MELCOR Severe Accident Analysis on the SMART Reactor

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1. Introduction

A severe accident is analyzed for Korea SMR reactor, SMART. Core melt down sequences are analyzed for SMART reactor core using MELCOR version 1.8.5. MELCOR is developed by Sandia National Laboratory for US NRC for the simulation of severe accidents in nuclear power plants. Two cases are simulated here and compared between them; one is the case for core having 3 concentric rings and the other is the case for core having 5 concentric rings. One inch break LOCA scenario is simulated and compared between these two core models. Time sequences for the thermal hydraulic behaviors of RPV and thermal heatup behaviors of reactor core are explained in graphically. Thermal hydraulic behavior such as the change of pressure, level, mass, and temperature of RPV is explained. Thermal heatup behavior of reactor core such as oxidation of cladding, hydrogen generation, core slumping down to lower plenum, and finally creep rupture of PRV lower head is explained. Engineered safety features such as safety injection systems (SIS), and Passive residual heat removal systems (PHRS), etc. are assumed to be not working.

2. Description of SMART

SMART is an SMR developed by KAERI and Standard Design Approval acquired from Korean Nuclear Regulatory Authority in 2012. It is an Integral PWR. All the RCS components such as reactor core, steam generators (SGs), pressurizer, reactor coolant pumps (RCPs), hot leg and cold legs, are merged in the reactor vessel. It has four RCPs (reactor coolant pumps) and eight helical coil steam generators. SG tube side is secondary side and shell side is primary side. (Figure 1)
It is combining innovative safety features and its own indigenous technologies with proven LWR technologies. SMART has substantially enhanced its safety with an integral layout of its major components, such as the reactor core, steam generator, coolant pump, and pressurizer which are integrated within a single pressure vessel.
SMART can serve as dual purposes for the seawater desalination and for the electricity generation.

Reactor core is composed of 57 standard PWR 17X17 fuel assemblies. The height of fuel assembly is a half (about 2 meter high) of that of standard PWR fuel assembly (4 meter high).

It has 4 trains of safety injection system (SIS) and two trains of shutdown cooling system (SCS). SIS and SCS pipings run through containment and auxiliary buildings. They are connected to the discharge side of RCPs. IRWST water is injected when LOCA signal occurs. At the top of the pressurizer, 2 safety depressurization valves and 2 safety relief valves are connected. If they are open then the water in reactor coolant system (RCS) is discharged to the In-containment refueling water storage tank (IRWST) via a reactor drain tank (RDT). IRWST is located at the inside bottom of the containment.
There is cavity volume below the reactor lower head. When the molten corium fallen down to the cavity, IRWST water is injected to the cavity by the actuation of the cavity flooding system (CFS).

When the reactor trips and the turbine trips, the main feedwater and steam line are closed and the passive residual heat removal system (PRHRS) is actuated to remove decay heat from the core through the SG tubes. PRHRS is composed of four (4) redundant trains. Each train of PRHRS has a big external cooling tank (ECT) on the top of the auxiliary building. The secondary coolant is cooled in tube side of the heat exchanger. The heat exchanger is located inside of the ECT tank. (Figure 2)

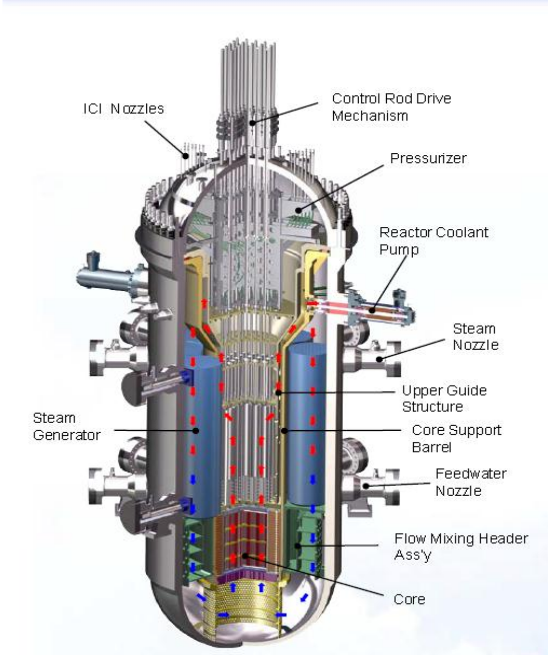

Figure 1 Integral Features of SMART RPV

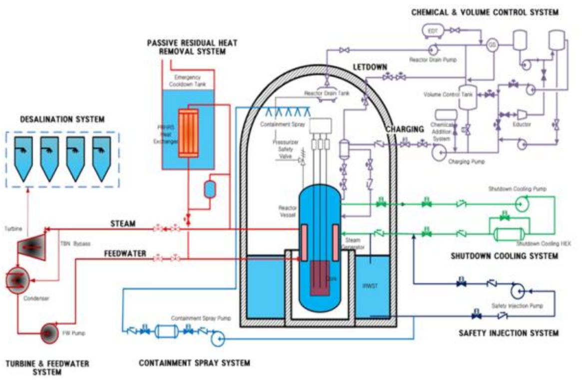

Figure 2 Engineered Safety Features of SMART Plant

3. MELCOR modeling

The core (COR) package of MELCOR code simulates melt down progression of core materials into the lower plenum and subsequent lower head failure behavior. Reactor core is modeled as having multiple concentric radial rings and multiple axial levels. Core is assumed to having 5 concentric rings. Total 16 axial levels are modeled. Levels 1 to 4 represent lower plenum. Level 5 represents core support plate. Level 6 to 16 represents active core region. (Figure 1).

Each cell (ring, level) is designated with three digits.
Cell ijj = ring i, level jj
I = 1 to 5
Jj = 01 to 14

For each cell the information on the geometry, the material mass and the heat transfer area should be given by user.

The core upper plate and the shroud (baffle) surrounding the core should be modeled has core HS (heat structure).

Each core cell may contain one or more components. A number of distinct intact components are modeled:
(1) fuel pellets;
(2) cladding;
(3) BWR canister walls, split into two parts: one part adjacent and another part that is not adjacent to the control blade (only permitted in a BWR);
(4) The PWR baffle (shroud) around the active core (only permitted in a PWR);
(5) PWR core formers between the baffle and the core support barrel (only permitted in a PWR);
(6) “supporting structure" (SS);
(7) “non-supporting structure (NS),” and
(8) “other structure (OS).”

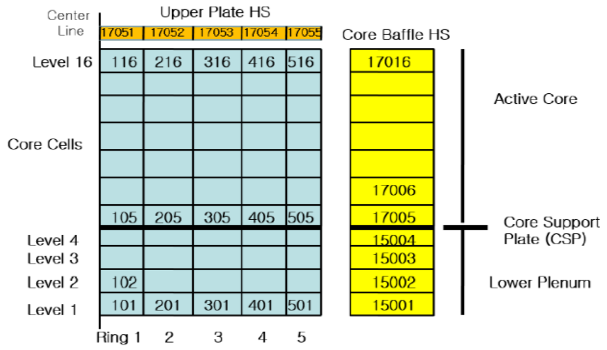

Figure 3. MELCOR COR Model for SMART Core (5 rings model)

CVH and FL packages simulate thermal hydraulic behaviors for the control volumes of RPV and Containment. (Figures 3 and 4).

Control volumes (CVs) in the reactor vessel are as follows.
CV150, Lower plenum (LP)
CV170, Core channel (channel)
CV180, Core bypass (bypass)
CV190, Upper plenum 1 (UP1)
CV191, Upper plenum 2 (UP2)
CV500, Pressurizer (PZR)
CV200, RCP suction (suction)
CV210, RCP discharge (discharge)
CV230, SG primary side, SG tube shell side, 4 SG are modeled as single volume
CV240, flow mixing header (FMHA) / downcomer (DC)

Control volumes (CVs) in the containment are as follows.
CV810, cavity volume below the reactor vessel lower head (cavity)
CV830, main volume of containment (CNT)
CV880, In-containment refueling water storage tank (IRWST)

Control volumes (CVs) in the SG secondary side are as follows.
CV630, SG secondary side, Inside of the SG helical coil tubes
CV628, Feedwater line
CV603, Steam line
CV940, turbine (TBN)

Flow path (FL) connects between two control volumes. Most of the flow paths are open normally. Some of the flow paths are modeled as “valve”, that is, those flow paths are closed normally, but they are open when they reach some specific conditions. The specific conditions are modeled by Control functions (CF). Some examples of valve modeling are as follows.

FL386, 1 inch diameter of LOCA (Pipe Break) occurs at time 0 s between CV 210 and CV 830.
FL603, When the turbine trip signal occurs, CV940 (TBN) is disconnected from the CV603.
FL512, SDS valve opens when RCS pressure increases above the specified pressure.
FL552, SRV valve opens and closes cyclically when RCS pressure increases above the specified pressure upper limit and RCS pressure decreases below the specified pressure lower limit.

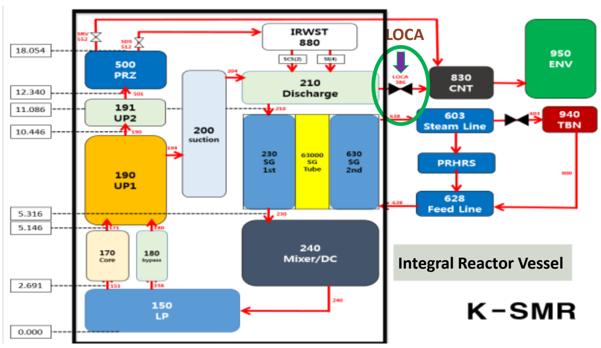

Figure 4 **MELCOR Control Volume and Flow Path Model for SMART RPV**

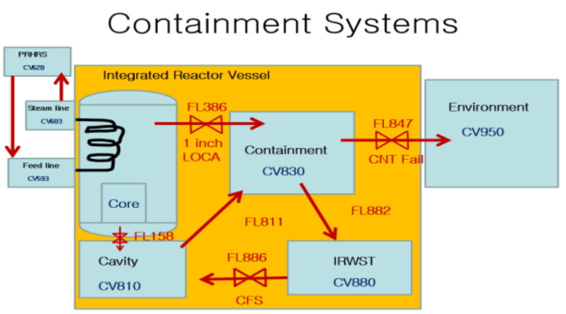

Figure 5 **MELCOR Control Volume and Flow Path Model for SMART Containment**

4. Accident Scenario

It is 1 inch LOCA (break) scenario. It happens at time 0 sec at FL386 (CV210 to CV380). CV210 is RCP discharge. CV830 is Containment. Break occurs in a pipe (maybe Safety injection line pipe or shutdown cooling line pipe). Because LOCA occurs in Reactor Vessel that The RCS Pressure will be decrease from normal operating pressure of 17 MPa to some lower pressure rapidly and eventually approach to atmospheric pressure when the lower head breaches by creep rupture. (Figure 6)
Table 1 describes major event sequences in the reactor core and rector pressure vessel. Coolant level in reactor vessel decreases to core top of active fuel (TAF) elevation at about 2 hour and it decreases to bottom of active fuel (BAF) elevation at about 6 hour. (Figure 7) When the TAF uncovery occurs, core and lower plenum temperatures will be increased rapidly (Figure 8) and zircalloy cladding starts to oxidize by metal steam reaction and hydrogen starts to generate. (Figure 9)
If coolant is boiled off in the reactor vessel then most of the fuel, cladding, and structural material (stainless steel) will be molten down and relocated to the lower plenum. Finally the lower head of reactor vessel will be broken by creep rupture and the molten corium will be falling down to cavity at about 12 hour. (Figure 10) In the cavity the molten corium will interact with the floor and wall concrete by MCCI (motel corium and concrete interaction). During the interaction of corium with cavity concrete, hydrogen and other non condensable gases will be generated and concretes will be ablated. MCCI phenomena are not shown graphically here. It will be described in future.

Table 1 Core Slumping Down Time Sequences

Events	time (sec)	time (hour)	time (hour)
Break (LOCA or SGTR)	9.72E+00	0.00	0.00
Rx Trip	4.28E+01	0.01	0.01
RCP Trip	5.58E+02	0.15	0.15
Fuel Top Uncovered : WATER-LEVEL=4.816 M	**7.26E+03**	**2.02**	**2.02**
Fuel Bottom Dryout : WATER-LEVEL=2.816 M	**2.28E+04**	**6.34**	**6.34**
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 104	**3.04E+04**	**8.45**	**8.45**
START OF DEBRIS QUENCH IN RADIAL RING 1	3.04E+04	8.45	8.45
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 204	**3.05E+04**	**8.46**	**8.46**
START OF DEBRIS QUENCH IN RADIAL RING 2	3.05E+04	8.46	8.46
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 304	**3.17E+04**	**8.82**	**8.82**
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 404	**3.44E+04**	**9.56**	**9.56**
LP Bottom Dryout : WATER-LEVEL=0.0 M	**4.74E+04**	**13.17**	**13.17**
THE LOWER HEAD IN RADIAL RING 1 HAS FAILED FROM CREEP-RUPTURE	**5.18E+04**	**14.39**	**14.39**
BEGINNING OF DEBRIS EJECTION TO CAVITY	**5.18E+04**	**14.39**	**14.39**
THE LOWER HEAD IN RADIAL RING 3 HAS FAILED FROM CREEP-RUPTURE	**5.40E+04**	**14.99**	**14.99**
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 502	5.65E+04	15.69	15.69
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 504	8.98E+04	24.94	24.94
END OF DEBRIS QUENCH IN RADIAL RING 5	9.12E+04	25.33	25.33
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 503	9.32E+04	25.90	25.90
CORE SUPPORT STRUCTURE (PLATE) HAS FAILED IN CELL 501	1.25E+05	34.82	34.82

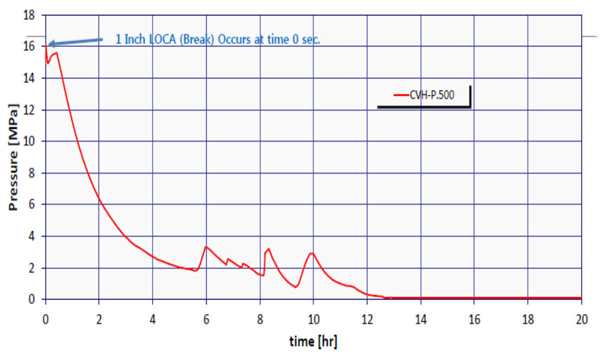

Figure 6 Reactor Vessel Pressure

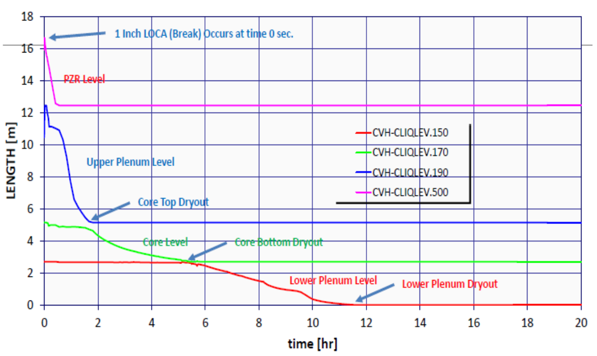

Figure 7 Reactor Vessel Water Level

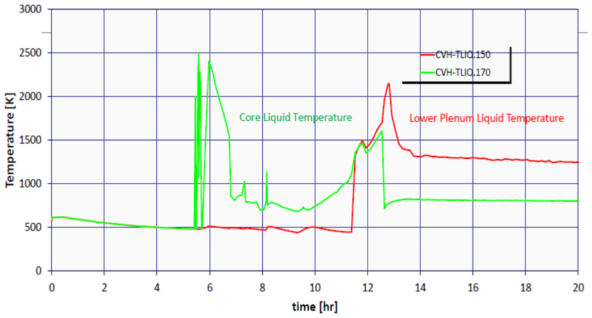

Figure 8 Core and Lower Plenum Water Temperatures

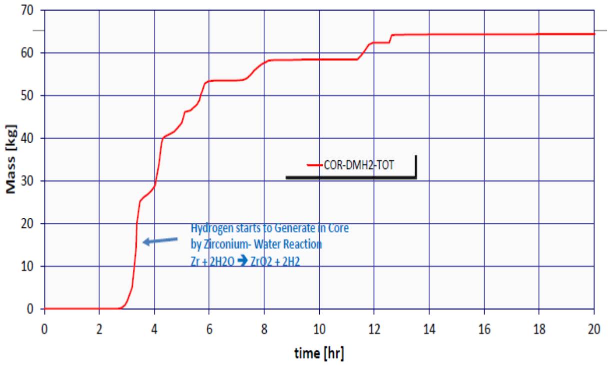

Figure 9 Hydrogen Generation in the Reactor Core

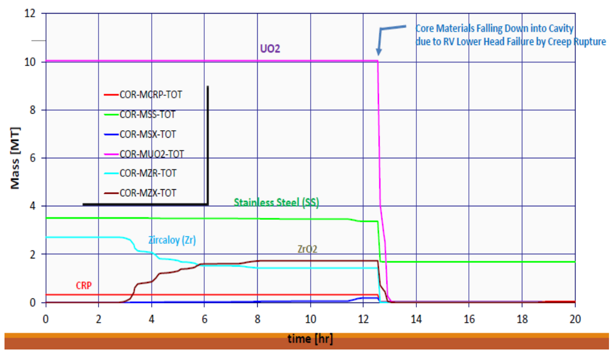

Figure 10 Mass of Core Materials Remained in the RPV

Two cases are simulated here and compared between them; one is the case for core modeled as 3 radial rings and the other is the case for core modeled as 5 radial rings. (Figure 11)

5 RINGS MODEL

	R1	R2	R3	R4	R5
LEVEL 16	4.20	4.20	4.20	4.39	5.81
LEVEL 15	3.76	3.76	3.80	3.89	4.00
LEVEL 14	3.69	3.69	3.75	3.86	4.01
LEVEL 13	3.74	3.74	3.79	3.89	4.06
LEVEL 12	3.84	3.84	3.90	3.95	4.23
LEVEL 11	3.92	3.92	3.94	3.99	4.86
LEVEL 10	4.00	4.00	4.06	4.36	5.65
LEVEL 9	4.31	4.31	4.53	5.25	5.76
LEVEL 8	4.92	4.97	5.29	5.61	6.93
LEVEL 7	5.36	5.64	5.79	5.79	7.04
LEVEL 6	6.60	6.60	6.67	7.10	11.74
LEVEL 5	6.92	6.92	7.10	7.27	12.15
LEVEL 4	7.25	7.25	7.25	7.25	18.70
LEVEL 3	7.16	7.16	7.18	10.10	20.29
LEVEL 2	7.27	7.27	7.27	7.27	18.71
LEVEL 1	10.10	10.33	10.83	11.04	28.47
LH FAIL	12.39	13.41	13.58		

3 RINGS MODEL

	R1	R2	R3
LEVEL 16	4.40	4.40	5.31
LEVEL 15	3.79	3.79	3.79
LEVEL 14	3.62	3.62	3.62
LEVEL 13	3.64	3.64	3.64
LEVEL 12	3.78	3.78	3.78
LEVEL 11	3.96	3.96	3.96
LEVEL 10	4.22	4.22	4.22
LEVEL 9	4.59	4.59	4.59
LEVEL 8	5.17	5.17	5.17
LEVEL 7	6.58	6.62	6.62
LEVEL 6	7.54	12.01	12.01
LEVEL 5	7.97	14.12	14.12
LEVEL 4	7.97	14.62	16.59
LEVEL 3	9.36	11.49	17.65
LEVEL 2	7.97	11.72	16.59
LEVEL 1	11.57	11.57	20.05
LH FAIL	15.62	15.71	

TIME (HR)	COLOR
0.0 - 3.99	
4.0 - 4.99	
5.0 - 5.99	
6.0 - 6.99	
7.0 - 8.99	
9.0 - 13.99	
14.0 – 30.0	
No failure	

Figure 9 Comparison of Core Cell Failure Times (hr) between 5 rings and 3 rings models

3. Conclusions

One inch break of severe accident is simulated on Korean SMR (SMART) Integral PWR with MELCOR code version 1.8.5. Core melt progression and lower head failure time is very slow compared to other commercial reactors.
Simulation on 3 and 5 radial rings core models gives very similar pattern in core cell failure timings.
Other various accident scenarios (for example, SBO in Fukushima) will be tried further.
Containment behaviors and source term behaviors in severe accident conditions will be analyzed in future.

Acknowledgements

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