Uncertainty Analysis of Source Term for OPR1000 Station Blackout Accident

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1. Introduction

The most important event during a severe accident at a nuclear power plant is the amount of source term in the containment that can be release to the environment. To evaluate the source term, it is necessary to estimate the amount of fission products that can be present in the containment as reallistically as possible-[1].

In this study, using the MELCOR computer code, the uncertainty analyses were performed by selecting variables that could affect the generation and transport of fission products in the actual nuclear power plant during the OPR1000[10] major severe accident process/ phenomena.

2. Selection of variables related to the radioactive source term

2.1 MELCOR code description [2]

The MELCOR code is an integrated code developed for the analysis of major accidents since the mid-1980s, developed by Sandia National Laboratory under the auspices of the U.S. Nuclear Regulatory Commission. The MELCOR code was developed to address the shortcomings of the STCP (Source Term Code Package), which had been used since the 1970s, and to expand its range of application. This computer code was developed to improve the practice of calculating individual phenomena with their respective codes, allowing multiple phenomena to be calculated with a single code. MELCOR 2.2 v15254 was used for this study.

2.2 Review of physical variables

The behavior of fuel melting and fission products during severe accident is closely related to the amount of source term in the containment.

The physical variables affecting the source term are divided into the COR package and the RN package. They were selected on the basis of previous research [4,5,6,7,8,9], as follows, and a detailed description can be found in reference [3]. The variables used in this uncertainty analysis are listed in Table 1.

Table 1. MELCOR Uncertainty Variables and Distributions

No	Varibles	MELCOR Input	Distribution			Rmks
			Min.	Mode	Max.	
1	Molten Zircaloy Melt Break-through Temperature	SC1131(2)	Triangular Distribution			
			2,100.K	2,400.K	2,540.K	
2	Core (Fuel) Component Failure Parameters	SC1132(1)	Triangular Distribution			
			2,400.K	2,500.K	2,700.K	
3	Candling Heat Transfer Coefficients	COR_CHT (1)HFRZZR	Linear Distribution			±10%
			6,750.	7,500.	8,250.	
4	Candling Secondary Material Transport Parameters	COR_CMT (5) FUOZR	Triangular Distribution			
			0.	0.2	0.5	
5	Molten Clad Drainage Rate	SC1141(2)	Triangular Distribution			
			0.1	0.2	1.0	
6	Time Constants for Radial Debris Relocation	COR_TST (10)ISPR SC1020(1)	Triangular Distribution			ISPR=0
			180.s	360.s	720.s	
7	Containment Convection Heat Transfer Multiplier	HS_LBT - (3)XHTFCL	Triangular Distribution			
			1.0	1.4	2.0	
8	Chemical Form of Iodine	RN1_CSC 7103 I2	log-normal distribution			
			μ =-9.94		σ =0.28	
9	Chemical Form of Cesium	RN1_CSC 7103 CSM	Beta Distribution (0<; <1.0)			
			α =9		β =3	
10	Dynamic Shape Factor	RN1_MS00 CHI	Beta Distribution			
			α =1		β =5	

3. Analysis Results

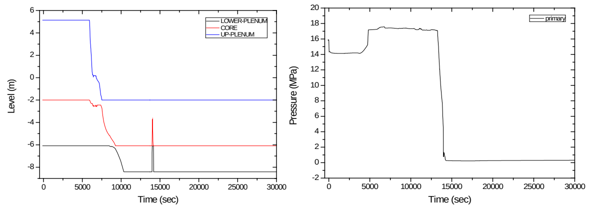
3.1 Evaluation of OPR1000 Station Blackout

Station Blackout accident is that the reactor, turbine generator, main feed pump, and auxiliary feed pump are stopped at time 0, and all safety systems except the safety injection tank are not available. The sequences of events of the MELCOR calculation and main thermohydraulic paremeters are shown in the Table 2 and Fig. 1.

Table 2. Sequences of Events

Time (sec)	Event
0.0	Reactor Coolant Pump trip Main Feedwater Pump trip Reactor trip, Main Steam Isolation Valve close.
3,525.0	Steam generator A empty
3,593.0	Steam generator B empty
4,814.0	Pressurizer Safety Valve open
7,470.0	Active fuel partially uncovered
9,280.0	All active fuel uncovered
10,963.0	Fuel clad melting starts
11,055.0	Start corium relocation to lower head
13,794.0	Reactor lower head fails and corium relocation starts to reactor cavity

13,964.0	Start injection of SIT
14,161.0	Safety Injection Tank empty



(a) Water Level (b) RCS Pressure

Fig 1. Major thermohydraulic parameters for OPR1000 by MELCOR during SBO

3.2 Review of the Source Term inside the Containment

Since the containment building is divided into sub-compartments, there will be significant concentration differences between compartments in the early phase, but it is judged that they can reach almost similar concentrations with continuous diffusion. According to many experiments, the fission products leaking from the reactor vessel can be categorized into noble gases and aerosols, and it is known that more than 80% of the total inventory is released in the form of aerosols. Due to the nature of aerosols, the amount of aerosol suspended in the air naturally decreases after release due to the unique characteristics of aerosol such as Brownian motion, thermophoresis, diffusiophoresis, electrophoresis, and hygroscopic growth phenomena.

Since the concentration of airborne aerosols is expected to decrease, it is considered as conservative to evaluate the source term based on the amount of fission products released from the reactor vessel into the containment building.

3.3 Uncertainty analysis Results

The Nuclear Safety Act of Korea has a probabilistic radiation source protection goal. The sum of the frequency of accidents resulting in the release of the radionuclide Cs-137 exceeding 100 TBq must be less than 1.0E-6/RY.

The 100 TBq of Cs-137 is equivalent to 31.25 g of Cs-137 based on a specific activity of 3.2 TBq/g, so a leak of 31.25 g of Cs-137 nuclide is assessed as a 100 TBq leak. However, there is no description of the leakage period.

The radioactive nuclides evaluated in this study were limited to iodine and cesium, and the inventory of fission products in the core is assumed to be proportional to the heat output and operating period for the same nuclear fuel.

The core fission product inventories for each group used as input to MELCOR in OPR1000 are shown in the Table 3, and correspond to 278.3 kg, 18.8 kg, and 357.7 kg for cesium, iodine, and molybdenum in the core, respectively.

The uncertainty calculations were performed using the Monte-Carlo Sampling method within the DAKOTA module developed by Sandia National Laboratories and embedded in NRC SNAP for the variables considered in Table 1 by generating 99 cases and performing calculations for each of them.

Table 3. OPR1000 MELCOR RN inventories

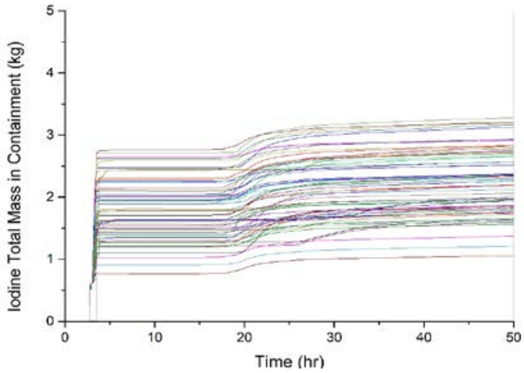
#	Class (representative)	BOC (kg)	MOC (kg)	EOC (kg)	SOARCA (kg)
1	Noble Gases (Xe)	246.89	341.82	489.01	495.44
2	Alkali Metals (Cs)	6.62	9.06	12.75	12.93
3	Alkaline Earths (Ba)	104.47	146.07	204.39	207.42
4	Halogens (I)	all in CsI	all in CsI	all in CsI	all in CsI
	……………	…….	……...	……...	……
16	Cesium Iodide (CsI)	19.38	26.87	38.86	38.49
17	Cesium Molybdate (Cs2MoO4)	….	….	….	….
	Total Cesium Class Mass	142.26	195.18	275.12	278.35
	Total Iodine Class Mass	9.46	13.12	18.98	18.80
	Total Molybdenum Class Mass	184.12	250.21	356.47	357.70

a) Base Calculation

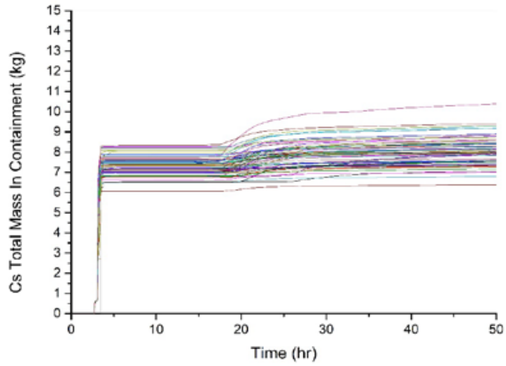
Iodine leakage is assumed to be in the form of CsI due to the nature of the MELCOR Radionuclide Package. The in-core inventory of iodine (following figures) was estimated to be approximately 19 kg in EOL condition and the leakage into the containment was estimated to be approximately 3 kg. This can be calculated as a leakage rate of 0.17 (17%).

The cesium calculation only considers leakage in the form of CsI, as Cs_2MoO_4 is not considered. The fission product inventory in the OPR1000 reactor core is 278.3 kg of cesium, and the total mass of leakage in the containment building is calculated to be about 10 kg. At the design leakage rate of 0.1 vol %/24 h without considering the containment failure, the 24-hour leakage is 10 kg of cesium in the containment building.

However, this value is considered conservative as it is not maintained at the containment pressure for 24 hours, and using it to evaluate the probabilistic safety objective, the leakage rate is 30 g over 72 hrs, so the probabilistic objective can be met up to the design leakage rate for 3 days.



(a) Mass of iodine in the containment



(b) Mass of Cesium in the containment

Fig 2. Mass of iodine and cesium in the Containment (base calculation)

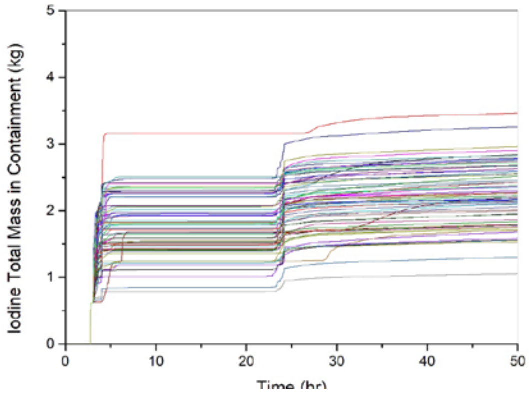
b) Sensitivity Analysis considering Cesium Molybdate

MELCOR categorizes more than 50 fission products in the reactor core into 16 groups according to their chemical and physical properties. Recent studies have shown that Cs_2MoO_4 leakage is more dominant than CsOH, so a 17th group is being created and modeled. To enable this, new input “Class Combination” was created to perform the calculation as follows.

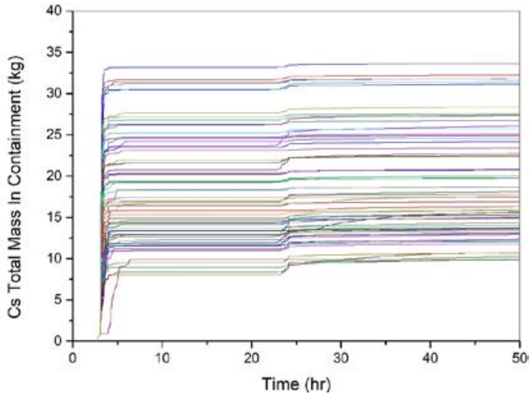
- Class combination : [Cs : Mo]
- Cs_2MoO_4 : 2Cs + 1Mo => [1:0.5] or [2:1]
- Input : [1:0.5]

As a result, the amount of iodine leaked into the containment building was about 3 kg, which is similar to the base calculation, and the amount of cesium leaked into the containment building was about 30 kg, which is about three times the base calculation. These results can be attributed to the additional consideration of Cs_2MoO_4, and it can be concluded that all of the increased cesium mass was released in the form of Cs_2MoO_4.

At the containment design leak rate of 0.1 vol %/24 h without considering the containment failure, the 24-hour leakage is equivalent to 30 g. This value is considered conservative because the same concentration is not maintained for 24 hours, but it satisfies the probabilistic objective at the design leak rate for 24 hours.



(a) Mass of iodine in the containment



(b) Mass of Cesium in the containment

Fig 4. Mass of iodine and cesium in the Containment (Sensitivity Analysis considering Cesium Molybdate)

c) Sensitivity Analysis considering Class Combination

The total amount of cesium for several representative class combination ratio [Cs:Mo], the amount of cesium in the containment building, and the amount of cesium in the air are shown in Table 4.

Table 4. Mass of cesium considering class combination ratio [Cs : Mo]

Cs : Mo	Total mass of cesium in containment (kg)	Mass Fraction of Cs in Containment to total Cs inventory	Mass Fraction of Cs in Containment air to total Cs inventory
N/A	~10	~0.035	~0.0025
1 : 0.5	**~33**	**~0.12**	**~0.003**
1 : 1	~29	~0.105	~0.003
0.5 : 1	~25	~0.09	~0.003
2 : 1	~33	~0.12	~0.003

It was found that the result of the ratio [1:0.5] of [Cs:Mo] is almost similar to the ratio [2:1], and the ratio of the number of atoms in the molecule as described above is judged to be an appropriate input.

3. Conclusions

In this study, the OPR1000 nuclear power plant was analyzed using MELCOR for the SBO source term, and a preliminary evaluation was made based on the probabilistic target value of cesium leakage including cesium molybdate. The time to the probabilistic safety target was calculated using the total mass of cesium in the containment, without containment failure.

Based on the total mass of cesium in the containment, 24 hours are required to reach the probabilistic safety target. Only considering the cesium in the air inside the containment, the total leakage reaches the probabilistic safety target value if the leakage continues for about 40 days.

For Future works, the following additional research will be required in the future.

- In this study, CsOH is ignored because the solubility of CsOH is very high. However, the possibility of leakage of CsOH should also be considered.
- Further investigation of the variables that may affect the amount of Cesium in the containment building and analysis of the uncertainties in these variables are required.

Acknowledgements

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