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Application of ITER Safety Analysis for KSTAR : Tritium Leakage from Fusion Power Termination System Failure Accident with MELCOR

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1. Introduction

International Thermonuclear Experimental Reactor (ITER) is a research fusion reactor in France to prove the technology and scientific feasibility of fusion energy. Nuclear fusion is one of the promising energy sources which can minimize the risk of hazards and environmental damage. However, to build torus plasma environment in vacuum vessel, high temperature for plasma environment and low temperature for high magnetic field are necessary for reactor vessel inside and magnet system structure respectively. This extreme reactor condition makes serious material limitation and emphasizes the importance of safety analysis. To get permission of construction license, previous researches like preliminary safety research have been analyzed risk assessments of fusion reactors. To simulate the severe accidents in fusion reactor, a number of thermal hydraulic simulation codes were used(ECART [1], INTRA [2], ATHENA/RELAP and so on). Before construction, to obtain ITER license about safety issue, MELCOR is chosen as the thermal hydraulic code to be used to simulate radioactive material release from severe accidents [3]. Capability of the simulation code in severe accident analysis is to simulate the cooling system in ITER, the transport of radionuclides during design basis accidents (DBAs) including beyond design basis accidents (BDBAs). MELCOR is 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 [4].

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

Not only ITER, the KSTAR(Korea Superconducting Tokamak Advanced Research) is also developing fusion research reactor. The scale of facility is rather smaller than ITER. This small scale facility makes the experimental flexibility to develop fusion technology. The major parameter deference between KSTAR and ITER is presented in Table 2. Fusion source difference between KSTAR and ITER is D-D(Deuterium-Deuterium reaction) fusion and D-T(Deuterium-Tritium reaction) fusion. This D-D fusion makes Tritium in the 50 percent chance. The radioactivity of tritium is small to consider, but, the accident analysis is indispensable.

In the present work, the conservatively estimated tritium inventory in KSTAR is used with one of the most severe accident in ITER; Fusion Power Termination System(FPTS) failure with multiple first wall pipe break. The MELCOR modified input deck is used to study and radioactive material leakage is simulated with aerosol release package to follow up the ITER safety analysis.

2. Accident and Plant system nodalization

The objective of this study is the estimation of aerosol leakage from the KSTAR vacuum vessel to environment. First, modified MELCOR input deck of this FPTS failure accident is simulated to compare with result from Preliminary Safety Report of ITER(RPrS) to validate this input deck. And then, conservatively calculated tritium inventory from D-D fusion is used in size-reduced ITER system to calculate tritium leakage. This D-D fusion reaction is presented in equation (1). The size of ITER 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.

This accident is initiated from fusion power growth due to overfueling of the plasma. This event is the bounding accident for all events related to possible plasma transients. Because of FPTS failure, the coolant temperature increases up to 170 oC which makes double ended pipe break. Flooding in vacuum vessel stops plasma fusion. After this, coolant ingress into vacuum vessel leads to pressurization. In the ITER, there are suppression system and detritiation systems to maintain pressure inside VV lower than atmosphere. In the KSTAR simulation, all of those safety systems are considered to control the radioactive material release to the environment.

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

In this research, input deck without cryostat structure was used to simulate FPTS failure accident. At the beginning, plant steady state is maintained until overfueling is started. After 1000 seconds, overfueling starts which leads increasing fusion power up to 1.9 GW. This plasma transient continues until coolant invades into vacuum vessel. This coolant pipe break begins when the temperature of outlet coolant reaches to 170 ^{o}C. Table III shows the input parameters and initial conditions.

$$\begin{aligned} {}^2_1D + {}^2_1D &\rightarrow {}^3_1T(1.01\ MeV) + p^+(3.02\ MeV) \quad 50\% \\ {}^2_1D + {}^2_1D &\rightarrow {}^3_2He(0.82\ MeV) + n^0(2.45\ MeV) \quad 50\% \end{aligned} \quad (1)$$

Table II. Comparison between KSTAR and ITER

Parameter	*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)	24m (H) 28 m (D)
Heating capacity	31 MW	110 MW

Table III. Initial values for system

Parameter	*Value*
Plasma chamber	
Main plasma chamber	
Pressure (Pa)	500
Volume (m^3)	2348
Suppression pool	
Pressure (Pa)	230
Volume (m^3)	2246
Bleed line	
Flow Area (m^2)	0.0716
Flow Length (m)	30
Pressure (kPa)	110
FW/IBB Loop	
FW	
Pressure (MPa)	3.576
Temperature (K)	429.5
Cold leg	
Temperature (K)	408.9
Hot leg	
Temperature (K)	461.3
Vault system	
Vault	
Volume (m^3)	10200
Pressure (kPa)	100
Temperature (K)	313
Low Vault	
Volume (m^3)	11200
Pressure (kPa)	100
Generic bypass room	
Pressure (kPa)	100
Temperature	293.23
Volume (m^3)	6000
Maximum fusion power	1900 MW
Break area	0.02 m^2
N-DS	0.2 volume per day
HVAC	24 volume per day

Figure 1 shows the simple description of ITER plant input deck that is used in this research. And figure 2 shows the nodalization of this ITER input deck systems without cryostat structure. 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 divertor system. Big difference between real ITER system and this inputdeck is the number of coolant loop. ITER has 3 FW cooling loops but this input deck uses 10 cooling loops. In this study, 1 loop which is not lumped is considered 3 loops in real ITER coolant loops. To calculate the radioactive tritum release from the system, the pre-defined data from input deck is used to define the initial inventory of HTO during accident.

To apply tritium leakage of KSTAR, the estimated D-D neutron source rate is used to calculate total tritium amount at the end of operation in conservative method. Table V shows the Operational parameters and neutron yields of the KSTAR tokamak. Full operation through 300 seconds, the peak D-D neutron source rate is about 2.5 x 10^{16}. This neutron generation rate is difference during operation time. But to consider conservatively, this maximum source rate is used to calculate amount of tritium. Because the probability of tritium production in D-D fusion reaction is same, neutron source rate is same with tritium source rate. So, using multiplication of time and source rate and HTO molecular mass, calculated HTO amount initially mobilizable is about 1g. And other HTO source is coolant inventory. Approximately, the output power of fusion reaction is assumed in 1/6 of that of ITER. So amount of HTO is assumed about 166.7 g. Amount of HTO is represented in Table IV.

Table IV. The inventory of aerosol

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

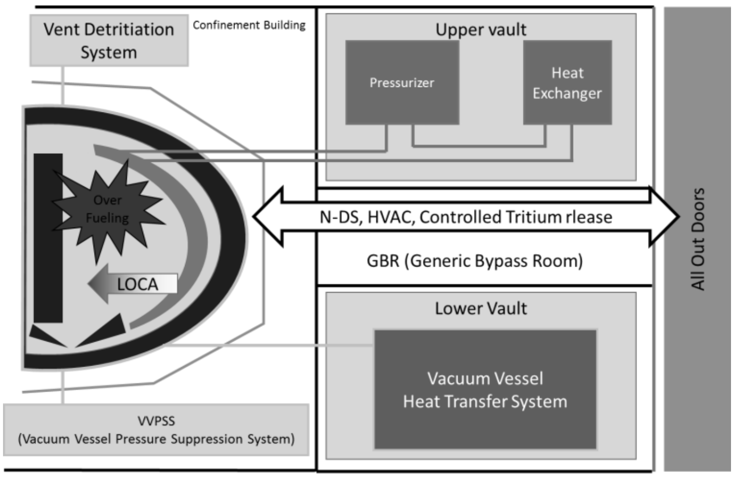


Figure.1 Simple description of ITER system

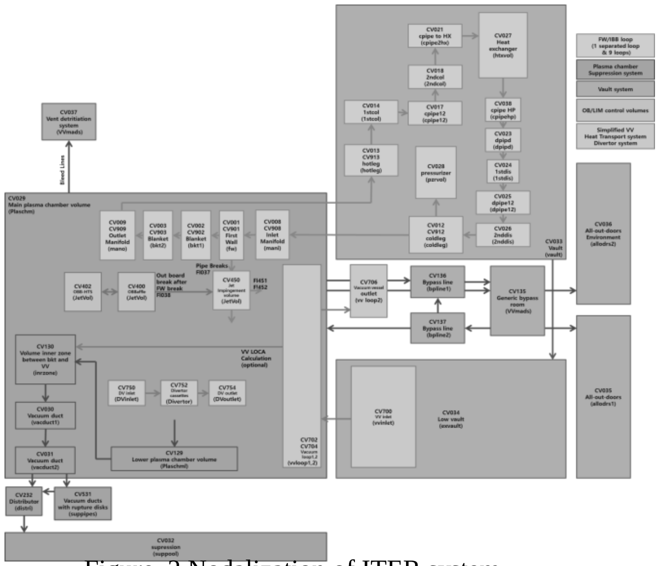


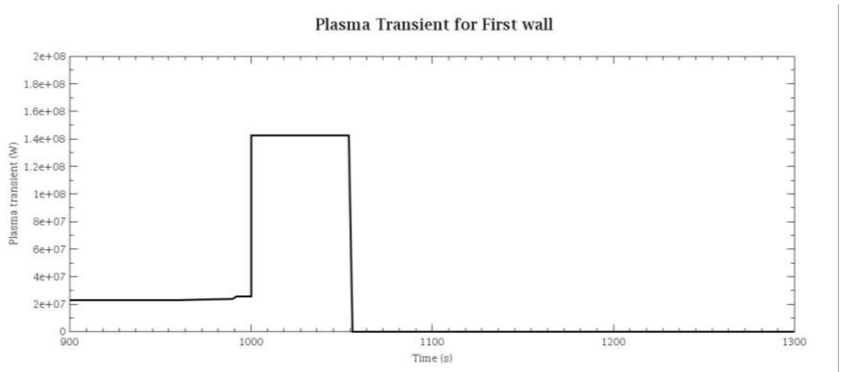
Figure. 2 Nodalization of ITER system

3. MELCOR simulation results and leakage analysis

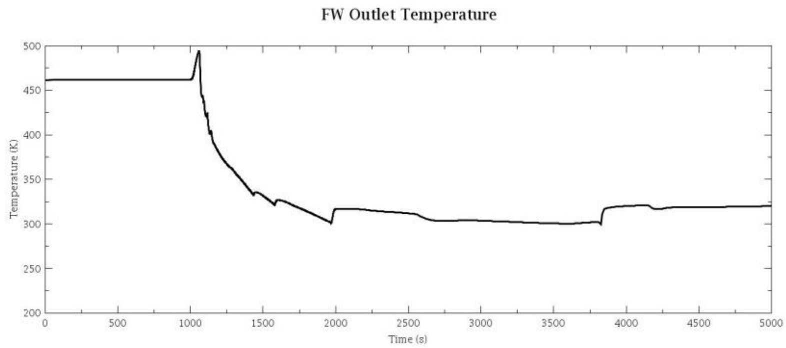
Figure 3 shows the results of accident in ITER. Plasma transient, FW outlet temperature, PHTS coolant inventory, vacuum vessel pressure, VVPSS pressure, HTO amount in VV by section, total amount of HTO in VV and HTO leakage to environment. Fig. 3 (a) shows the fusion power transient. Before 1000 s, the steady state is maintained. After 1000 s, because of overfueling, fusion power increased up to 1.9 GW until coolant invades to vacuum vessel. About 1 min later, outlet temperature of FW coolant loop makes coolant disposal to VV. The outlet temperature of FW coolant loop in fig. 3 (b). In RPrS, the failure of coolant loop starts 40 s after overfueling. This difference is caused by additional unbroken and lumped coolant loop in the input deck. Fig. 3 (c) is total coolant inventory of FW broken loop. And (d) represents the pressure of vacuum vessel and vacuum vessel suppression system. Fig. 3 (e) shows the HTO amount in VV sorted by its particle size(section). (f) shows the total amount of HTO in VV. And (g) shows the amount of released HTO aerosol from HVAC(Heating, Ventilating, and Air Conditioning) system. The pressure of GBR did not exceed 105 kPa and HVAC is not isolated. As a result, the HTO aerosol release is lower than the criteria. Table VI shows the accident sequence of this study and original RPrS research. Fig. 4 is result of KSTAR aerosol analysis. Because of size difference, total aerosol and section distribution behavior is similar each other but its mass. Also, the effect of safety systems that can decrease pressure inside building can reduce the radioactive material leakage to environment below the guideline.

Table V. Operational parameters and neutron yields of the KSTAR tokamak

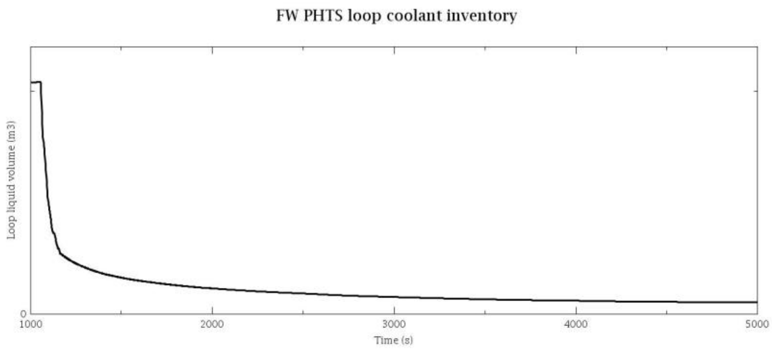
	Initial Operation	*Final operation*
Pulse length (s)	20	300
Peak D-D neutron source rate (s^{-1})	1.5 x 10^{16}	2.5 x 10^{16}
Peak D-D neutrion source rate (yr^{-1})	1.2 x 10^{17}	3.0 x 10^{18}
	At 2.45 MeV	At 2.45 MeV
	3.6 x 10^{15}	9.0 x 10^{16}
	At 13.06 MeV,	14.06 Mev
	25 shot d^{-1} x 40 yr^{-1}	2 shot d^{-1} x 20 yr-1
	= 10000shot yr^{-1}	



(a)

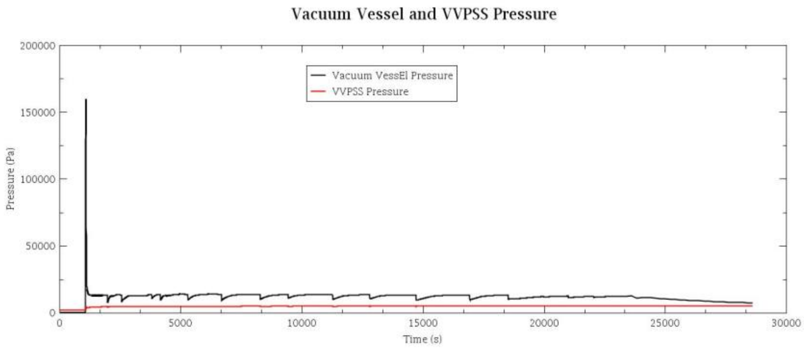


(b)

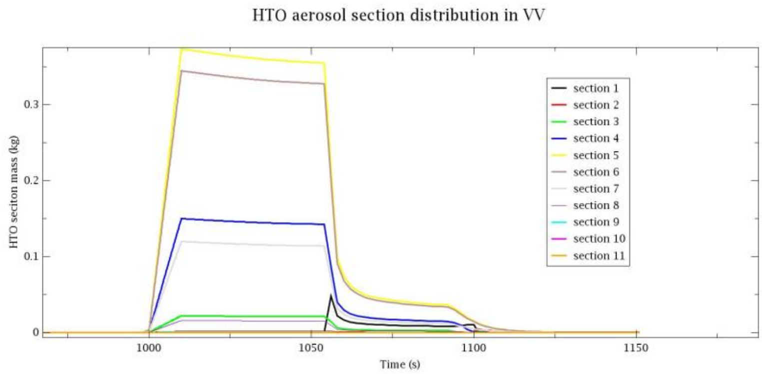


(c)

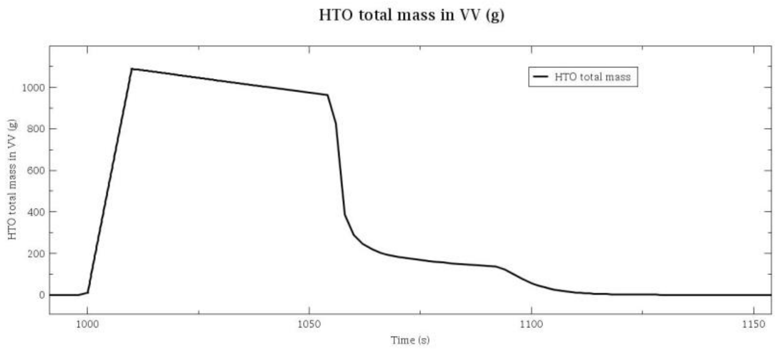
Figure. 3 The result of Fusion Power Termination System failure accident analysis.



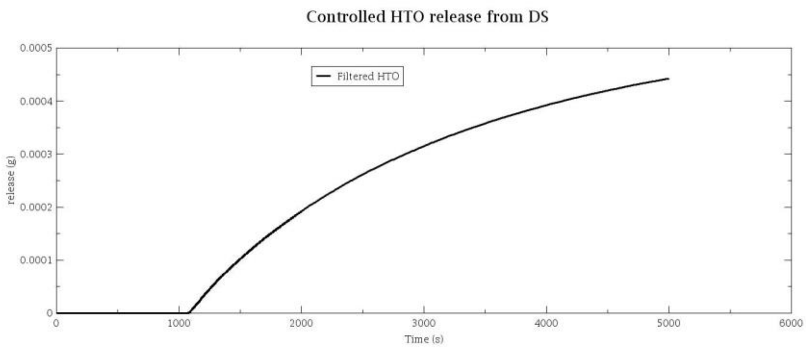
(d)



(e)

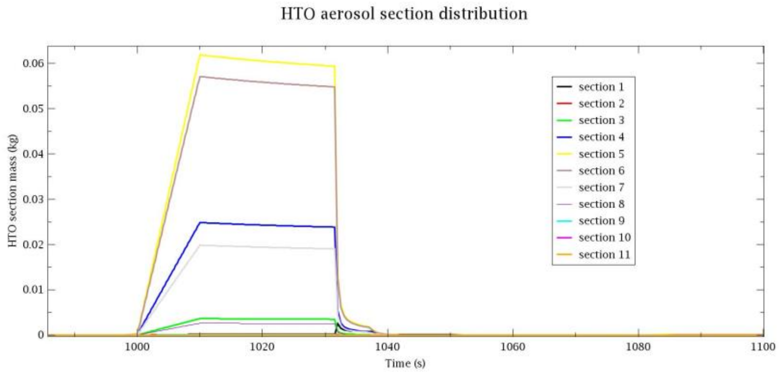


(f)

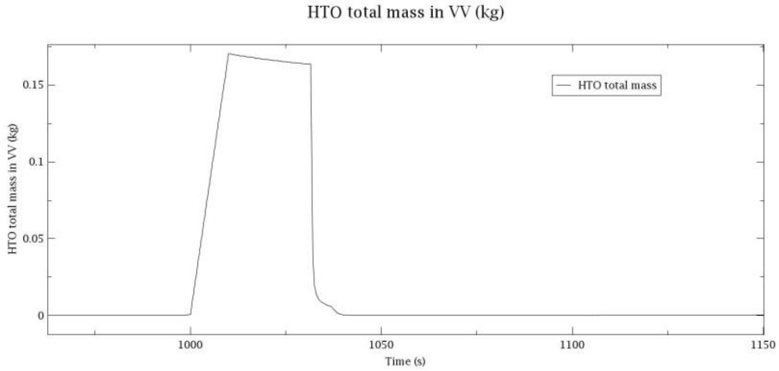


(g)

Figure. 3 The result of Fusion Power Termination System failure accident analysis.
(continued)



(a)



(b)

Figure. 4 Aerosol behavior in KSTAR Vacuum vessel

Table VI. accident time sequences between RPrS and this research

Event sequence	*RPrS (s)*	*This Study (S)*
Start of plasma transient “over fueling” with fusion power increase up to 1.9 GW	0	0
Double ended tube ruptures in all 3 FW/BLK cooling loops inside the VV	40	60
VV pressure reaches 94 kPa, bleed line opens	50	64
Steam pressure reaches the maximum of 150 kPa, rupture disks to VVPSS open	54.7	92
Pressure in the VV reaches the maximum of 151.3 kPa	55	92 (163 KPa)
Stop water ingress in VV	1800	2000
VV and pressure in FW cooling pipe stabilizes within 120-130 kPa pressure range	1900	2200 (130-140 kPa)

4. Conclusion

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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