Consequence Analysis of Severe Accidents at Nuclear Power Plants

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1. Introduction

A nuclear accident was defined by the International Atomic Energy Agency (IAEA) as a radiation release event that led to significant consequences for people, the environment or the nuclear facility where it occurred [1]. When safety measures were not properly observed by nuclear plant operators, a nuclear accident could occur with serious consequences for the environment, human health and public opinion [2]. Factors like wind speed, wind direction, temperature, and humidity could influence the dispersion process of radioactive materials and the mixing process [3]. This study aimed at predicting the radiological environmental consequence of a severe accident of nuclear power plant. Total Effective Dose Equivalent (TEDE), Thyroid Committed Dose Equivalent (CDE), air concentration, and deposition were predicted. TEDE was calculated as a combination of Inhalation Committed Effective Dose Equivalent (CEDE), cloud shine and four-day ground shine. Korea classifies the emergency planning zones (EPZs) around nuclear power plants as precautionary action zones (PAZs) and urgent protective action planning zones (UPZs). The PAZ had a radius range of 3~5 km while the UPZ was of 20~30 km. The Korean standard protective actions were classified as; sheltering (10 mSv within 2 days), evacuation (50 mSv within 1 week), distribution Iodine Prophylaxis (100 mSv), temporary relocation (30 mSv and 10 mSv in the first one month and the following month, respectively) and permanent settlement (1Sv/lifetime) [4].

2. Methods and Results

2.1 RASCAL

RASCAL computer code Version 4.3.3, developed by Nuclear Regulatory Commission (NRC), was applied to calculate source term and dose. The code provided a tool for the rapid assessment of an incident or accident and helped a decision-making process in implementing protective actions [5]. The Source Term to Dose (STDose) model and Source Term Merge option which allowed users to assess the consequences from a multi-reactor event model in RASCAL was applied. STDose included the following sub-modules: event type, event location, source term, release path and meteorology [6]. The conventional straight Gaussian equation used in RASCAL was as follows; [6].

$$\chi(x,y,x) = \int_{-\infty}^{\infty} \frac{Q' F_y F_z}{(2\pi)^{3/2} \sigma_x(x) \sigma_y(x) \sigma_z(x)} \exp\left[\frac{1}{2}\left(\frac{x-ut}{\sigma_x(x)}\right)^2\right] dt \quad (1)$$

Simplified version of the straight-line Gaussian model

$$P'(t+\Delta t) = P(t) + V(P,t)\Delta t \quad (2)$$

where,
X = average concentration, Q' = release rate,
F_yF_z, = lateral and vertical exponential terms
x= downwind distance at which χ, σ_x, σ_y and σ_z, are evaluated,
u = wind speed, t = time

2.1.1 Benchmarking study of Fukushima accident

The simulated source term released to atmosphere according to RASCAL was 1.3×10^{18} Bq. The leak rates used were as used in RASCAL 4 [6]. The default leak rate was changed from 0.5%/day to 1%/hour at the beginning of core damage, 25% per hour for 1 hour for containment venting and to 50%/hour for 1 hour following the Unit 1 and 3 explosions. Following containment venting and hydrogen explosions, the leak rate was returned to 1%/hour. ^{131}I and ^{137}Cs were found to be the two most important radionuclides for dose assessment because the two adversely affected human health through contamination of air, water, soil and food. To achieve the objective of benchmarking, ^{131}I and ^{137}Cs source terms were compared with the other computational results as shown in Fig. 1. Further a comparison of the release rates of this study with estimates was derived using reverse modeling as shown in Fig. 2. Reverse modelling involved optimizing the estimates derived from simulations to fit, measurements of radioactive material in the environment. The comparison showed some correlation and a number of differences which might be attributed to the code modeling differences and uncertainties. The highest peaks of the release rates and activities as shown in Fig. 2 were due to the explosions of Unit 1 and 3 respectively. The over-estimation might be attributed to the code as it did not consider secondary building hence no delay in the radioactive material movement between containment and the atmosphere [6]. This might also be due to the leakage rates used.

Table I: Time Sequence of FDNPP unit 1

Date	Time	Event

11/3/2011	14:46	Reactor shut down
11/3/2011	15:37	EDGS, Alternating Current (AC) and Direct Current (DC) lost
11/3/2011	18:10	Core uncovery
12/3/2011	14:30	Start Venting
12/3/2011	15:36	Explosion

Table II: Time Sequence of FDNPP unit 2

Date	Time	Event
11/3/2011	14:46	Reactor shut down
11/3/2011	14:50	Start of core cooling
11/3/2011	14:47	EDGs automatically started
11/3/2011	15:35	EDGs off due to tsunami
13/3/2011	11:46	Core uncovery
	01:06	Core recovery
15/3/2011	02:00	Venting, opening of valve
15/3/2011	12:00	End Venting, valve closure

Table III: Time Sequence of FDNPP unit 2

Date	Time	Event
11/3/2011	14:46	Reactor shut down
11/3/2011	15:37	AC power was lost
13/3/2011	9:20	Start Venting, opening valve
13/3/2011	12:46	Core uncovery
13/3/2011	15:06	Core recovery
13/3/2011	20:10	Start venting
14/3/2011	1:00	End venting
14/3/2011	6:00	Start venting
14/3/2011	11:01	Explosion

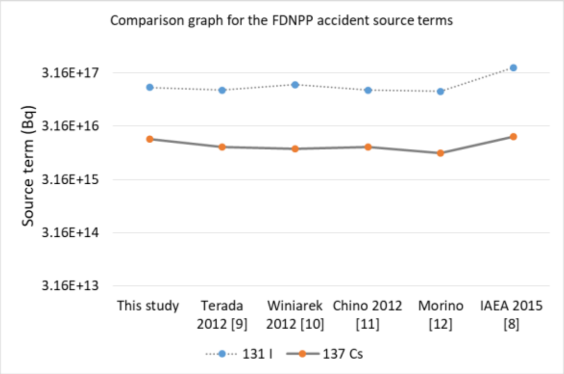

Fig. 1. Comparison of source terms.

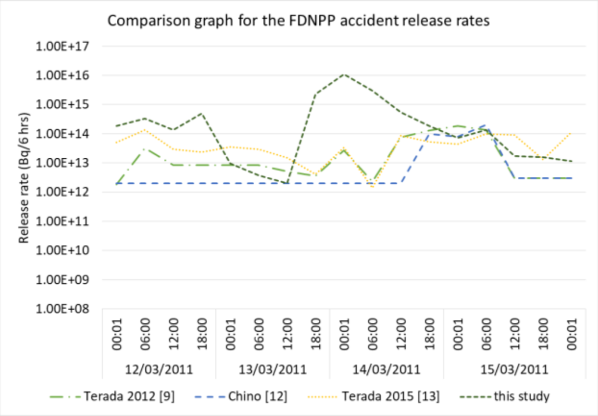

Fig. 2. Comparison of the FDNPP accident release rates.

2.1.2 *Simulation of the accident at Shin Kori NPPs*

Considering a scenario related to Fukushima accident, a long station black out at Shin Kori NPP was simulated as shown in Table IV and Table V. Units 3 and 4 contained the APR-1400 pressurized water reactors. Source term from the two units was calculated for a period of 96 hours using Source Term Merge option in RASCAL. The calculated total release of radioactive material was 4.1×10^{16} Bq. No deterministic effects would be expected since the maximum TEDE falls below 100 mSv. ^{131}I was the radioiodine of concern and was simulated at a value of 9.3×10^{14} Bq. Based on the Korean standards for emergency response, sheltering would be required in the first four days simulated as the highest accumulated TEDE was calculated at 38 mSv. Thyroid effects would not be expected to occur according to Fig.3 since the highest thyroid CDE received by a person in 50 years was below 100 mSv.

Table IV: Accident sequence of Shin Kori unit 3

Date	Time	Event
2018/08/10	01 :00	Loss of offsite power, Reactor shut down
2018/08/10	01 :00	Emergency core-cooling available for about 8 hours
2018/08/10	17:00	Core uncovery
2018/03/10	23:00	Leak rate 0.10 %/day
2018/03/10	21:00	Core recovered

Table V: Accident sequence of Shin Kori unit 4

Date	Time	Event
2018/08/10	01 :00	Reactor shut down
2018/08/10	01 :00	Spray off, ECCS available for about 8 hours
2018/08/11	09:00	Core uncovery after 3 hours Leak rate 0.10 %/day
2018/08/11	12:00	Core recovered

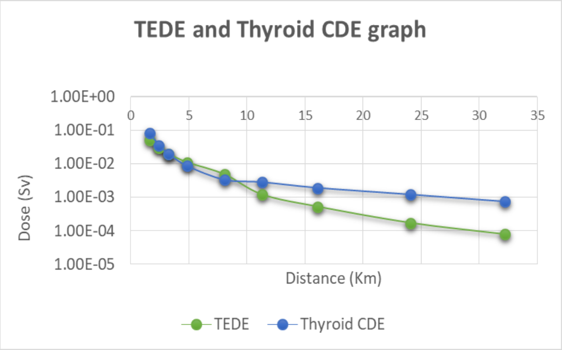

Fig. 3. TEDE and Thyroid CDE within distance of 32 km.

2.2 HYSPLIT

Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), a Lagrangian dispersion model developed by National Oceanic and Atmospheric Administration (NOAA) was applied. The model computed simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation. The code was used in this study to calculate air concentration and deposition. HYSPLIT could estimate forward and backward trajectory of air mass by assuming either puff or particle dispersion [7]. Meteorological data output from the Global Data Assimilation System (GDAS) was applied. The computation of the new position at a time step (t + Δt) due to the mean advection by the wind determined the trajectory that a particle or puff would follow. Considering a particle; the particle followed the wind and its trajectory was just the integration of the particle position vector in space and time (t). The final position was computed from the average velocity (V) at the initial position (P) and first-guess position (P′). The dispersion process was represented by adding a turbulent component to the mean velocity obtained from the meteorological data, namely [7]

$$P(t+\Delta t)=P(t)+0.5[V(P,t)+V(P'\ t+\Delta t)]\Delta t \qquad (3)$$

$$P'\ (t+\ \Delta t)=\ P(t)+V(P,t)\Delta t \qquad (4)$$

$$X_{final}\ (t+\Delta t)\ =\ X_{mean}\ (t+\Delta t)\ +U'\ (t+\Delta t)\Delta t \qquad (5)$$

$$Z_{final}\ (t+\Delta t)\ =Z_{mean}\ (t+\Delta t)\ +W'\ (t+\Delta t)\Delta t \qquad (6)$$

where;
U' and W' correspond to the turbulent velocity components,
X_{mean} and Z_{mean} are the mean components of particle positions, and
X_{final} and Z_{final} are the final positions in the horizontal and vertical, respectively.

2.2.1 Air concentration and deposition at Shin Kori NPPs

The top six radionuclides of ^{137}Cs, ^{134}Cs, ^{133}Xe, ^{131}I, ^{132}Te and ^{132}I important to dose in the first week of a nuclear accident were analyzed using HYSPLIT. It was observed that the radioactive material released to the atmosphere was largely dispersed over the main land of South Korea due to frequency of the Eastern winds. The air concentration was calculated between 1.2×10^{2} and 1.4×10^{-5} Bqm^{-3} where the ground deposition ranged from 7.7×10^{4} to 9.7×10^{-9} Bqm^{-2} as shown in Fig. 4 and Fig. 5. The deposition was majorly contributed by ^{137}Cs and ^{134}Cs particles and the precipitation on 10th and 11th August according to the weather analysis from Korea Meteorological Administration.

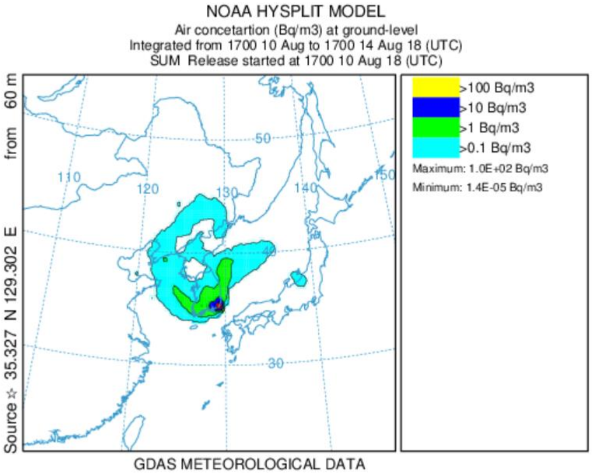

Fig. 4. Air concentration for the hyponthical accident at Shin Kori NPPs.

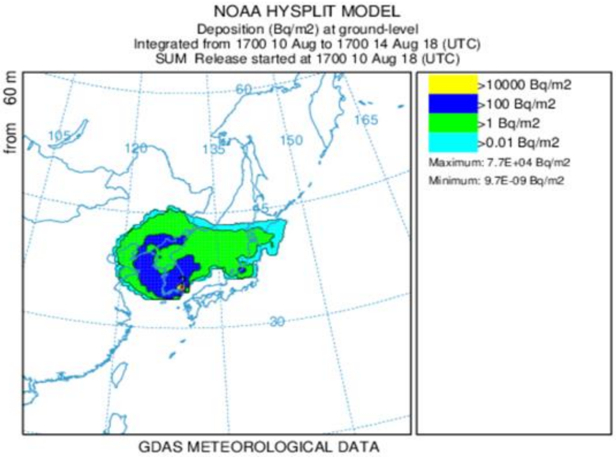

Fig. 5. Ground deposition for the hyponthical accident at Shin Kori NPPs.

3. Conclusions

Benchmarking of FDNPP showed that RASCAL code could be used in the case of emergency and estimate good results. The high values and inconsistency especially in the benchmark of the FDNPP accident was attributed to the leakage rates used. The source term merge tool in RASCAL was used to calculate the source term and dose and it assumed that the accidental release occurred at the same location and therefore this exaggerated the source term from multiple units near the release point. In addition, the code did not consider secondary building and thus there was no delay of the radioactive material to the environment. This might have led to overestimation of the source term. In the case of the analysis of a severe accident as Shin Kori NPP, it was observed that the first release would led to air concentration and deposition of large radioactive material around the Korea main land. A total release of 4.1×10^{16} Bq was projected to have been released to the environment. The air concentration ranged between 1.2×10^{2} to 1.4×10^{-5} $\mathrm{Bqm^{-3}}$ while the ground deposition ranged from 7.7×10^{4} to 9.7×10^{-9} $\mathrm{Bqm^{-2}}$. The deposition was majorly contributed by the precipitation on 10th and 11th August according to the weather analysis and input. The accumulated dose within 5 km ranged from 11 mSv to 50 mSv for the first two days therefore would require immediate action of sheltering and evacuation according to the emergency preparedness and response plans of Korea. Distribution of Iodine Prophylaxis would not be necessary since the thyroid CDE falls below 100 mSv.

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