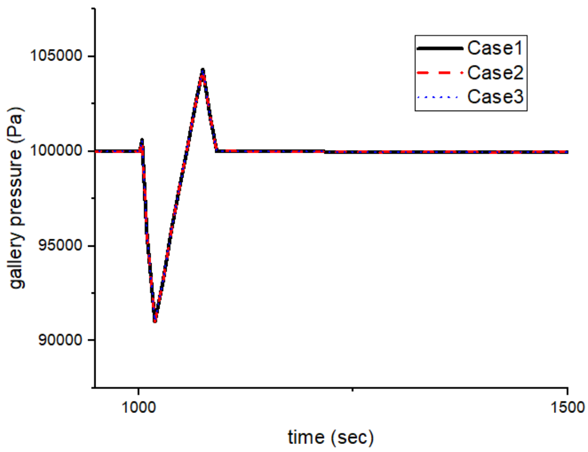

Fig. 3. Pressure transient inside gallery for each Case.

The filtered result shows 20 % filter performance for 3 times of processing rate. This can be shown that this processing rate is not sufficient for decrease pressure inside confinement building. But, as shown in Figure 3, the pressure transients inside gallery for each case below the atmospheric pressure (below 100 kPa). Those results show that this type of detritiation system is enough to suppress the confinement building but the filtering performance is not enough. To satisfy this filtering performance, other system is needed not with just detritiation system through gallery.

ACKNOWLEDGMENT

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