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KSTAR Severe Accident Analysis using MELCOR : Ex-vessel Coolant Pipe Break with Failure of Fusion Power Termination System

Sung Bo Moon, In Cheol Bang*
School of Mechanical and Nuclear Engineering
Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gil, Ulju-gun, Ulsan, 689-798, Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

International Thermonuclear Experimental Reactor (ITER) is a fusion research reactor in France to test and prove the nuclear fusion technology and scientific feasibility for future safe energy source. Nuclear fusion is one of promising energy source which can minimize the risk of hazards and environmental damage because of low radioactivity of tritium (much lower than radioactivity of plutonium and uranium). However, building strong torus magnetic field environment to sustain plasma needs high temperature for plasma environment and low temperature for high magnetic field. This extremely cold structure is maintained by cryostat. This reactor condition makes serious material limitation and gives the importance of safety analysis. To get permission of construction of fusion reactor, ITER preliminary safety research analyzed risk assessments. To investigate the consequence of severe accidents in fusion reactor, a number of thermal hydraulics simulation codes were used (ECART, INTRA, ATHENA/RELAP and so on). MELCOR is chosen as the thermal hydraulics code to simulate the consequence of radioactive material release from accident in preliminary safety report [1]. Capability of the simulation code for fusion reactor severe accident analysis is ability to simulate the hydraulic system in ITER and the transport phenomenon of radionuclides. MELCOR is a fully integrated code that models the accidents in Light Water Reactor (LWR). To analyze the accidents in ITER, MELCOR 1.8.2 version is modified [2].

The amount of released radioactive material is acceptance criteria in the nuclear fusion safety. There are three kinds of radioactive materials in fusion reactor; tritium (or Tiritiated water: HTO), activation products (AP) of divertor or first-wall and activated corrosion products(ACP). In generic Site Safety Report (GSSR), the release guidelines for tritium and activation products are listed for normal operation, incidents, and accidents. And this guidelines presented in Table 1.

Not only ITER, the KSTAR (Korea Superconducting Tokamak Advanced Research) is also developing fusion research reactor. The scale of facility is smaller than ITER but this small scale of facility offers the experimental flexibility to develop fusion technology. The major differences between KSTAR and ITER systems are presented in Table 2. Fusion source difference between KSTAR and ITER is D-D fusion reaction (Deuterium-Deuterium fusion reaction) and D-T fusion reaction (Deuterium-Tritium fusion reaction). This D-D fusion makes one tritium by 50 percent chance. The radioactivity of tritium is small to consider compared to radioactive materials in nuclear fission reactor. This reaction is presented in equation (1)

In the present work, conservatively estimated tritium inventory amount in KSTAR is used with one of the most severe accident in ITER; Ex-vessel pipe break with Fusion Power Termination System (FPTS). The MELCOR KSTAR input is made by scaling down the ITER input deck. So, the detail system is not same with the real KSTAR system. But important systems are furnished to study the effect of each system. Accident analysis is carried out after steady state is maintained for 1000 sec. As a result, radioactive material leakage is simulated with aerosol release package to compare to release guideline.

2. Accident and KSTAR system nodalization

2.1 Ex-vessel Coolant Pipe Break with Failure of FPTS

The objective of this study is the estimating the mobilized aerosol behavior and aerosol leakage from the KSTAR vacuum vessel to environment for Fusion power termination system failure accident and ex-vessel pipe break. First, modified MELCOR ITER input deck without transient input is simulated to maintain steady state. And then, conservatively calculated tritium inventory inside vacuum vessel and primary heat transfer system from D-D fusion reaction is used to trace and study the tritium leakage behavior. This D-D fusion reaction is presented in equation (1). The size of KSATR vacuum vessel system is about six times bigger than that of KSTAR. So the ITER input deck is modified into 1/6 reduced size of primary system.

Ex-vessel Primary Heat Transfer System pipe is beginning of this severe accident. The fusion power termination system is also failed. This accident is one of most dangerous accident. Power transient from failure of fusion power termination system increases the FW temperature up to 1080 ºC which makes double ended pipe break of first wall. Coolant from first wall pipe into

Table I: Project Release Guideline

Events or Conditions	**Project release guideline (a)**
Normal operation	<1 g-T as HT and 0.1 g-T as HTO and 1 g-metal as AP and 5 g-metal as ACP per year
Incidents	<1 g-T as HT or 0.1 g-T as HTO or 1 g-metal as AP or 1 g-metal as ACP or equivalent combination of these per event
Accidents	<50 g-T as HT or 5 g-T as HTO or 50 g-metal as AP or 50g-metal as ACP or equivalent combination of these per event
(a) HT: elemental tritium (including DT); HTO: tritium oxide (including DTO); AP: divertor or first wall activation products; ACP: activated corrosion products	

$$\begin{aligned} &{}^2_1D + {}^2_1D \rightarrow \\ &\quad {}^3_1T\,(1.01 MeV) + \mathrm{p}^+(3.02\ MeV)\ 50\% \\ &{}^2_1D + {}^2_1D \rightarrow \\ &\quad {}^4_2He(0.82\ MeV) + n(2.45 MevV)\,50\% \end{aligned} \tag{1}$$

Table II: Comparison between KSTAR and ITER

Parameters	**KSTAR**	**ITER**
Radius	1.8 m	6.2 m
Plasma Current	2.0 MA	15 MA
Plasma duration	300 sec	400 sec
Plasma fuel	H, D-D	H, D-T
Magnetic field	3.5 Tesla	5.3 Tesla
Main system	8.6 m (H) 8.8 m (D)	24 m (H) 28 m (D)
Heating capacity	31 MW	10 MW

vacuum vessel terminates plasma fusion reaction. Coolant ingress into hot vacuum vessel leads to pressurization of reactor systems because of boiling. There are suppression systems and detritiation systems to maintain pressure inside confinement building lower than atmospheric pressure. In the KSTAR simulation, all of those safety systems are considered to control the radioactive material release to the environment. Also, as parametric study, safety systems which needs electric power are shut down.

In this research, input deck without cryostat heat structure was used to simulate accident. And some ITER accident scenarios are applied. After modify ITER input deck into KSTAR, plant steady state is maintained until overfueling is started. 1000 seconds after, PHTS loop in upper vault breaks. The break size is 0.3422 m^2. Failure of fusion power termination induced by loss of coolant in PHTS loop is also considered. This criteria is from ITER Accident Analysis Report (AAR)

One extreme phenomenon of severe accident of fusion reactor is pressurization of vacuum vessel. Vacuum circumstance is essential to maintain plasma. If this vacuum boundary is destroyed by accident (pipe break, vacuum vessel penetration, leak through bypass), radioactive aerosol can be transport out of vacuum vessel. High temperature inside of vacuum vessel can expand air and vaporize coolant from first wall cooling pipe. So depressurization is important. For this, Vacuum Vessel Pressure Suppression System (VVPSS) is installed to suppress pressure inside vessel. Rupture disk (open when vessel pressure is larger than 94 kPa), and valve (open when vessel pressure is larger than 150 kPa) can operate VVPSS in the accidents. If radioactive aerosol reach to Generic Bypass Room (GBR), detritiation system operates to eliminate tiritium or other aerosols. Normal detritiation system (N-DS) is assumed to exchange 0.2 volume per day. Heat, Ventilating, and Air Conditioning (HVAC) circulates air between GBR and environment. This HVAC system is isolated after accident not to release hazardous material.

Figure 1 shows the description of severe accident scenario. And also shows the nodalization of input deck without cryostat structure. Cryostat is not implemented. The nodalization was divided into 5 systems; FW/IBB loop (1 separated loop and 9 averaged loops), plasma chamber and suppression system, vault system, OB/LIM control volumes and simplified VV heat transport system with diverter system. Difference between real ITER system and this input deck is the number of coolant loop (ITER has 3 FW cooling loops but this input deck uses 10 primary cooling loops). To calculate the tritum release from the system, time dependent function is defined to model the release of generated radioactive material and initially contained in vacuum vessel.

To apply tritium leakage of KSTAR, the D-D neutron source rate is used to estimate the total tritium amount at the end of operation in conservative method. Table 3 [3] shows the estimated operational parameters and neutron yields of the KSTAR tokamak.

Using full operation time about 300 seconds, the peak D-D neutron source rate is calculated about 2.5 x 10^{16}. This neutron generation rate changes over operating time. To consider conservatively, this maximum source rate is maintained during operation to calculate amount of tritium inside vessel. Because the probability of tritium production in D-D fusion reaction is 50 %, neutron source rate can be considered same with tritium source rate. So, initially mobilized amount of HTO is calculated about 1 g using multiplication of time and source rate and HTO molecular mass. Approximately, the output power of fusion reaction is assumed 1/6 of ITER. So amount of HTO is assumed about 166.7 g. Amount of HTO is represented in Table 4

Table III: Operational parameters and neutron yields of the KSTAR tokamak

	Final Operation
Pulse length (s)	300
Peak D-D neutron source rate (s^{-1})	2.5 x 10^{16}
Peak D-D neutron source rate (yr^{-1})	3.0 x 10^{18} At 2.45 MeV 9.0 x 10^{16} At 14.06 MeV

Table IV. The inventory of aerosol in VV

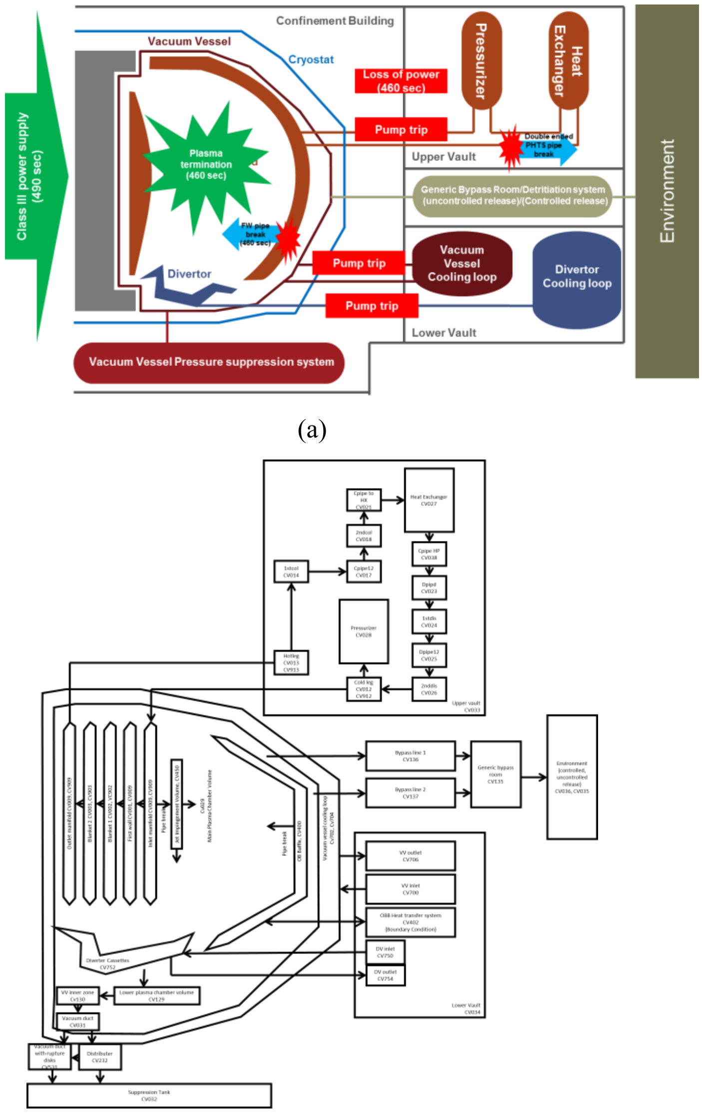
	Aerosol	**Source**	**Mass**
ITER	HTO	FW/IBB	1000 g
KSTAR	HTO (initially)	D-D reaction	1 g
	HTO (coolant)	Coolant-structure interaction	166.7g

3. MELCOR simulation results

Figure 2 shows the results of accident. Each graph represents Dust aerosol mass in Vacuum Vessel, first wall temperature, Tocamak Cooling Water System pressure and Vacuum vessel coolant leak rate. At the beginning of accident, because of corrosion of first wall plasma facing structure, 1 tone of dust is formed.

This amount of radioactive dust is fatal to environment. But the coolant leak after first wall coolant pipe break suppresses this aerosol leakage from vacuum vessel. Aerosol can be deposit on heat structure, adhere each other. So the aerosol section (aerosol mass categorization) converges into high section (heavy aerosol). The leakage to environment is too small to consider. Figure 2 (b) shows the temperature of first wall. Failure of fusion power termination makes the higher first wall temperature above 1080 °C.

Table 5 shows the result of KSTAR simulation and AAR simulation. Because of small volume of vault, the pressurization of TCWS vault is much faster than that of ITER. But the time for heating up the FW to 1080 °C is almost same as ITER design. Bleed line between VV and suppression tank is not opened in KSTAR case. This means the pressure in VV is not sufficiently increased to the its upper limit, 94 kPa. The reason is that all of the coolant in PHTS is spilled to TCWS vault.



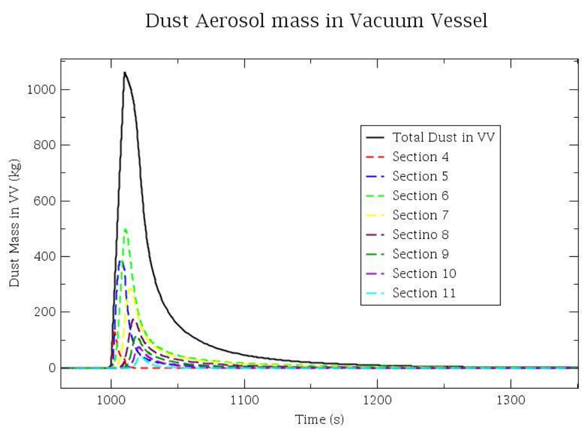
(a)

(b)

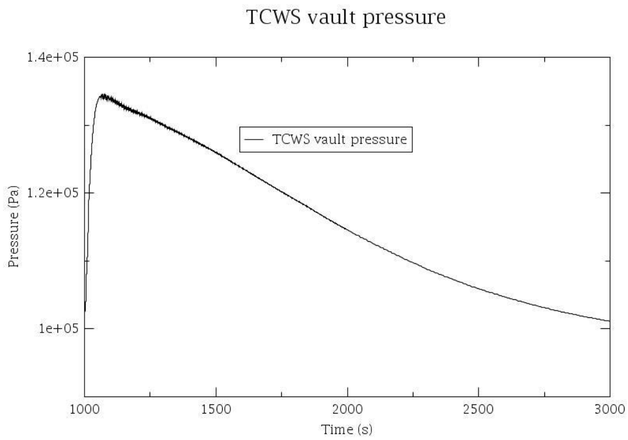
Fig. 1. (a) Detailed accident scenario diagram from accident analysis report (AAR) and (b) system nodalization

Table V: accident time sequences between RPrS and this research

Event sequence	AAR (s)	This Study (s)
Double ended pipe break in FW/BLK PHTS inside TCWS vault	0	0
TCWS vault pressure reaches 105 kPa	30	5
FW surface temperature reaches 1080 ^oC	460	499
Plasma termination, nuclear heating drops to decay heat	460	499
Loss of off-site power	460	499
In-vessel coolant leak	460	499
Bleed lines open between VV and suppression tank (set point at 94 kPa)	900	X



(a)



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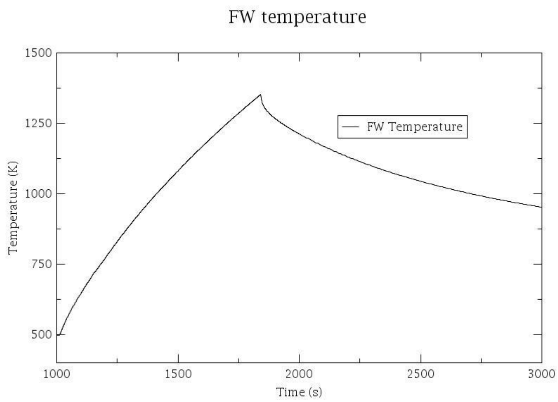

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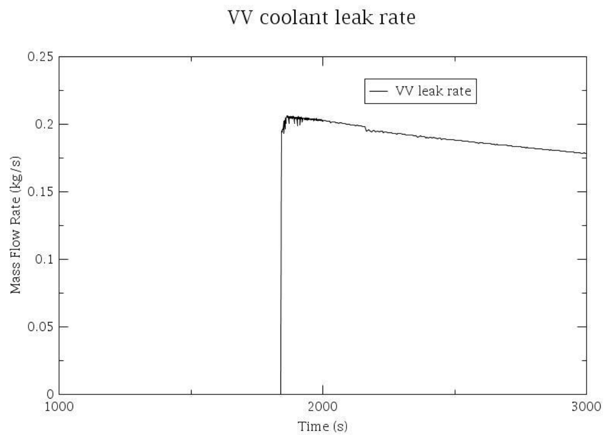

(d)

Fig. 2. The result of Fusion Power Termination System Failure accident analysis

3. Conclusions

In this research, follow-up study of safety analysis and simple safety analysis application in KSTAR was conducted with MELCOR. Although the input deck is not perfectly same as real ITER system and KSTAR system, the result of accident time sequence is not significantly different. And also the aerosol leakage of both type of research reactor is not significant compared to IAEA radioactive material release guideline because of safety systems which reduce the pressure inside VV and other spaces.

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