Analysis of Accident of 1400 MWe Nuclear Power Plant with SIRIUS in CINEMA

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1. Introduction

Severe accident integrated analysis code, which is Code for Integrated severe accident Evaluation and MAnagement (CINEMA), has been developed in Korea Atomic Energy Research Institute (KAERI) since 2011 as there was a growing need for a domestic severe accident code. The CINEMA consists of three parts; 1) analysis module of in-vessel phenomenon (CSPACE) 2) analysis module of ex-vessel phenomenon (SACAP) 3) analysis module of fission product (FP) behavior (SIRIUS) [1]. The SIRIUS calculates the amount of FP in reactor coolant system (RCS) under severe accident conditions. The FP behavior calculation includes calculation of initial inventory of FP in the fuel, release from fuel, aerosol or gas transport and removal [2]. In this study, the amount of FP released to containment was calculated with SIRIUS. The target plant is 1400 MWe nuclear power plant (NPP) and accident scenarios are LLOCA, SLOCA, TLOFW, and SBO.

2. Accident Scenarios

2.1Plant Nodalization

The FP behavior is calculated from the thermal hydraulic data, such as temperature, pressure and gas flow rate. Thermal hydraulic calculation was conducted with plant nodalization in Fig. 1. Core region was divided into 3 radial rings and 5 axial levels, and other parts such as steam generator, hot legs, pressurizer, cold legs are also modeled, as shown in Fig. 1. Accident scenarios considered in this study are LLOCA, SLOCA, TLOFW and SBO. LLOCA has traditionally been selected as accident scenario in the safety analysis of nuclear power plants due to the sudden loss of coolant caused by a rapid accident. In addition, since the probability of occurrence of LLOCA is extremely low in 1400 MWe NPP, SLOCA was selected as one of the loss of coolant accident case. According to probabilistic safety evaluation for 1400 MWe NPP, the possibility of electric power outage is significant, but core degradation accident usually occurred when the heat removal in secondary system failed. Thus, TLOFW and SBO scenario were selected. In the calculation, it was assumed that severe accident entrance condition is that the core exit temperature exceeds 922 K.

2.2 Boundary conditions

Calculation conditions which contain the safety system operating condition are indicated in Table 1. In LLOCA case, hot leg rupture was assumed at 0 sec with diameter of 9.6 inch. Moreover, manually operation of POSRV was not considered. However, the other cases considered the operation of POSRV manually. Passive operation of the safety injection tank (SIT) was assumed in all cases, and no operation of motor driven auxiliary feed water (MDAFW), turbine driven auxiliary feed water (TDAFW), high pressure injection (HPI), low pressure injection (LPI), fan cooler, containment spray (CS), in-vessel injection (IVI), external reactor vessel cooling (ERVC), emergency containment spray backup system (ECSBS) was also assumed. It was also considered in all cases that operation of cavity flooding system (CFS), igniter and passive autocatalytic recombiner (PAR).

2.3 Accident Analysis Results

CINEMA calculation results for thermal hydraulics are summarized in Table 2 and it is described below.

2.3.1 LLOCA

At time 0 seconds, the RCS pressure begins to drop due to the 9.6 inch pipe breakage. The SIT runs in 238 seconds in conjunction with the primary pressure, but the SIT was depleted at about 1,500 seconds due to a large amount of coolant loss through the damaged area. After the initial exposure of the core in 1,968 seconds, the coolant was reduced to the bottom of the core at 2,608 seconds, and the core area was completely exposed and hydrogen was generated after about 130 seconds. Overheating steam continues to be generated, causing a severe accident at 2,982 seconds. At 3,858 seconds, the corium in the core area was relocated to the lower head and the bottom head of the reactor vessel was broken at about 7,759 seconds.

2.3.2 SLOCA

At time 0 seconds, the RCS pressure begins to drop due to the 2.0 inch pipe breakage. At the time of 4,106 seconds, the top of fuel starts to be exposed, and hydrogen starts to be generated at 4,480 seconds. Because of high temperature superheated steam, core exit temperature (CET) reach 922 K at 4,561 seconds. After that, SIT operated in 4,966 seconds to recover the water level in the reactor vessel. However, since the loss

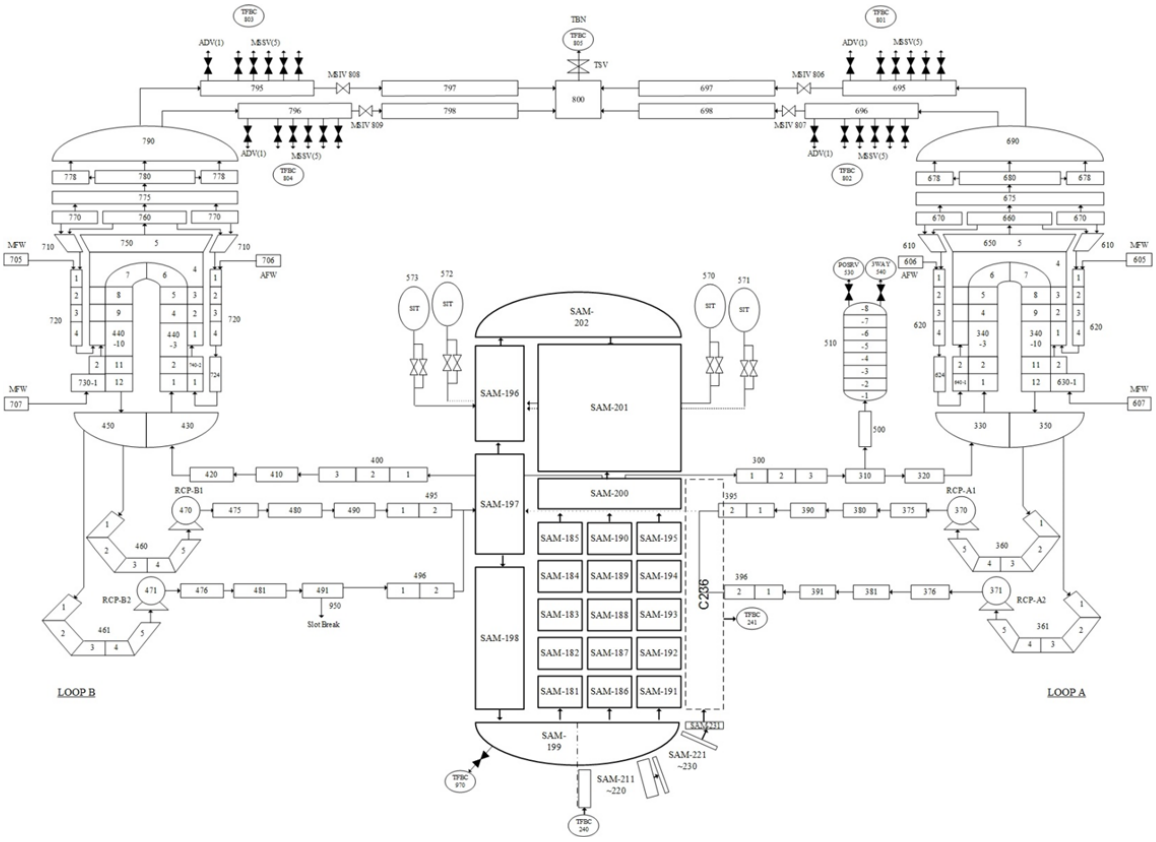

Fig. 1. 1400 MWe nuclear power plant nodalization for FP behavior analysis

of coolant through the damaged part continued, the coolant reduced up to the level of the lower support in 13,141 seconds. After about 15,364 seconds, the corium was relocated to the bottom head and the lower head vessel failure was observed at about 9,166 seconds after relocation.

2.3.3 TLOFW

It was assumed that the main feed water and the auxiliary feed water system are completely lost at time 0 seconds, so that POSRV opening and closing operation was repeated. Then, the top of fuel starts to be exposed at 2,889 seconds, hydrogen starts to be generated at 3,015 seconds. The CET reach 922 K at 3,059 seconds. At the same time, the POSRV was manually opened by the operator, so the SIT was opened and the coolant in the RCS was recovered. However, since the secondary side heat removal was not performed properly, the coolant begins to be depleted soon, and the core region was completely uncovered at 7,234 seconds. The corium relocation to lower head occurred at 9,496 seconds and vessel failure was observed at 13,412 seconds.

Table I: Calculation conditions with safety system operating condition

Event	LLOCA	SLOCA	TLOFW	SBO
Description	Dia.: 9.6 inch Hot leg	Dia.: 2 inch Hot leg	Loss of MFW, AFW	
POSRV	No manual operation	Manually open after 30 min. of SA	Manually open right after SA	Manually open right after SA
MDAFW, TDAFW, HPI, LPI, fan cooler, CS, IVI, ERVC, ECSBS	No operation	No operation	No operation	No operation
SIT	Passive operation	Passive operation	Passive operation	Passive operation
CFS	Initiated after 30 min. of SA	Initiated after 30 min. of SA	Initiated after 30 min. of SA	Initiated after 30 min. of SA
Igniter, PARs	Operation	Operation	Operation	Operation
Calculation period	12 hrs	12 hrs	-	12 hrs

2.3.4 SBO

At 0 seconds, the complete loss of power was assumed, and both the RCP and the secondary water

Table Ⅱ: Calculation results with accident scenarios

Phenomenon	LLOCA (sec)	SLOCA (sec)	TLOFW (sec)	SBO (sec)
Initiation	0	0	0	0
SIT injection	238	4,966	3,153	7,281
Core uncovered initiation	1,968	4,106	2,889	6,026
Fully Core uncovered	2,608	13,141	7,234	13,646
Hydrogen generation	2,732	4,480	3,015	7,160
Entrance of SA (CET=922 K)	2,982	4,561	3,059	7,201
Fuel relocation	3,858	15,364	9,496	14,337
CFS open	4,782	6,361	4,859	9,001
Reactor vessel failure	7,759	24,530	13,412	23,023

Table Ⅲ: FP initial inventory in fuel

Species	Initial inventory (kg)
A (noble gas)	401.2005
B (Alkali metal iodides)	15.6
C (Alkali metal hydroxides)	196.0005
D (Chalcogens)	36.36
E (Alkaline earths)	175.9995
F (Platinoids)	379.9995
G (Rare earths)	355.9995
H (Structural materials)	24811.2

supply pump were stopped. When the primary coolant temperature rises and reaches the POSRV pressure set point, opening and closing were repeated. At 6,026 seconds, the top of fuel starts to be exposed, hydrogen starts to be generated at 7,160 seconds. At the same time, the POSRV is manually opened, so the SIT was opened and the coolant is recovered. However, because the RCP and secondary feed water pump were not recovered, the coolant begins to deplete soon, and the core region was fully exposed at 13,646 seconds. Lower head vessel failure occurred at 23,023 seconds.

3. FP Behavior Analysis Results

FP behavior in each accident scenario was calculated with SIRIUS. FPs considered in SIRIUS were divided into 8 groups; Noble gases(1), Alkali metal iodides(2), Alkali metal hydroxides(3), Chalcogens(4), Alkaline earths(5), Platinoids(6), Rare earths(7) and Structural material(8). The FP initial inventory was distributed in core region (SAM-185~195 in Fig. 1) and the initial FP inventory is indicated in Table 3. As the fuel temperature increased, FPs in the fuel were released and transported to adjacent node. When the lower head vessel failure occurred, FP could be transported to containment.

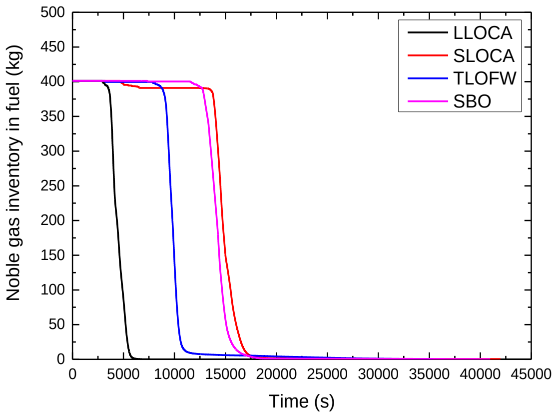

Fig. 2. Noble gas inventory in fuel with accident scenario

3.1FP Inventory in Fuel

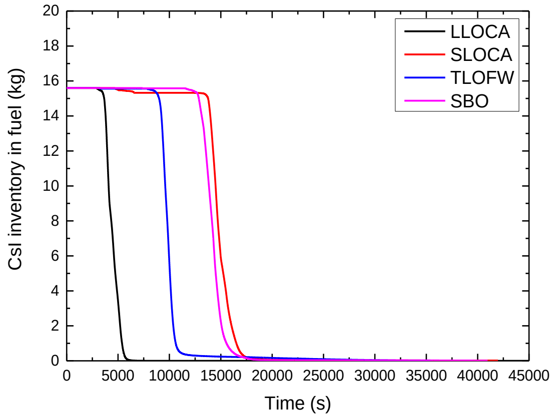

Fig. 3. CsI inventory in fuel with accident scenario

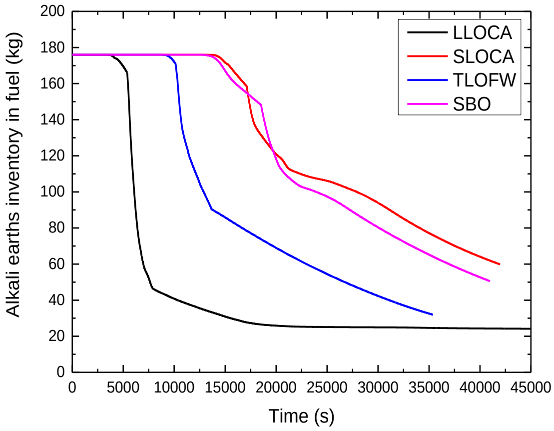

Fig. 4. Alkali earth inventory in fuel with accident scenario

As the FPs in the fuel released, the FP inventory in fuel decreased. The decreasing trend was different with the release rate of FP species. The initial inventory variation of group 1, 2, and 5 were indicated in Figs. 2, 3 and 4. It was shown in the Figs. 2 and 3 that the inventory of each species behavior is very similar because both species are volatile. Group 5 is non-volatile species, so it shows different behavior. In the case of group 1 and 2, almost all FP were released from fuel in all accident scenario. In group 5, over than half of initial inventory were released. In the LLOCA scenario, the severe accident entrance time was faster than other cases, and it means that the fuel temperature increased faster than other accident scenarios. Furthermore, fuel relocation time was also earlier than other cases, and it was found that high fuel temperature is maintained in the LLOCA case. The fuel relocation time of TLOFW scenario is also earlier than SLOCA and SBO case, and it was directly related with FP inventory decrease trend. Although the severe accident entrance time of SLOCA is faster than SBO, the fuel relocation time of SLOCA is slower. Thus the FP release rate of SLOCA is larger than SBO before about

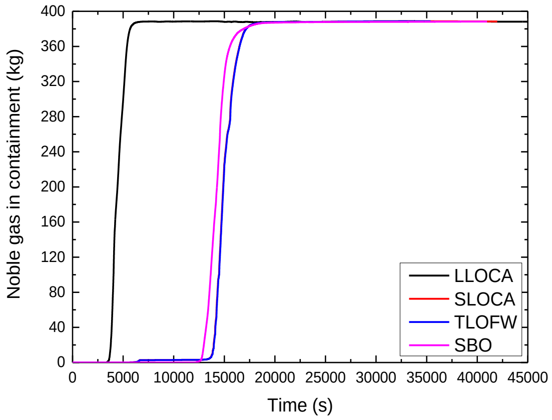

Fig. 5. Noble gas mass in containment with accident scenario

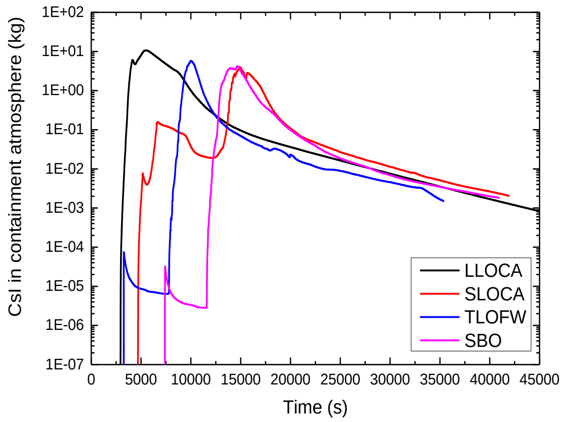

Fig. 6. CsI mass in containment with accident scenario

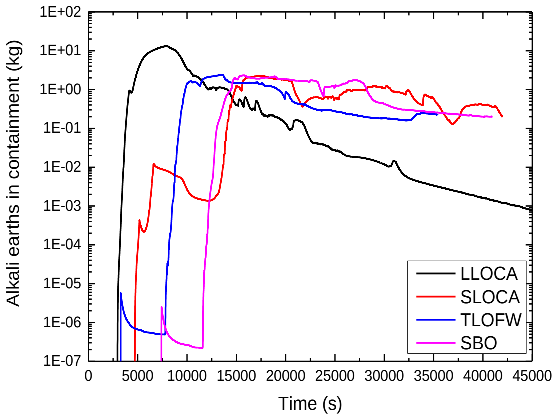

Fig. 7. Alkali earth mass in containment with accident scenario

15,000 seconds, the release rate was reversed after the time.

3.2 FP Mass in Containment

FP released from the fuel was transported to the other node, such as hot leg, steam generator tube and cold leg. The FP could be released to the containment when the lower head vessel failure occurred. The containment also consists of several nodes though it is not shown in the paper, and it was shown in the Figs. 5, 6 and 7 that the amounts of released FP into the containment of group 1, 2 and 5. The FP mass in the containment increased with the vessel failure. In the case of noble gas, almost all species were released into the containment because it exist as a gas phase. However, in the case of group 2 and 5, the mass in containment is much smaller than the released mass from the fuel. This is because that the species in group 2 and 5 could be existed in the aerosol form and the aerosol could be removed by agglomeration, deposition, diffusiophoresis and thermophoresis. It was observed in the containment that the airborne FP mass in group 2 and 5 is decreased with time. It is also originated from the aerosol removal mechanism in the containment nodes.

4. Conclusions

Severe accident integrated analysis code, which is CINEMA has been developed in KAERI and four accident scenarios were calculated with CINEMA in severe accident condition. Analysis of FP behavior was performed with SIRIUS using CINEMA thermal hydraulic data. FP inventories and FP mass in containment of each scenario were analyzed and it was found that the models in the SIRIUS were operated reasonably. In the future, validation of SIRIUS will be performed with relevant tests, and the results will be compared with MELCOR RN package [3, 4].

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