Analysis of APR1400 Core Degradation under Cavity-flooded Condition using MELCOR

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ABSTRACT

APR1400 nuclear power plant is considering an IVR-ERVC (In-Vessel Retention of molten corium through External Reactor Vessel Cooling) to manage severe accidents. In this paper, the core degradation process and its transient thermal hydraulic behaviors of APR1400 for large break loss-of-coolant accident scenario are analyzed using MELCOR 2.1 when the cavities are fully flooded. As a result, core materials are completely relocated in the lower plenum from about 6000 to 9000 s. About 60 % of the total core materials are in the form of molten pool and more than half of oxidic materials are in the form of particulate debris. Temperature of the lower head is sequentially increased as relocating core materials at the undermost part of the lower head and spreading to radial direction. The maximum heat flux to the cavities is about 0.5 MW/m^2 at the lower head where particulate debris is relocated and heat-focusing effect is observed near the metallic molten pool.

KEYWORDS
APR1400, core degradation, IVR-ERVC, molten pool and MELCOR

1. INTRODUCTION

If core materials start to be relocated and they are not adequately cooled, they may be ejected to an external vessel of the reactor and its results are following in the phenomena which can threaten containment structural integrity; MCCI (Molten Corium-Concrete Interaction), FCI (Fuel-Coolant Interaction) and DCH (Direct Containment Heating). IVR (In-Vessel Retention) concept is considered in order to guarantee the containment structural integrity by holding damaged core materials in a reactor and this is realized representatively by ERVC (External Reactor Vessel Cooling) strategy. In order to adapt the IVR-ERVC as a severe accident management strategy, complicate physical phenomena in a reactor and effective heat removal methods at the external vessel wall should be considered simultaneously. ECCM (Effective Convectivity Conductivity Model), CFD (Computational Fluid Dynamics), LPM (Lumped Parameter Method) and severe accident system codes have been used to analyze thermal hydraulic behaviors of reactors, which are adopting ERVC strategy [1-4]. However, the analysis results by those methods should be used complementary since the levels of physical phenomena to investigate are different from one another. LPM, which assumes conservative bounding conditions for thermal loading, was used for regulatory audit calculations [1-2] and the thermal loading conditions such as mass of core materials and decay heat, etc. were derived from other engineering assumptions or the analysis results of severe accident system codes.

SCDAP/RELAP5, MAAP5 and MELCOR, which are the representative system codes for severe accidents, have developed the capabilities to analyze the damage of core materials and thermal behavior of the lower head. MELCOR is a fully integrated, engineering-level computer code which models the progression of severe accidents in light-water reactor nuclear power plant and is developed at Sandia National Laboratory for the U.S. Nuclear Regulatory Commission [5]. The original purpose of the code is PRA analysis considering simple models based on experiments and several sensitivity variables.

However, nowadays it is also used to analyze severe accidents since numerical schemes and detailed models based on realistic physical phenomena have been included and fine nodalization has become possible. Core degradation is analyzed in the COR package whose main capabilities are to predict thermal response and relocation of core materials during melting, slumping and forming molten pools and debris. The COR package does not include the gap-cooling model at the interface between relocated core materials and the lower head, however.

Meanwhile, APR1400 is a GEN III+ nuclear power reactor, which adopts IVR-ERVC as a severe accident management strategy, and it is under construction as Shin-Kori 3&4 at first. In this research, core heat-up, degradation and relocation processes of APR1400 using MELCOR are analyzed in order to determine initial conditions for LPM analysis, which is to review IVR-ERVC design.

2. MODELING

The overall event is analyzed using MELCOR 2.1 6342 with SNAP 2.2.10 interface. The RCS (Reactor Coolant System) in Figure 1, which is modeled using CVH package, includes a reactor core, 2 steam generators, 4 reactor coolant pumps, and the other primary and secondary systems with DVI (Direct Vessel Injection). The reactor core, which is modeled using the COR package, includes 6 radial rings and 16 axial levels (96 cells in total). Core cells of the lower plenum and segment nodalization of the lower head are shown in Figure 2. The decay heat is modeled according to the ANS 79 curve. And the reactor cavities are modeled using the CVH package as shown in Figure 3 to be fully flooded at the start of the event. This is done to consider the boiling heat transfer at the external vessel wall. The lower head failure is assumed not to have occurred by setting higher melting point of the lower head material than the default value and eliminating ICI (In-Core Instrumentation) penetrations. This is to eliminate the uncertainties of the lower head failure criteria in the analysis code and to evaluate long-term behaviors of core materials and the effect of boiling heat transfer at the external vessel surface. Thermophysical properties of core materials are shown in Table I. The cold-leg large break loss-of-coolant accident with full depressurization and without safety injection is considered as the accident scenario. It is assumed that 30-inch diameter cold-leg double-ended break has occurred at the start of the event. The safety injection by the safety injection tanks is set to allow. The main/auxiliary feed water system and RCP (Reactor Coolant Pump) is assumed to have been tripped with the start of the event. Core materials during core degradation are usually liquefied at the temperature which is lower than their melting points by eutectic reaction and this is a crucial factor in the analysis of core material relocation by severe accidents. MELCOR introduces new materials such as ZRO2-INT, UO2-INT whose melting points can be modified to consider eutectic reaction. In this analysis, melting points of ZrO_2 and UO_2 are modified as 2500 K which is known as appropriate eutectic temperature by the Phébus-FP experiment [6].

Table I. Thermophysical properties of main core materials

	UO_2	Zr	ZrO_2	Stainless steel	Oxide of stainless steel	Control poison
C_p (J/kg-K)	460.23 ~ 503.0 (2400 ~ 5000 K)	356 (> 1248 K)	544.3	728.4	500	500
k (W/m-K)	2.56 ~ 3.96 (2400 ~ 5000 K)	58.4 (> 2089.2 K)	2.39 (> 1500 K)	34.5 (> 1700 K)	20	2
ρ (kg/m^3)	10960	6500	5600	7930	5180	2520

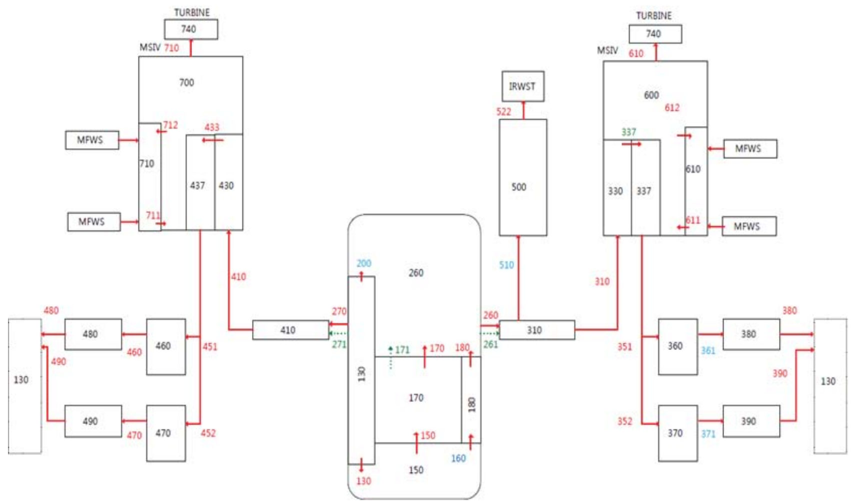


Figure 1. Schematic of APR1400 RCS MELCOR nodalization

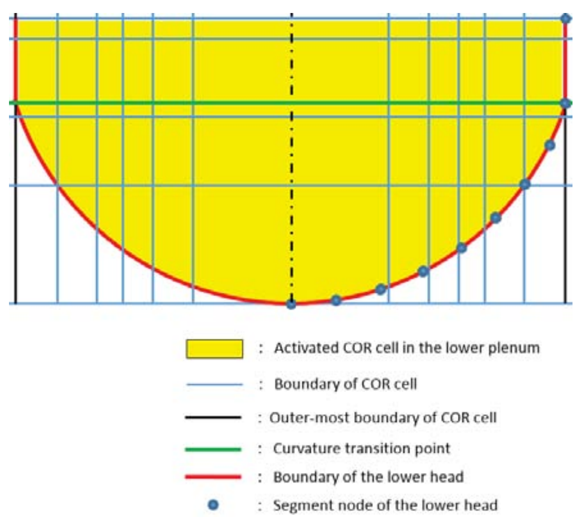


Figure 2. Core cell and lower head nodalization in the lower plenum

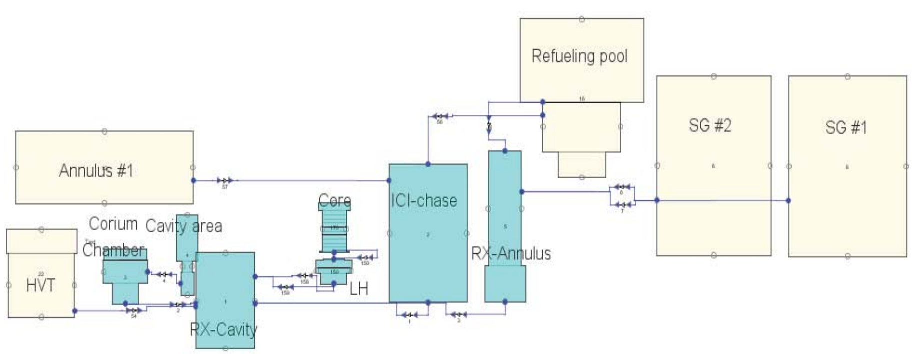


Figure 3. Flow path between reactor, reactor cavities and other control volumes

3. ANALYSIS RESULTS

3.1. Chronology of the Event

The following timeline is the chronology of the event by the MELCOR analysis.

- 0.0 s: Occurrence of LOCA / RCP and MFW (Main Feed Water) trip
- 0.5 s: Reactor trip
- 2.97 s: Start of core uncovering
- 10.02 s: Start of safety injection by SIT (Safety Injection Tank)
- 41.00 s: Stop of safety injection by SIT - inventory exhaustion
- 782.1 s: Start of core support structure failure by loss of support
- 1520 s: Start of cladding melting
- 4168 ~ 4362 s: Start of debris quench
- 5788 s: Start of UO_2 relocation to the lower head
- 6658 ~ 9262 s: End of debris quench
- 6680 s: Exhaustion of coolant in the reactor

The behaviors of structures and core materials in the reactor by the progress of the event are represented in Figure 4. Each step is defined according to the above timeline and the main stages of core material relocation on the lower head. In Figure 4. (d), which is just before debris quench, most core materials are in the form of molten pools on the core support plate. After the failure of the core support plate, the lower support structure and instrument nozzle assembly are sequentially collapsed and the core materials are relocated in the lower plenum. At the stage which core materials are settled stably on the lower head in Figure 4. (l), metallic molten pool, oxidic molten pool and particulate debris layers are well stratified.

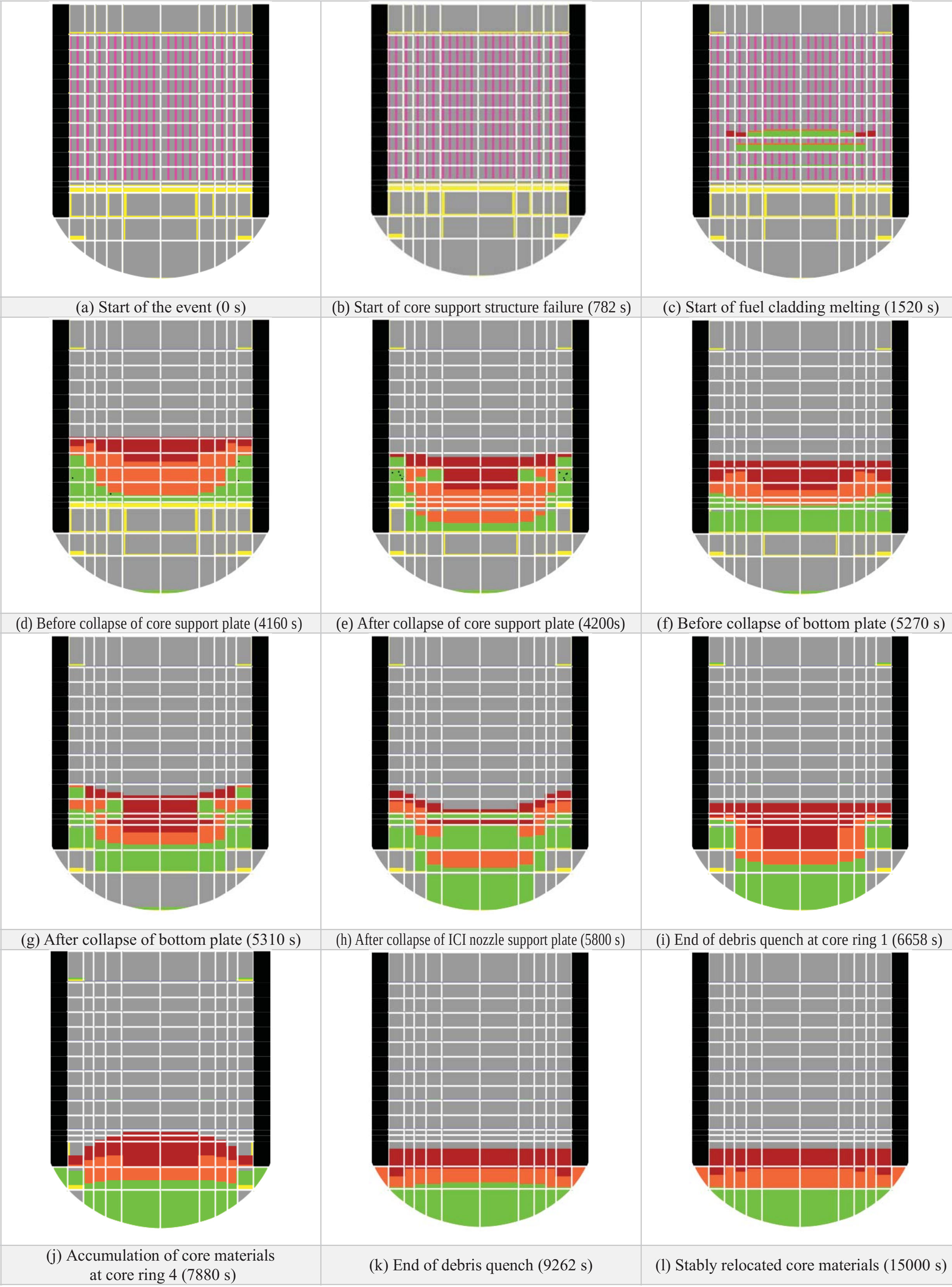
3.2. Main Thermal Hydraulic Behaviors

3.2.1. System coolant behaviors

Most RCS coolant is ejected to the containment through the broken pipe in 10 s after occurrence of the event. The pressure of the reactor is decreased rapidly and maintains 0.3 MPa in 20 s. And the pressure of the steam generator is slightly decreased after the event. The elevation of the reactor core is decreased continuously and the coolant is exhausted perfectly at 6680 s (Figure 5). The temperature of water in the reactor cavities shown in Figure 6 is increased after exhaustion of coolant in the reactor (about 8000 s) since no heat sinks and natural circulation at the coolant channel for ERVC are modeled.

3.2.2. Generated and transferred heat in the reactor

The inside of the reactor is heated up by fission power, decay heat and heat by oxidation according to the accident progress. And the heat is transferred to the coolant and structures in the reactor. It is shown in Figure 7. (a) that main generated heat during the event is decay heat, and fission power becomes very small in 200 s. The heat by oxidation of core materials is generated up to 200 MW in the beginning of the event during about 800 ~ 3300 s. The generated heat is then transferred to mainly coolant in the reactor and heat transfer by radiation to structures in the reactor seems relatively small (Figure 7. (b)). The cladding temperature according to radial rings at axial level 13 of the core cells is shown in Figure 8. The temperature is increased up to 2500 K, which is the failure temperature of the cladding in MELCOR, at ring 1 ~ 3 and the whole cladding fails at 3300 s. The cumulative mass of hydrogen, which is generated by oxidation of metallic materials in the reactor, is increased up to about 400 kg at the end of cladding failure. The cumulative energy which is generated, transferred and internally existent in the reactor is



(a) Start of the event (0 s)	(b) Start of core support structure failure (782 s)	(c) Start of fuel cladding melting (1520 s)
(d) Before collapse of core support plate (4160 s)	(e) After collapse of core support plate (4200s)	(f) Before collapse of bottom plate (5270 s)
(g) After collapse of bottom plate (5310 s)	(h) After collapse of ICI nozzle support plate (5800 s)	(i) End of debris quench at core ring 1 (6658 s)
(j) Accumulation of core materials at core ring 4 (7880 s)	(k) End of debris quench (9262 s)	(l) Stably relocated core materials (15000 s)

Figure 4. Core degradation behavior

shown in Figure 9 and this helps to understand the relationship between the timeline of the event and internal energy which is accumulated in the core materials. At first, the summation of transferred and internal energy is matched well with generated energy. The successful implementation of reactor vessel cooling strategies such as IVR-ERVC usually depends on how much internal energy is to be reduced. The internal energy in core materials is decreased because the generated heat is mainly transferred to the coolant in the reactor at the beginning of the event. Then the energy is recovered to the beginning level of the event at 782 s with the start of the core support structure failure. The heat transfer to the coolant in the reactor is increased slightly with start of the cladding melting at 1520 s. However, the generated energy is mainly transferred to the core materials and internal energy becomes larger until the start of debris quench at 4168 s. The heat transfer to the coolant is increased again after start of debris quench, and the heat transfer to structures in the reactor is increased slightly after end of debris quench.

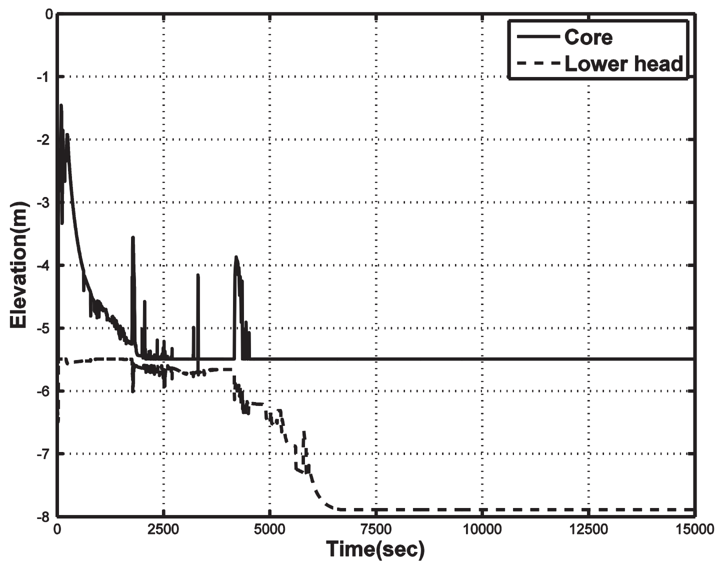


Figure 5. Coolant elevation in the reactor core

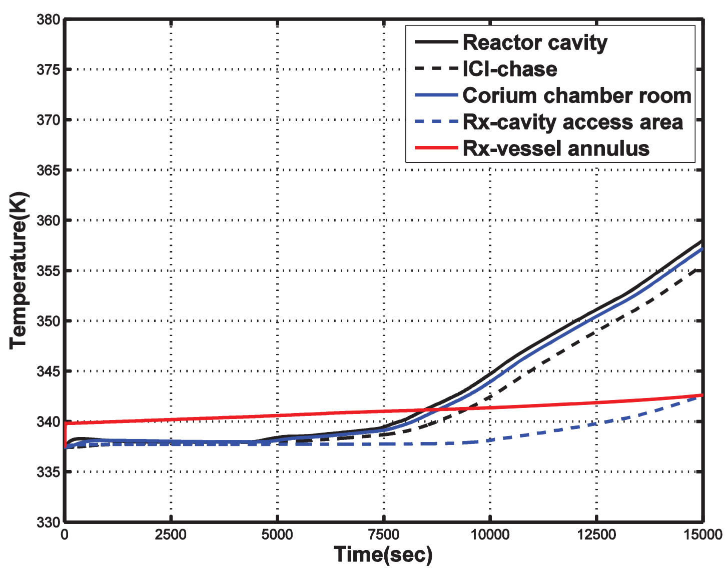
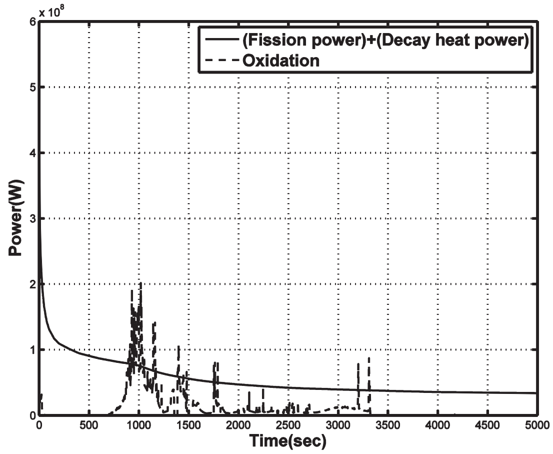
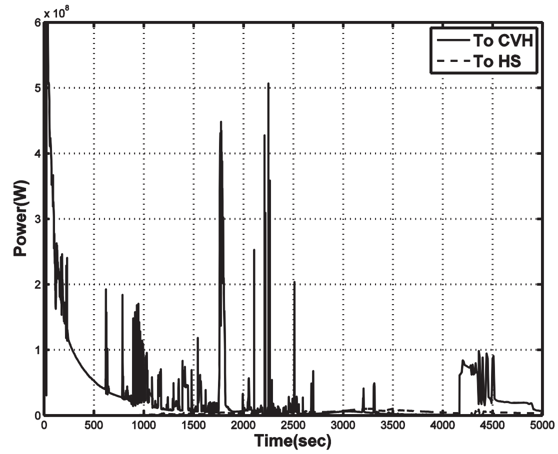


Figure 6. Temperature of the reactor cavity



(a) Generated heat



(b) Transferred heat

Figure 7. Generated and transferred heat in the reactor core

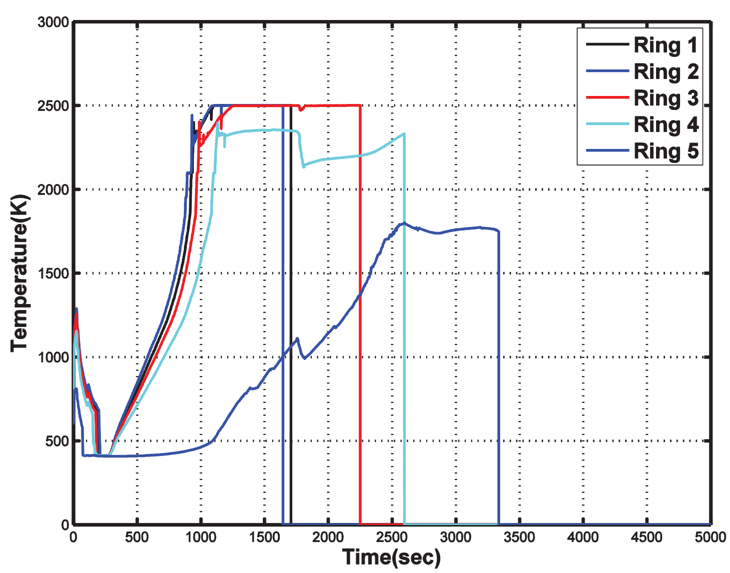


Figure 8. Temperature of fuel cladding (at axial level 13)

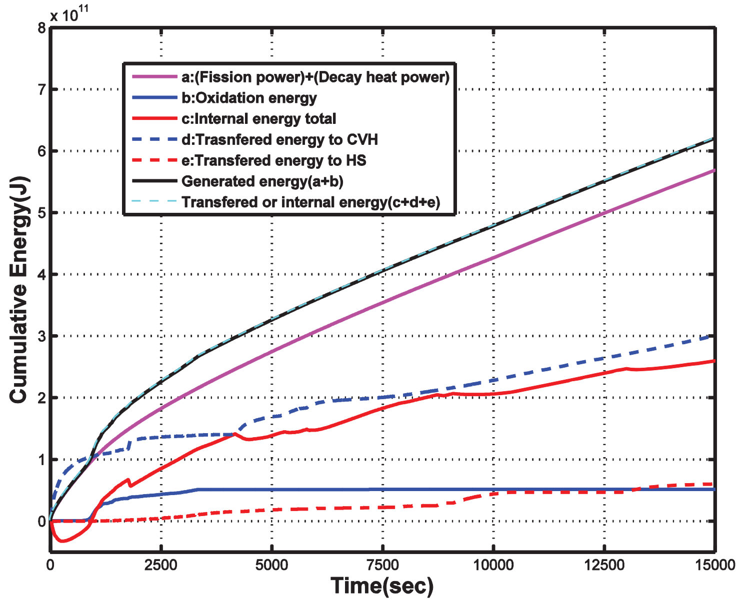


Figure 9. Cumulative energy (generated, internal and transferred energy in the reactor core)

3.2.3. Behaviors of core materials

Core materials in the reactor are relocated in the lower plenum according to the accident progress. It is shown in Table II and Figure 10 that overall UO_2 is relocated at about 7250 s. Zr and ZrO_2 complete the relocation at about 7900 s, and stainless steel and its oxide at 8990 s. The total mass of the oxides, which are relocated in the lower plenum, is about 130 tons, and the mass of metals is 54.2 tons. Zr and stainless steel are oxidized with the ratio of 27 and 3.7 % respectively. The types of relocated core materials in the lower plenum are divided into molten pools and particulate debris. About 60 % of overall core materials are relocated in the form of molten pool as shown in Table III. With respect to molten core materials in the upper and lower plenum shown in Figure 11, the maximum oxidic molten pool exists in the upper plenum just before the collapse of the core support plate and it is transferred to the lower plenum after collapse. Then, metallic molten pool is also transferred to the lower plenum and its mass is maintained without change to particulate debris after end of debris quench. The mass of oxidic molten pool in the lower plenum is slightly increased by melting of particulate debris from about 12000 s. This is because the transferred heat to the coolant in the reactor cavities is not enough to cool down the generated heat in the core. And about 40 % of oxides in the lower plenum are melted and the rest is in the form of particulate debris. The amount of metallic and oxidic molten pool are similar to each other.

Table II. Mass of core materials in the reactor core

Materials	Initial mass in the reactor core (kg)	Relocated mass in the lower plenum (kg)
UO_2	1.178E+05	1.178E+05
Zr	2.882E+04	2.104E+04
ZrO_2	0	1.050E+04
Stainless steel	3.441E+04	3.314E+04
Oxide of stainless steel	0	1.665E+03
Control poison	1.287E+03	1.262E+03

Table III. Mass of relocated core materials in the lower plenum by type

	By molten pools (kg)	By Particulate debris (kg)	Total relocated mass (kg)
Metallic	5.346E+04	7.200E+02	5.418E+04
Oxidic	5.273E+04	7.724E+04	1.300E+05
Total	1.062E+05	7.796E+04	1.841E+05

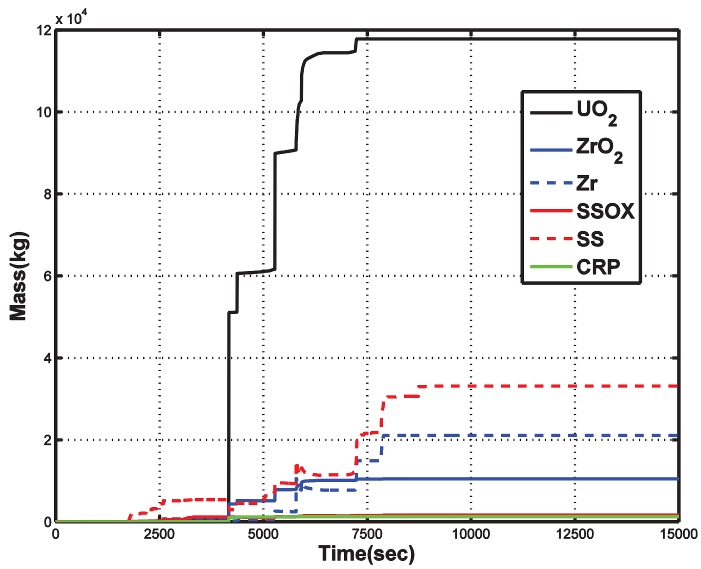


Figure 10. Mass of relocated core materials in the lower plenum

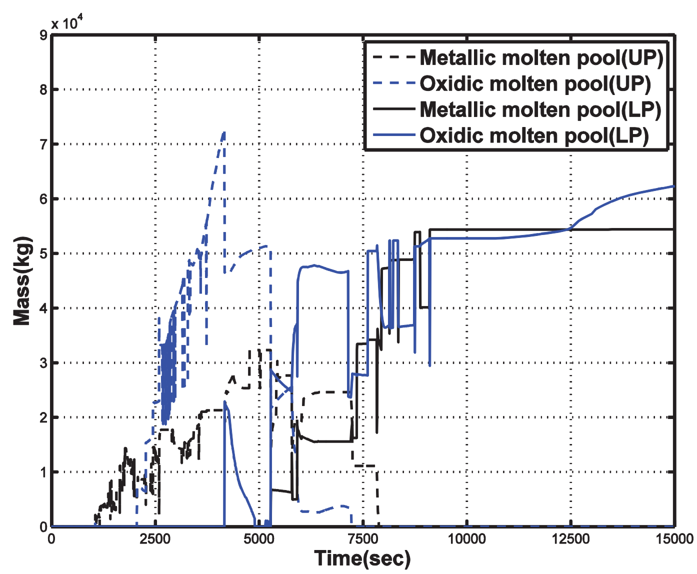


Figure 11. Mass of molten pools in the upper and lower plenum

3.2.4. Heat transfer through the lower head

The lower head consists of carbon steel whose melting point is 1810 K as a default value in MELCOR. The time lapses of temperature of the internal vessel wall are shown in Figure 12. At first, relocated core materials increase the temperature at the undermost area of the lower head. Then, the other parts of the lower head are heated sequentially by continuously relocating materials in a radial direction. The temperature of the internal vessel wall is being increased more than the original melting point as core materials are relocated on the lower head. However, the temperature of the external vessel wall is only increased slightly up to the saturation temperature of the pool (about 410 K) due to the coolant in the reactor cavities. The downward-facing saturated pool boiling model which is a default model in MELCOR[5] treats three heat transfer regimes; that is, fully-developed nucleate boiling, transition boiling and stable film boiling. The criterion to separate nucleate and transition boiling is the critical heat flux dependent on the inclination angle and it is given by

$$q_{CHF}(\theta) = \left(0.034 + 0.0037\theta^{0.656}\right)\rho_v^{1/2} h_{lv} \left\{g\sigma\left(\rho_l - \rho_v\right)\right\}^{1/4} \quad (1)$$

where θ : inclination angle of the surface (degree)
ρ_l and ρ_v : densities of water and steam, respectively
g : acceleration of gravity
σ : interfacial surface tension between steam and water, and
h_{lv} : latent heat of vaporization of water

The critical heat flux according to the inclination angle based on Eq. (1) is shown in Figure 13. The minimum value is at the undermost area of the lower head and it is more than 0.5 MW/m^2.

The transferred heat from the lower head is quantified by heat flux at the vessel wall, and it is shown in Figure 14. At segment 1 ~ 6 of the lower head, where mainly particulate debris is relocated, heat flux is gradually increased from the moment of relocation up to about 0.5 MW/m^2 and is settled down to about 0.35 MW/m^2. At segment 7 ~ 9, heat flux is increased by the formation of molten pools after end of debris quench. And heat flux at segment 8 ~ 9 is increased rapidly by focusing effect in the metallic molten pool. The boiling regime on the external vessel wall in this analysis is only the nucleate boiling because the level of the calculated heat flux is under the critical heat flux shown in Figure 13. And the overall heat flux behavior is different from that of the typical 2-layer molten pool [1-2] to consider heat balance with components in steady state by LPM.

4. CONCLUSIONS

Core degradation and related thermal hydraulic phenomena of the severe accident by large break loss-of-coolant accident for APR1400 are analyzed using MELCOR 2.1. Under the assumption of fully flooded reactor cavities and no failure of the lower head, the coolant in the reactor is exhausted at about 7000 s and most core materials are relocated in the lower plenum at about 9000 s. As core materials are moved to the lower plenum due to collapse of the support plates in the reactor, they are relocated from the bottom of the lower head and the stratified configuration is observed with the layers of metallic molten pool, oxidic molten pool and particulate debris. About 60 % of relocated core materials are in the form of molten pool. Oxidation of metals is completed at about 3500 s and the ratio of oxidation for Zr is about 30 %. The temperature of the lower head is increased sequentially from the bottom to the upper part as core materials are relocated. The mass of oxidic molten pool is increased even after end of debris quench because the reactor is not cooled down enough by ERVC to remove the generated heat in the reactor. And it is not realistic that the temperature of the internal vessel wall exceeds the original melting temperature of carbon steel. This is also because of insufficient heat removal by ERVC modeling of the analysis. Heat flux at the lower head from the bottom to 50 degrees as inclination angle, where mainly particulate debris is relocated, is increased and it converged to about 0.35 MW/m^2 after end of debris quench. And heat flux near metallic molten pool is increased after about 12000 s because of focusing effect. In the future, the remaining uncertainties of the effect of cooling through the cavity flooding, ejection of core materials by reactor vessel failure and eutectic reaction temperature of core materials should be investigated in-depth supplementary.

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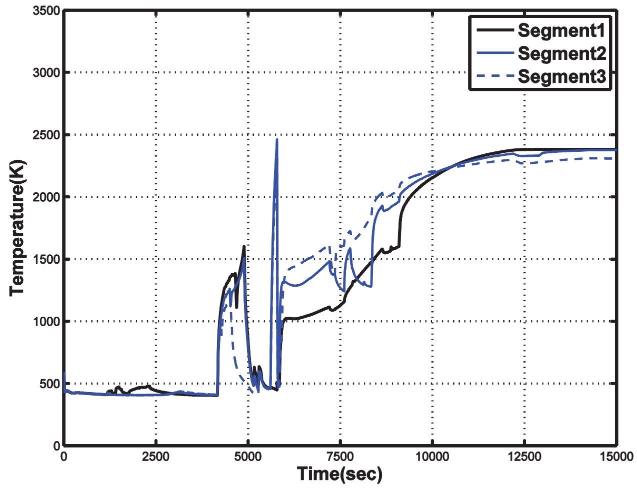
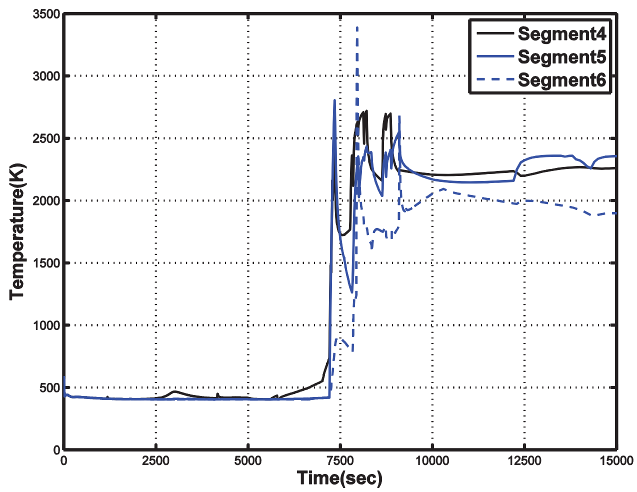
REFERENCES

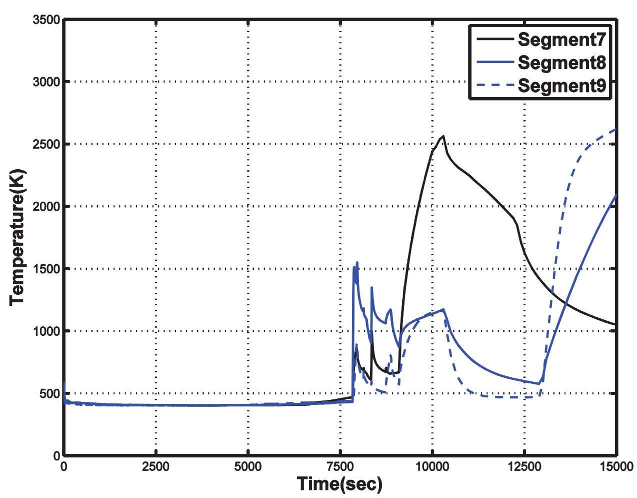
1. T. G Theofanous, C. Liu, S. Addison, S. Anglelini, O. Kymalainen, T. Salmassi, *In-Vessel Coolability and Retention of a Core Melt*, DOE/ID-10460, 1995
2. H. Esmaili et al., *Analysis of In-Vessel Retention and Ex-Vessel Fuel Coolant Interaction for AP1000*, NUREG/CR-6849, ERI (2004)
3. C. T. Tran, *Development, Validation and Application of an Effective Convectivity Modeling for Simulation of Melt Pool Heat Transfer in a Light Water Reactor Lower Head*, Ph. D dissertation, KTH (2007)
4. Tae-Hyub Hong, Yu Jung Choi and Hyeong Taek Kim, "Numerical analysis of phase change heat transfer and two phase flow in IVR-ERVC", *2011 KSME fall conference*, **2011**(10), pp. 1962-1966 (2011)
5. R. O. Gauntt, J. E. Cash, R. K. Cole, et al., *MELCOR Computer Code Manuals*, Sandia National Laboratory, NUREG/CR-6119, Vol. 2, Rev. 3, 2005
6. Bal Raj Sehgal, et al., *Nuclear Safety in Light Water Reactors*, Academic Press (2012)



(a) Segment 1 ~ 3



(b) Segment 4 ~ 6



(c) Segment 7 ~ 9

Figure 12. Temperature of internal vessel wall of the lower head

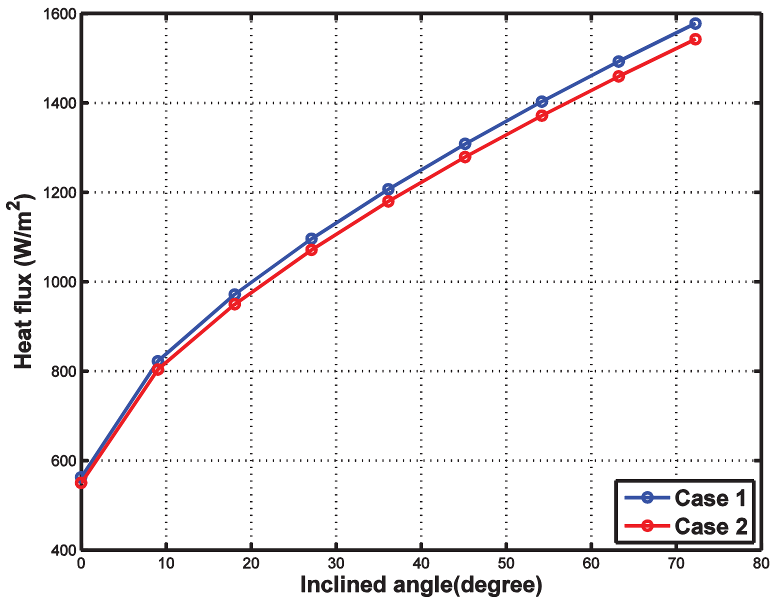


Figure 13. Critical heat flux on the external vessel wall

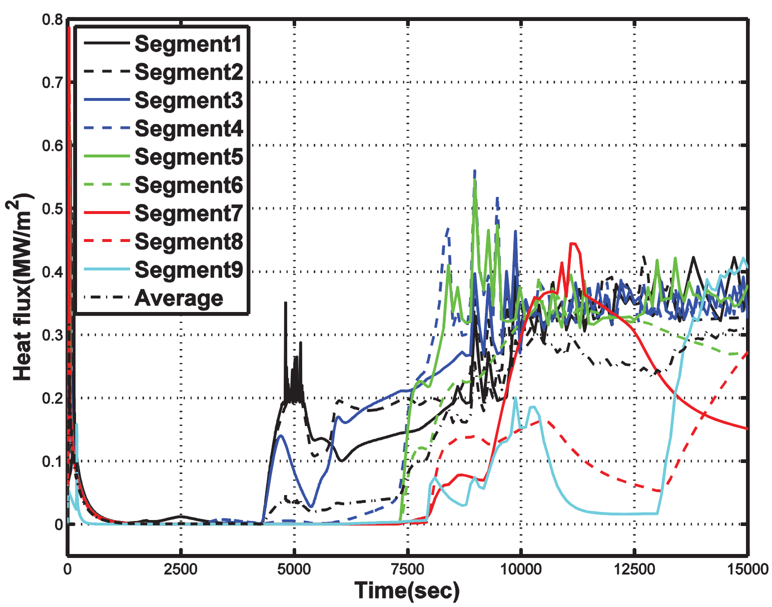


Figure 14. Heat flux at the lower head