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Comparison of the Thermo-Hydraulic Response of MELCOR 1.8.6 and 2.1 for SBO Accident for APR 1400 Reactor

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ABSTRACT

An analysis of thermohydraulic response during a station blackout (SBO) accident for the APR 1400 nuclear power plant is performed using MELCOR version 1.8.6. MELCOR 1.8.6 results for the SBO scenario are benchmarked with MELCOR 2.1. The simulation of the SBO accident with MELCOR 2.1 was done by the APR 1400 reactor designer company (KEPCO). This research consists of two parts; the first part is related to the results of MELCOR 1.8.6, and the thermo-hydraulic analysis of MELCOR1.8.6 has been done. Analysis of thermohydraulic response is focused on investigating thermohydraulic parameters, such as core pressure, fuel clad temperature, water mass flow rate in the core, time of fuel clad failure, time of lower head failure, and time of containment failure. In the second part, the results of MELCOR version 1.86 have been benchmarked with the results of MELCOR 2.1. The results of the analysis of containment pressure changes in version 1.8.6 showed that the effect of pressure increase in containment is mostly due to the increase in carbon dioxide mass, but in version 2.1, the increase in pressure is more due to water vapor.

INTRODUCTION

The Fukushima-Daiichi accident showed that severe accidents like station blackout (SBO) could occur even at a plant in a shutdown condition. An SBO accident leads to core damage and subsequent release of radioactive materials into the environment. [1] After the core was damaged, fission products are released in the reactor pressure vessel (RPV), and molten fuel debris starts moving in the RPV lower head. The in-vessel release is from the damaged fuel in the RPV during fuel degradation and depends strongly on the scenarios of core melt progression [2]. The ex-vessel phase starts when the RPV lower head fails and molten corium discharges into the cavity and radionuclides are released into the containment during the molten corium-concrete interaction. Fission products and radionuclide materials are then transferred into the containment [3]. Simultaneously with the transfer of fission products into the containment and molten corium-concrete interaction, containment pressure increases until the pressure inside the containment exceeds the designed pressure and the containment fails, and radioactive materials are released into the environment. The magnitude of the severe accident source terms depends on the plant design and the accident scenarios. NUREG-1150 [2] estimated the source terms for five nuclear power plants in the USA. The type of concrete in the cavity, the core debris composition, temperature, and water in the cavity affect ex-vessel release.

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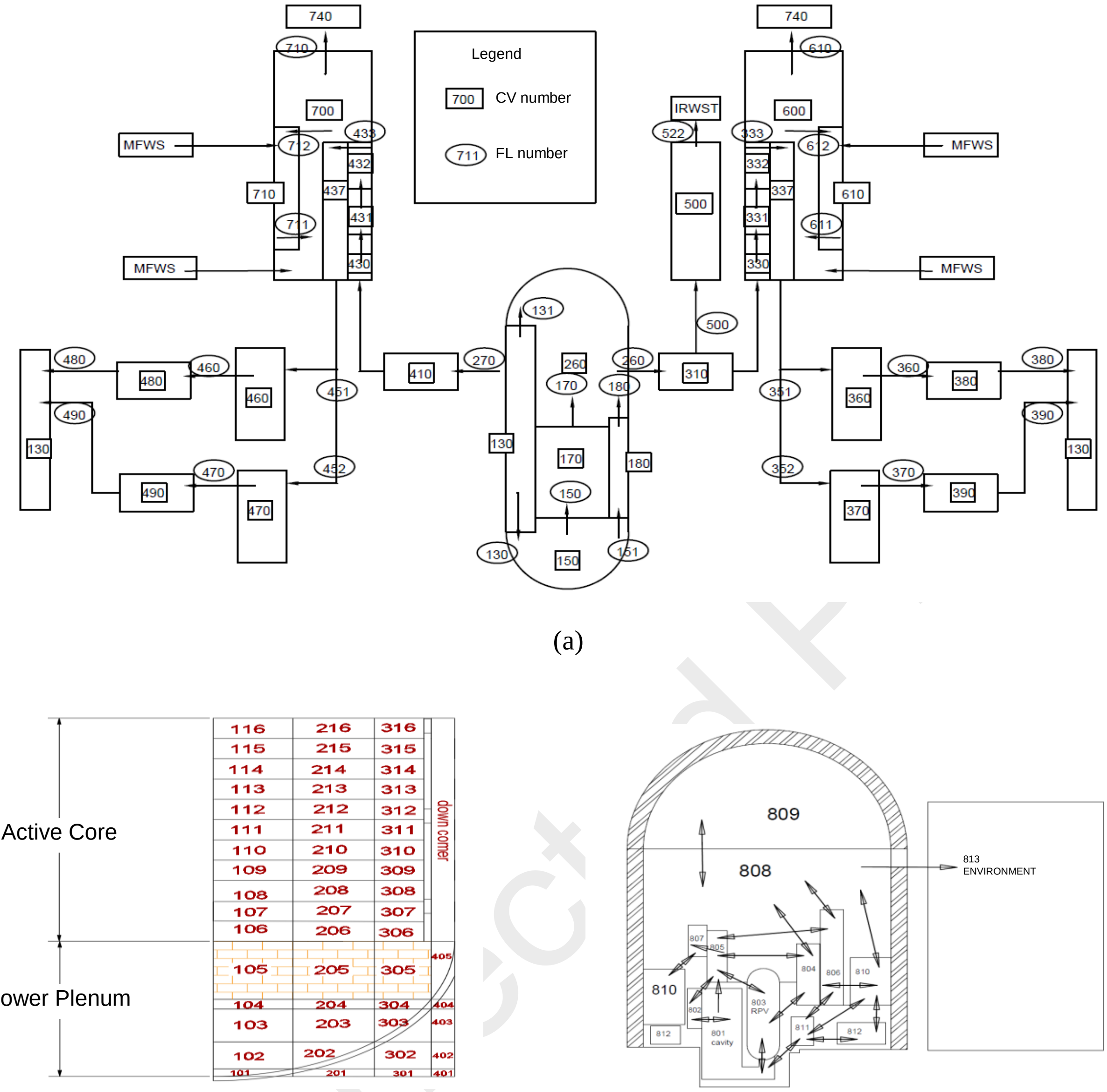
A containment spray system, IRWST pool, and aerosol filter can perform the removal of radioactive materials in the containment. In 2017, Thi Huong Vo & Jin Ho Song [4] performed a station blackout accident scenario by using MELCOR 2.1. The analysis results show that the containment failure occurs at about 84.14 h [4].

Before the failure of the reactor vessel, the containment pressure increases slowly. Then, a rapid increase of the containment pressure occurs when a large amount of hot molten corium is discharged from the reactor pressure vessel to the cavity. The molten corium-concrete interaction (MCCI) is activated when water is flooded over a molten corium in the cavity [5]. The boiling of water in the cavity causes a rapid increase in the containment pressure. During the early phase of the accident, a large amount of steam is condensed inside the containment due to the presence of the heat structures. This results in a mitigation of a containment pressure increase. During the late phase, the containment pressure increases gradually due to the addition of steam and gases from MCCI and water evaporation. It was found that two-thirds of the total mass of steam and gases in the containment is from MCCI and one-third from water evaporation [4]. In this study, a simulation of the station blackout accident for the APR1400 is performed using MELCOR version 1.8.6 [6]. Analysis of thermohydraulic response is focused on investigating thermohydraulic parameters, such as core pressure, fuel clad temperature, water mass flow rate in the core, time of fuel clad failure, time of lower head failure, and time of containment failure. The calculated results in this research are benchmarked with the results of previous research [5] which was done by the MELCOR 2.1 code.

APR 1400 MELCOR modeling

APR 1400 [5] is a 1400 MWe two-loop PWR. A schematic diagram of the reactor coolant system (RCS) nodalization for MELCOR 1.8.6 is shown in Fig. 1(a) [7,8,9]. Each RCS loop has 11 control volumes; a hot leg, a steam generator inlet plenum, three control volumes for the SG U-tube hot side, one control volume for the SG U-tube cold side, an SG outlet plenum, two intermediate legs, and two cold legs. The pressurizer is connected to the hot leg of loop A. One pilot-operated safety relief valve (POSRV) is located on top of the pressurizer (CV 500) and is designed for controlling RCS pressure. POSRV fully opens at a high pressure of 17.51 MPa and closes when the RCS pressure is reduced to a blowdown set point of 17.50 MPa.

Core and lower plenum nodalization are shown in Fig. 1(b). The whole core is divided into 4 control volumes. These control volumes are the core channel, downcomer channel, bypass channel, and lower head plenum. The core is radially divided into 5 rings and axially divided into 16 levels. Three rings are in the active core region. Ring 4 is located in the bypass control volume channel and ring 5 is located in the downcomer control volume channel. For axial levels nodalization [5,10,11,12], six levels are located in the lower head plenum and 10 levels are inactive core and bypass and downcomer channels. A failure of the lower head will occur if any of the following criteria are satisfied [6]: (1) the temperature of the penetration or innermost node of the lower head reaches a failure temperature (TFAIL); (2) a creep-rupture failure of a lower head segment occurs; or (3) the differential pressure between the lower plenum and reactor cavity reaches the failure pressure (PFAIL). Pressure failure for this study is 20.0 MPa and TFAIL is taken as the default value in MELCOR (1273.15 K). The failure of the lower head due to creep rupture Occurs when the plastic strain in the vessel's lower head node reaches 18 % [6]. APR 1400 containment is shown in Fig. 1(c). Containment is subdivided into 12 control volumes. [7]. Containment control volumes consist of cavity (CV801), chamber room (CV802), RPV Annulus (CV803), refueling room (CV 804), two steam generator components (CV 805 & CV 806), pressurizer component (CV 807), upper component (CV808), containment dome (CV 809), annular component (CV 810), hold up volume tank (CV 811), and IRWST tank (CV 812) [4]. The environment is modeled by CV 813. FL 848 valve is used to model containment failure. This valve is a connection between containment and the environment [7]. It is only opened when the containment failure occurs. It is assumed that the containment will fail when the containment pressure reaches 1.027 MPa [7]. The flow area for FL848 is 0.065 m^2 [4].



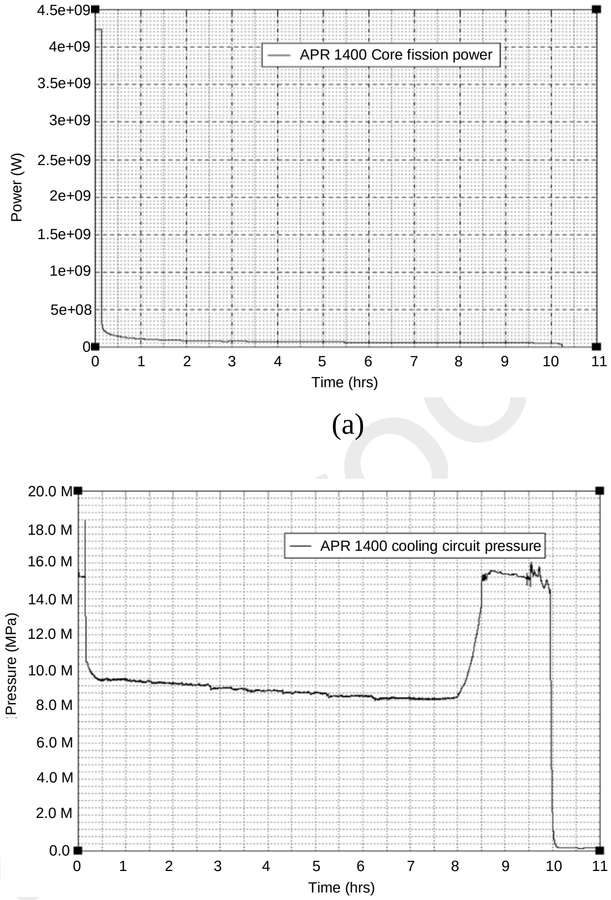
(b) (c)

Fig. 1. (a) APR 1400 RCS MELCOR nodalization; (b) Core nodalization schemati; (c) APR 1400 containment model for MELCOR.

Station blackout accident analysis

An SBO is initiated by a loss of AC power, at this moment reactor trips occur, and all main coolant pumps and emergency safety system main steam isolation valves are disabled. It is assumed that the loss of DC power occurs at the same time as the SBO accident. In this study, Auxiliary Feedwater System (AFWS) is unavailable [13]. The leakage from the main coolant pumps is not considered because there is uncertainty about seal timing and size. All emergency core cooling systems are unavailable. SBO is applied at a time of 500 seconds. Before that reactor works at full power. The reactor shuts down immediately after pumps fail due to DC power cuts off. Decay heat is still generated in the core after the reactor shutdown. The RCS pressure decreases due to the failure of pumps and reactor shutdowns. The RCS pressure starts to increase again when the steam generator dries out. Then POSRVS starts to open and close. POSRVS starts to discharge two-phase water into the IRWST. Because the RCS pressure remains at a pressure higher than the IRWST pressure the water inventory in the reactor core cannot be recovered. Consequently, the fuel rod temperature increases until the temperature of the fuel rods reaches the melting temperature and the fuel rod melts downward and molten corium moves to the lower head, and finally, lower head failure occurs. Figure 2(a) shows events that occur in RCS after SBO is applied to the simulation. After reactor trips occur, core fission power decreases rapidly from 4023 MW to 311 kW. Figure 2(a) shows that the pressure inside the reactor core was 15.2 MPa up to 500 seconds before the SBO accident. At the moment of the SBO accident (time = 500 seconds), a scram signal is issued to shut down the reactor. Four seconds after the scram signal is sent, the pressure inside the reactor core reaches 18.34 MPa [14]. The reason for this increase in pressure inside the reactor core is that it takes a few seconds from the time the scram signal is sent to the control rods entering the core and the reactor shuts down [15]. During this time range (between 500 and 504 seconds), because the pumps have failed the mass of water in the reactor core has decreased and the reactor is still operating at full power, the water temperature suddenly rises, and the pressure inside the reactor core increases at the time of 504 seconds. At this moment, control rods drops into the reactor core and the reactor shuts down. Then, the reactor core pressure drops to 9.5 MPa. The pressure inside the reactor core starts to increase at 8 hours. The increase in pressure is caused by the rise in the temperature of the fuel rod and the water inside the reactor [16]. At this time, the interaction of water and metal begins, and hydrogen gas is produced. By producing hydrogen and constantly increasing the temperature of the fuel rods and water, the pressure inside the reactor increases simultaneously at the time of 8.55 hours. At identical time, the POSRV valve opens, injecting gas and steam from the reactor core into the IRWST and controlling the pressure inside the reactor. At 9.33 hours, the temperature of the fuel rod reaches 2030 °C, and the fuel rod begins to melt. Before the lower head is destroyed, a leak will occur in it. The start time of this leak is at 9.67 hours, where the water and hydrogen (H_2) start leaking into the cavity. At 9.67 hours, the pressure inside the reactor 229 core suddenly drops sharply causing lower head 230 failure to occur and molten material enters the cavity (Fig. 3(a) and Fig. 3(b)) [17]. An amount of 148,657 kg of corium was released into the cavity as shown in Fig. 6. The reactor power behavior curve is shown in Fig. 2(b) in a logarithmic scale. After the reactor is tripped, the power of the reactor core decreases from 4.230e+9 W to 560e+8 W. At the moment when failure of the lower head occurs, molten corium ejects from the reactor pressure vessel, and the amount of heat production due to decay heat inside the reactor core reaches zero.

For considering high-pressure melt ejection effects on containment pressure, the HPME model in the FDI package is activated in this study, and Direct Containment Heat (DCH) is considered. DCH [18,11] is important because core melt ejection occurs at high pressure and there are heat transfers from ejected particulate debris to the cavity pool, containment heat structures, and atmosphere. The containment pressure change is shown in Fig. 4(a). Containment pressure changes during SBO accidents could be divided into two phases [15].

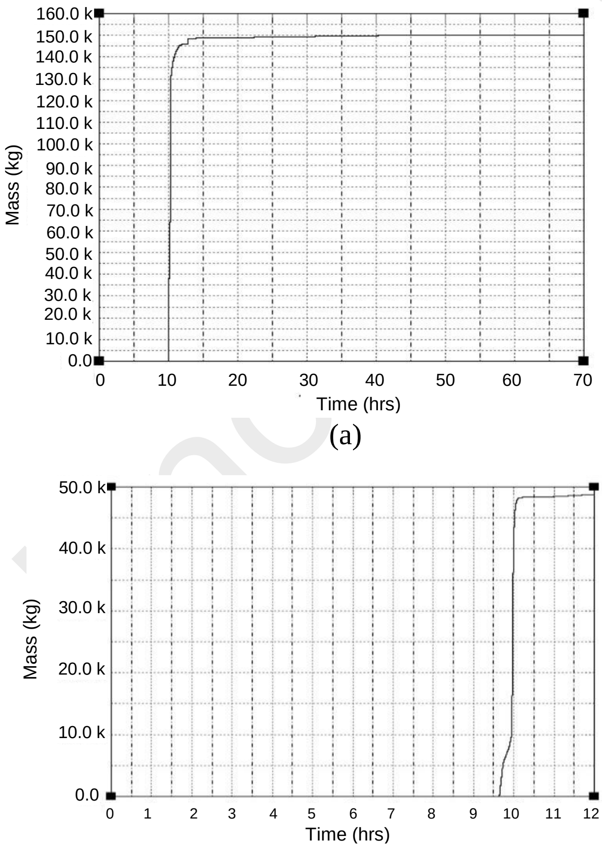


(a)

(b)

Fig. 2. (a) APR 1400 core pressured at 12 hours after the accident; (b) Core fission power response 12 hours after the accident.

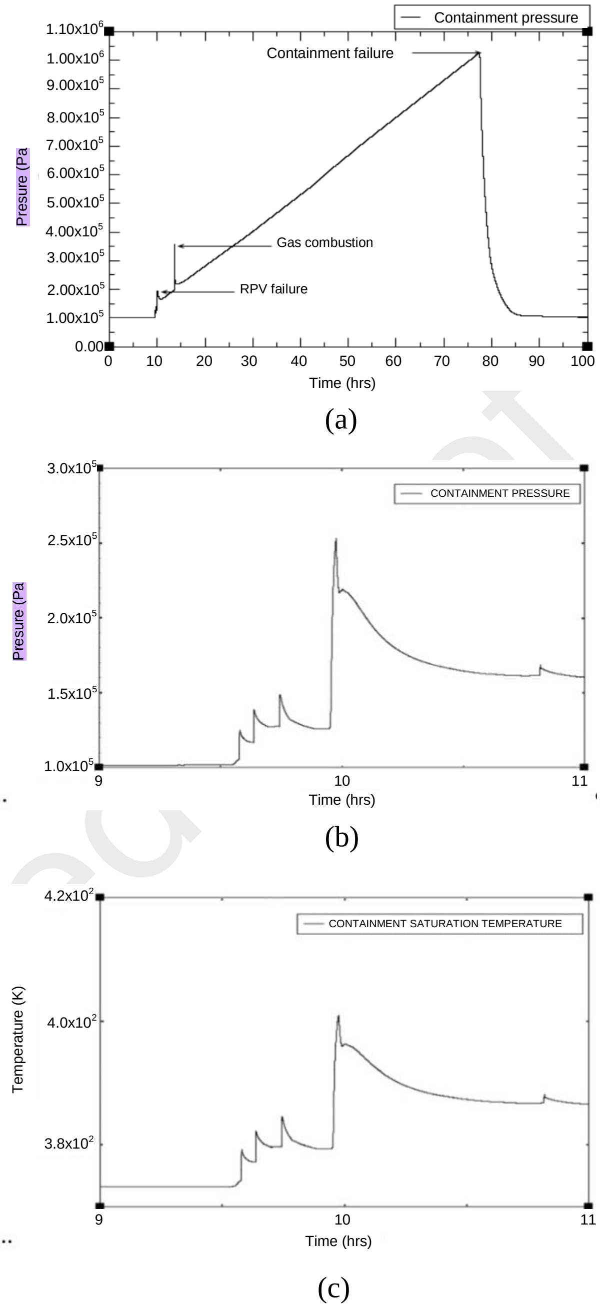
The first phase starts from the beginning of the accident until RPV failure occurs, and phase two is from the time of RPV failure until containment failure occurs. In phase 1, before RPV failure occurs at the time of 9.57 hours, the pressure inside the containment building does not change because the steam from the POSRV valves is directly transferred to the IRWST tank, and the steam is not transferred inside the containment building. As shown in Fig. 9, before RPV fails, there are three peaks on the containment pressure curve. During this period, the saturation temperature of the steam inside the containment building will increase at 3 points, and the pressure increases momentarily. Then due to the existence of leakage in the RPV reactor and hydrogen gas leakage in the containment, the pressure increases. Lower head failure occurs at a time of 9.57h. The burning package in the MELCOR code shows that in a time of 9.57 hours as Fig. 5 shows, hydrogen combustion occurs in the control volume of 802, and 3.56 kg of hydroge gas is burned. As a result of this combustion, the pressure and saturation temperature inside the containment building increase momentarily (Fig. 4(b) and Fig. 4(c)). In phase 2, a huge volume of molten corium and hydrogen gas entered into the cavity, and water discharged from IRWST to the cavity for cooling ejected molten debris [19]. A substantial amount of corium is ejected into the cavity, as can be seen in Fig. 3(a). RCS pressure drops quickly to set point pressure of IRWST of 101 KPa. After the lower head failure, the cavity package in the MELCOR code shows that after 9.57 hours, the production of carbon monoxide, hydrogen, water vapor, and carbon dioxide begins. At first, the production of carbon monoxide and hydrogen gas is larger than other gases. As a result, the pressure inside the containment building increases again. At 14.37 hours, the burning package shows that the combustion of hydrogen and carbon monoxide gases occurs and the pressure increases momentarily. Then, after the second combustion, as shown in Fig. 4(a), due to the continuous production of steam and carbon dioxide gas, the pressure inside the containment building increases. Finally, the containment building will be destroyed in 77.5 hours and radioactive materials will release into the environment.



(a)

(b)

Fig. 3. (a) Total debris mass ejected through vessel breach; (b) Leakage of water and hydrogen before RPV destruction.



(a)

(b)

(c)

Fig. 4. (a) Containment pressure during SBO accident; (b) Containment pressure before RPV fails; (c) Containment pressure and saturation temperature before RPV fails.

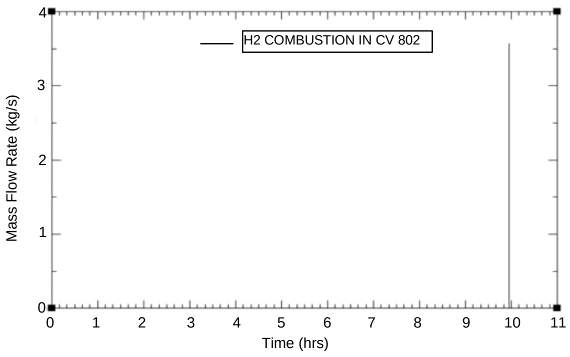


Fig. 5. Hydrogen combustion in control volume 802 in 9.57 hours.

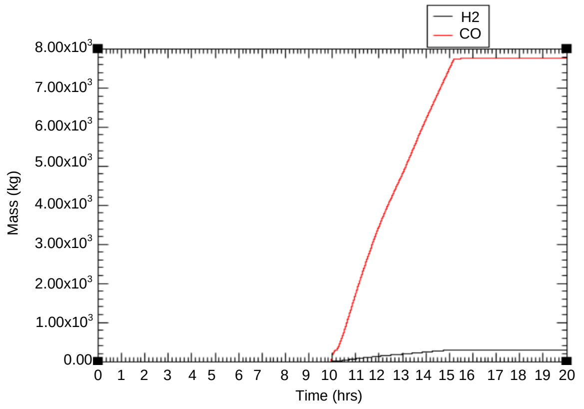


Fig. 6. Time to start production of hydrogen and carbon monoxide in the reactor cavity based on the response of the MELCOR code cavity package.

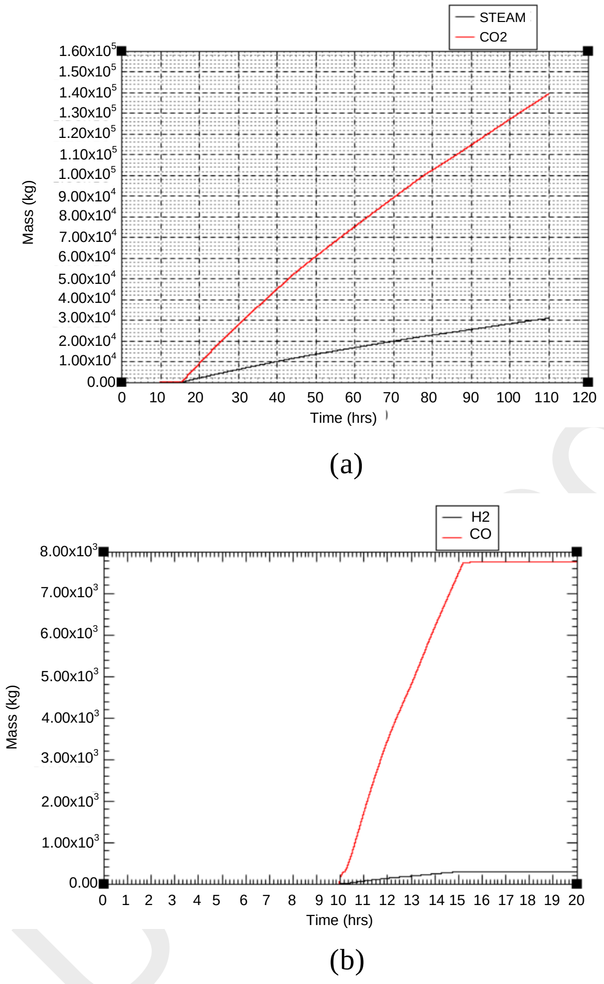


Fig. 7. (a) The amount of gas and steam production in the reactor cavity during the accident; (b) Gas accumulation in the containment building of the reactor.

After the second combustion, the pressure inside the containment building starts to increase steadily. This increase in pressure is caused by the accumulation of carbon dioxide gas (Fig. 7(a)), which accumulates inside the containment building over time. The contribution of the accumulation of hydrogen gases in the increase in pressure is insignificant, as shown in Fig. 8. Also, MELCOR code calculations showed that the amount of steam increases continues when containment failure occurs (Fig. 7(b)). At this time, the pressure inside the containment is immediately reduced due to the crack formation, and this leads to the water evaporation in the heat structures in the containment building.

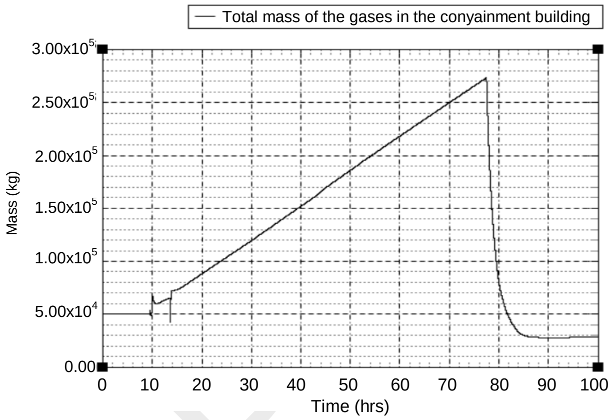


Fig. 8. Gas accumulation in the containment building of the reactor.

BENCHMARK

In this section, some results of two versions of the MELCOR code are benchmarked. An analysis of the thermohydraulic responses of the containment for an APR 1400 nuclear power plant was conducted using MELCOR version 1.8.6. The results show that without any containment heat removal and/or a venting system, and ECCS the containment integrity is maintained for more than three days (77.57 h) after the initiation of an SBO. The results of this study are benchmarked with the results of the study conducted by Vo et al. [4]. They modeled the station blackout scenario for APR 1400 by using MELCOR 2.1. Containment nodalization for that study is shown in Fig. 9. Containment in the previous study is subdivided into two control volumes, but in this study, containment is subdivided into twelve control volumes as shown in Fig. 3. First, in the first 12 hours of the SBO accident, both versions of the MELCOR code are examined. In the first 12 hours of the accident, melting of the reactor core, failure of the RPV, and leakage of the corium into the cavity occur. First, the pressure changes in the reactor cooling circuit are examined [20], which is shown in Fig. 10. The change in cooling circuit pressure in MELCOR version 2.1 is such that the circuit pressure decreases when the pumps stop working. The water temperature rises due to the heat produced in the core of the reactor and turns into steam. This steam is transferred to the containment space through the POSRV. This steam transfer by the safety valves causes fluctuating pressure changes that occur in MELCOR version 2.1 between 2 and 6 hours and version 1.8.6 between 8 and 10 hours (Fig. 10).

By reducing the height of the water level, SIT tanks inject water into the core of the reactor and increase the pressure and water level in the core of the reactor, in the MELCOR 1.8.6 model, these tanks transfer water to the reactor cavity. In the cooling circuit pressure curve of MELCOR 1.8.6, it can be seen that the circuit pressure suddenly increases in 8 hours (Fig. 10). MELCOR calculations show that the bottom failure of the RPV lower head occurs in 6.02 hours in version 2.1 and 9.57 hours in version 1.8.6. Fig. 11(a) shows the pressure changes in the reactor containment building. In the MELCOR code version 2.1, the destruction of the containment building takes place in 84.4 hours, but in the MELCOR 1.8.6, the destruction time is 77.56 hours. This difference in the time of failure of the containment building can be caused by the use of multiple control volumes. Using multiple control volumes makes steam and other gaseous fission products scatter in multiple control volumes and pressure increment is divided between control volumes.

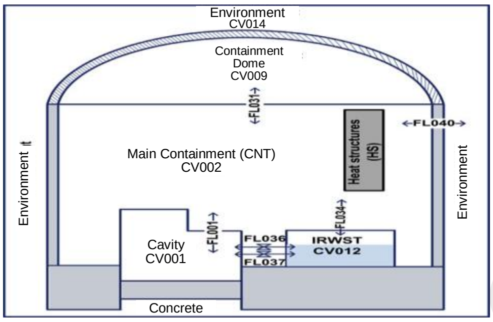


Fig. 9. Containment model in the MELCOR analysis [4].

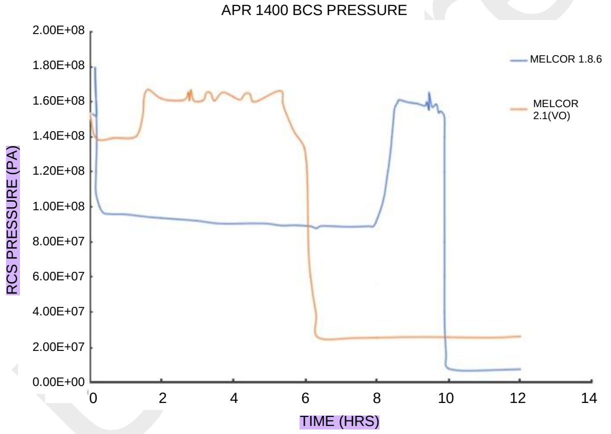
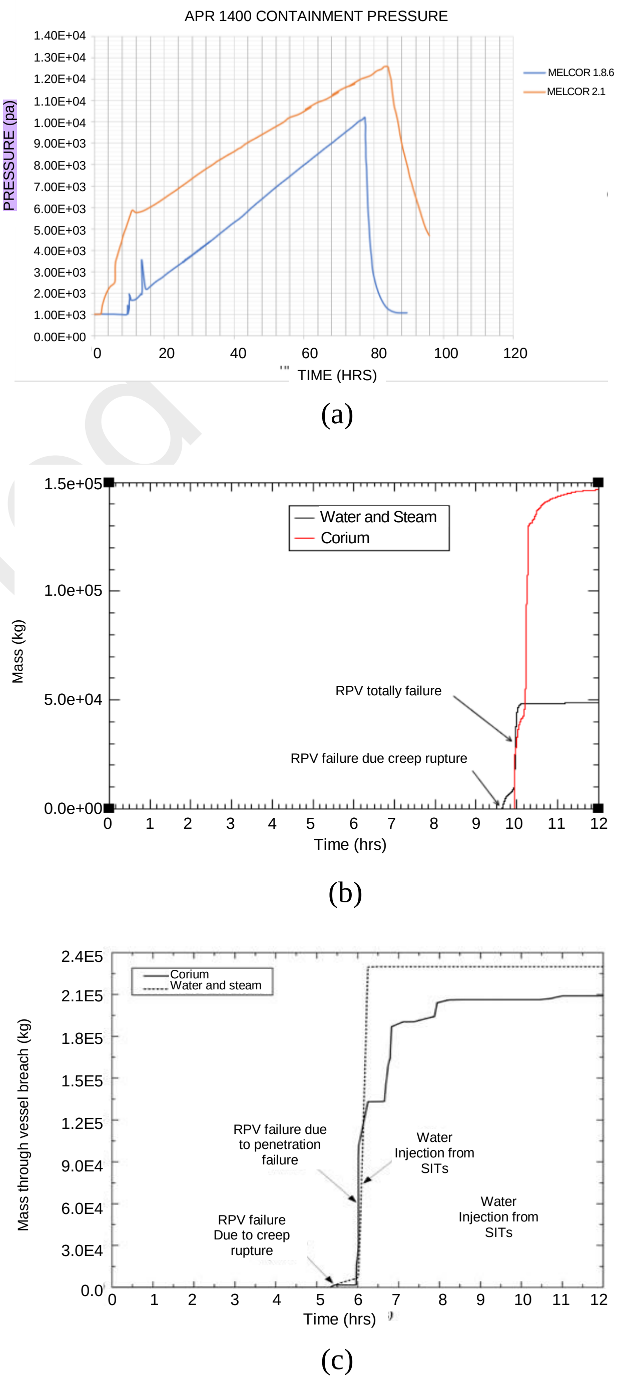


Fig. 10. Comparing the pressure changes of the cooling circuit in the first 12 hours of the SBO accident in both versions of the MELCOR code.

Figures 11(b) and 11(c) show the release of corium and water into the reactor cavity. Almost in terms of both codes, they are similar. In MELCOR 1.8.6 (Fig. 11(b), it takes approximately 19 minutes from the moment a crack is created in the RPV body to the complete failure of the body, and an amount of 1.51e+5 kg of corium enters the reactor cavity, but in MELCOR 2.1 (Fig. 11(c)), the time is approximately 35 minutes and the amount of 2.1e+5 kg of corium enters the reactor cavity. In version 1.8.6, the SIT tank injects water directly into the reactor cavity [21,22,23], but in version 2.1, this tank injects water directly into the RPV and a higher volume of water from the RPV side enters the reactor cavity. The amount of gaon in the two versions is quite different. In version 2.1, the amount of 344542 kg of gas has been produced in 96 hours, while in version 1.8.6, the amount of 186705 kg has been calculated (Fig. 12(a)).

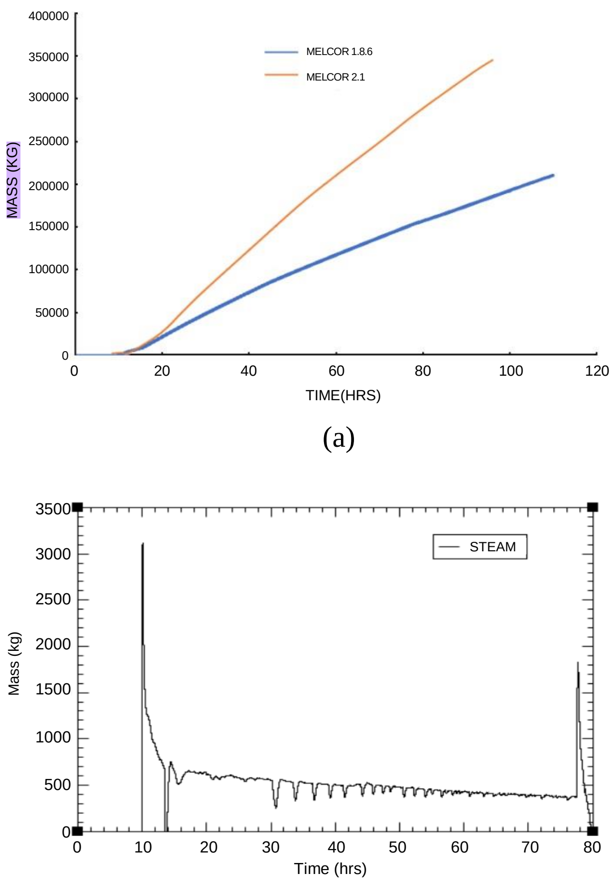


(a)

(b)

(c)

Fig. 11. (a) APR 1400 pressure change during SBO scenario; (b) Mass of corium and water through vessel breach to the cavity by MELCOR 1.8.6; (c) Mass of corium and water through vessel breach to the cavity by MELCOR 2.1.[4].



(a)

(b)

Fig. 12. (a) masses of gases and steam from the cavity during an SBO accident; (b) The amount of water vapor in the containment building of the APR 1400 reactor during the SBO accident.

Table 1. Comparison of calculated values of MELCOR 1.8.6 and 2.1.

Parameter	Unit	MELCOR 1.8.6	MELCOR 2.1
Initiation of SBO	second	500.0	0.0
RPV failure	hour	9.57	5.63
Start of gas generation in the cavity	hour	10.0	6.00
Start of SIT injection	hour	10.0	6.00
Containment failure	hour	77.57	84.14

Figure 12(b) shows the amount of steam in the containment building from the time of the SBO accident to the destruction of the containment building. It can be seen that during the destruction of the RPV, that is, in 9.57 hours, an amount of 3118 kg of steam enters the containment building. Its amount decreases quickly because part of the steam turns into liquid on the heat structures and the other part is transferred to other available control volumes. Also, during the demolition of the containment building, the amount of water vapor suddenly increases because with the reduction of the pressure in the containment building, 1816 kg of water evaporates quickly and the amount of steam suddenly increases and is released into the environment.

CONCLUSION

An analysis of the thermal-hydraulic responses of the containment for an APR1400 nuclear power plant was conducted using MELCOR version 1.8.6. The modeling results with MELCOR 1.8.6 code have been benchmarked with MELCOR 2.1. The simulation of the SBO accident for the APR 1400 reactor was carried out using MELCOR 2.1 code by KEPCO. In this research, as indicated in Table No. 1, the time of the accident is 500 seconds. However, in Vo et al. [5], the start time of the accident is from time zero, and this difference of 500 seconds is part of the reason for the time differences in comparing the results of both studies. The results show that without any containment heat removal and/or a venting system, the containment integrity is maintained for more than three days (77.56 h) after the initiation of an SBO. Before RPV fails, steam from the core transfers into the IRWST poolside, and steam condensate prevents pressure increases inside the containment building. A rapid increase in containment pressure occurs when the lower head of the vessel fails. This is due to the ejection of a large amount of corium as well as water and steam from the RPV to the cavity. Selecting the small control volumes directly affects the duration of containment integrity against pressure increase. During 14.37 hours, the pressure of the containment building increases momentarily due to the combustion of hydrogen and carbon monoxide. It mitigates the sharp increase in containment pressure. During the later phase of an accident, the containment pressure increases gradually due to the generation of steam and non-condensable gases and water evaporation. The total mass of steam and gases in the containment from these processes is about 209,768 kg. The calculation results of MELCOR code 1.8.6 were benchmarked with version 2.1. The comparison of the results is given in Table 1. The results show that the two versions have a large difference in calculating the time of phenomena. For example, the failure time of the RPV, which took 9.57 hours to be destroyed in version 1.8.6, but in version 2.1, this value is 5.96 hours. Between these two versions of the MELCOR code, there is a time difference of approximately 3.5 hours in the calculation of the destruction time of the reactor's metallic RPV. This difference can be caused by the way containment is divided in both research. In this research, the containment building is divided into 12 control volumes, and in each of these control volumes, steam and gas released from the accident are spread and the pressure inside the containment, takes a longer time to reach the breaking point. This difference in the time of destruction of the metal RPV can be caused by the nodalization of the reactor core and the newer update in the MELCOR 2.1 code. It can also be seen in version 1.8.6 that the reason for the increase in pressure in the building is to control the accumulation of carbon dioxide gas, but in version 2.1, the accumulation of steam is the main reason for the increase in pressure. The calculations related to the amount of corium mass in the two versions of MELCOR are significantly different, around 41 %. As can be seen in Table 1, the calculated mass of corium entering the reactor cavity is 148,000 kg in MELCOR 1.8.6 and 210,000 kg in MELCOR 2.1. This difference can be caused by the volume of the reactor core and the modifications made in the reactor core model in MELCOR 2.1. According to the updates made in MELCOR 2.1, it is recommended to use this version to perform accident simulations.

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AUTHOR CONTRIBUTION

F. Ghaderinia, M. Rahgoshay, J. Jafari and F. Saverio Dauria were equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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