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The Variation of Health Effects Based on the Scenarios Considering Release Parameters and Meteorological Data

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Abstract

The variation of health effects resulting from the severe accidents of the YGN 3&4 nuclear power plants was examined based on scenarios considering the release parameters and meteorological data. The release parameters and meteorological data considered in making basic scenarios are release height, heat content, release time, warning time, wind speed, rainfall rate, and atmospheric stability class. The seasonal scenarios were also made in order to estimate the seasonal variation of health effects by considering seasonal characteristics of Korea. According to the results, there are large differences in consequence analysis from scenario to scenario although an equal amount of radioactive materials is released to the atmosphere. Also, there are large differences in health effects from season to season due to distinct seasonal characteristics of Korea. Therefore, it is necessary to consider seasonal characteristics in developing optimum emergency response strategies.

1. Introduction

After the TMI and Chernobyl accidents, the importance of consequence analysis resulting from severe accidents at a nuclear power plant has increased because the influence of severe accidents on the environment and human beings is large in spite of their low occurrence probability. If a severe accident of a nuclear power plant were to proceed to containment failure, radioactive materials would be released to the atmosphere. When such an accidental release occurs, the radioactive materials in the plume while dispersing in the atmosphere would be transported by a prevailing wind. In result, the radioactive materials would contaminate the environment, and finally the population would be exposed to radiation. The consequences resulting from such an accidental release are health effects and economic impacts. These consequences are estimated by a sequence of mathematical and statistical models such as atmospheric dispersion, deposition of the material onto the ground, and the effects of airborne and deposited materials on humans and the environment.

The potential importance of offsite health and economic consequences of an accidental release from a nuclear power plant is a function of many factors such as the source term, weather condition, emergency response plan, and so on. The estimation of the total influence of these factors on offsite health and economic consequences is very complex. Therefore, it is useful to quantify their separate influences on offsite health and economic consequences based on their relative importance. Jeong and Ha[1] investigated the relative influences of source term release parameters such as release height, heat content of the plume, release time, release duration, and warning time on offsite health consequences. Also, Jeong and Ha[2] examined the relative influences of meteorological data such as wind speed, rainfall rate, and atmospheric stability class on offsite health consequences. They examined the variation of health effect cases such early fatalities, early injuries, cancer fatalities, cancer injuries, early fatality risk, and cancer fatality risk resulting from the change of source term release parameters and meteorological data.

Although the unique accident sequence and source term release rate are considered in the consequence analysis, the resulting offsite health effects may be different if the source term release parameters and weather conditions are different. Therefore, we have made basic scenarios based on the relative importance of source term release parameters and meteorological data on offsite health effects. We then investigated the variation of health effects resulting from the severe accidents of the YGN 3&4 nuclear power plants from scenario to scenario by using MACCS code[3]. Also, we have investigated the seasonal variation of health effects based on scenarios considering seasonal characteristics because we have four distinct seasons in Korea. The information obtained through this research will be very useful in developing optimum emergency response strategies for reducing offsite risks from the viewpoint of accident management.

2. Atmospheric Dispersion and Meteorological Data

If a severe nuclear power plant accident were to proceed to containment failure, a fraction of radionuclides in the form of noble gases, halogens, and aerosols would be released to the atmosphere. An assessment of the impact of such releases to the environment and the general public requires the calculation of airborne and ground concentrations of each radionuclide at various distances from the reactor. When released into the atmosphere, radioactive gases and aerosols will follow prevailing winds and be diffused due to atmospheric turbulence. Predictions of dispersion are most commonly made from the Gaussian plume model[4] due to its economy of computing time, simplified input requirements, and reasonable agreement with experimental data over flat terrain. It is also very useful for repetitive calculations and sensitivity studies.

As the plume of radioactive material travel downwind from the reactor, material is removed from the plume by radioactive decay and by deposition onto the ground. Deposition onto the ground is caused by two process: dry deposition due to gravitational settling onto, impaction on, and diffusion to surfaces, and wet deposition due to the scavenging of material by precipitation. Also, the basic dispersion model is usually modified to take account of a number of additional effects such as radioactive decay, the turbulent wake of the reactor building, the broadening of the time-averaged plume as a function of release duration to account for plume meander, mixing layer depth, surface roughness, and plume rise due to the thermal buoyancy of the plume.

Plume rise, dispersion, downwind transport, and deposition onto the ground depend on the prevailing weather conditions such as wind speed, rainfall rate, and atmospheric stability. In most consequence analysis codes, the meteorological data file of the site region is used. This file is usually composed of one year of hourly wind speed, rainfall rate, and atmospheric stability recorded at the site or nearby weather service station. The atmospheric transport models implemented in MACCS require hourly readings of wind speed, rainfall rate, and atmospheric stability as input. For each weather sequence, 120 hours of weather data are required. In addition, four values of the mixing height, one for each season of the year, must also be specified. In MACCS, there are five ways to specify the required 120 hours of weather data that constitute a weather sequence: constant weather conditions, a user specified weather sequence, a user specified start time, stratified random sampling, and structured Monte-Carlo sampling.

The meteorological data of 1992 measured and recorded at the neighboring site tower of the YGN 3&4 nuclear power plants are assumed to be representative for the site. The constant weather conditions are selected among the five ways to specify the required 120 hours of weather data that constitute a weather sequence because it is possible to estimate the variation of health effects due to the change of values of meteorological data. First of all, seasonal average wind speeds are obtained by using the monthly average wind speed that is obtained by averaging the hourly wind speed. The resulting seasonal average wind speeds are 3.0 m/sec for spring, 3.4 m/sec for summer, 3.6 m/sec for fall, 4.0 m/sec for winter. These values are assumed to be representative for each season, and are used in the formation of seasonal scenarios. The maximum rainfall rate of hourly meteorological data is selected as the representative rainfall rate for each season because the early fatalities and early fatality risk increase as the rainfall rate increases[2]. These values are 9.4 mm/hr for spring, 50.0 mm/hr for summer, 9.0 mm/hr for fall, 11.4 mm/hr for winter. The frequencies of the six atmospheric stability classes defined by Pasquill[5] are listed in Table 1. The most frequent atmospheric stability class is slightly stable(E) for spring, neutral(D) for summer, slightly unstable(C) for fall, and slightly stable(E) for winter. These atmospheric stability classes are assumed to be representative for each season and are used in the formation of seasonal scenarios.

Table 1. The frequencies of atmospheric stability classes for four seasons

Atmospheric Stability(%) Season	A	B	C	D	E	F
Spring	0.7	1.4	3.4	33.7	59.4	1.5
Summer	3.2	7.8	20.5	34.2	33.7	0.6
Fall	4.1	11.2	38.6	31.5	13.0	1.5
Winter	2.7	5.0	12.7	32.7	44.7	2.2

3. Evaluation of Health Effects

3.1 Modeling and Assumptions

The source term profiles which were derived from the Individual Plant Examination (IPE) of the YGN 3&4 nuclear power plants[6] were used to evaluate health consequences. According to the IPE results, 19 source term categories (STC) are defined by categorizing similar containment failure modes. The calculated source term release fractions are listed in Table 2. The core inventory data for fission products used for health effect calculations were derived from the ORIGEN2[7] calculations using the end-of-cycle inventory of fission products for the conservative evaluation because fission product buildup is greatest at the end-of-cycle conditions.

The MACCS code is used to evaluate the health effects resulting from the source terms of the YGN 3&4 nuclear power plants. In MACCS, the dispersion and deposition of radionuclides released from the reactor containment to the atmosphere were modeled with a Gaussian plume model. Radiation doses to the population were calculated based on the radionuclide concentration that is predicted by the dispersion models. The exposure pathways considered in the evaluation of health effects are: (1) exposure to the passing plume, (2) exposure to radioactive materials deposited on the ground, (3) exposures to deposits on skin, (4) inhalation of radioactive materials directly from the passing plume, (5) inhalation of radioactive materials resuspended from the ground by natural and mechanical processes, (6) ingestion of contaminated foodstuffs, and (7) ingestion of contaminated water.

Table 2. Fractional Source Term Release for Release Categories

Nuclide Group	STC 1 & 2	STC 3	STC 4	STC 6 & 10	STC 7 & 11	STC 8 & 12
Noble Gases	0.0	1.0	1.0	1.0	1.0	1.0
Iodine	0.0	6.77E-02	2.22E-01	8.01E-03	8.41E-04	2.58E-02
Cesium	0.0	8.82E-02	2.23E-01	6.33E-03	1.14E-03	3.36E-02
Tellurium	0.0	1.07E-02	3.49E-02	1.71E-03	6.12E-04	3.71E-02
Barium	0.0	1.00E-03	3.29E-03	4.31E-05	1.08E-06	1.57E-03
Strontium	0.0	7.71E-04	2.52E-03	3.22E-05	8.05E-07	3.87E-03
Ruthenium	0.0	1.38E-03	4.51E-03	2.30E-05	5.75E-07	2.30E-05
Lanthanium	0.0	4.87E-04	1.59E-03	5.04E-07	1.30E-08	5.04E-07
Cerium	0.0	4.88E-04	1.60E-03	7.56E-07	1.90E-08	7.56E-07

Nuclide Group	STC 14	STC 15	STC 16	STC 17	STC 18	STC 19
Noble Gases	1.0	1.0	1.0	1.0	1.0	7.41E-01
Iodine	6.95E-01	0.97E-01	5.02E-03	6.02E-02	3.59E-01	1.13E-01
Cesium	5.85E-01	1.29E-01	3.29E-03	3.95E-02	2.35E-01	9.24E-02
Tellurium	1.96E-01	3.59E-02	9.12E-04	1.09E-02	6.53E-02	9.27E-02
Barium	6.45E-03	1.18E-03	3.01E-05	3.61E-04	2.15E-03	1.46E-03
Strontium	4.02E-03	7.36E-04	1.87E-05	2.24E-04	1.34E-03	1.15E-03
Ruthenium	2.04E-03	3.74E-04	9.52E-06	1.14E-04	6.79E-04	8.21E-04
Lanthanum	1.00E-04	1.83E-05	4.66E-07	5.59E-06	3.33E-05	1.80E-05
Cerium	1.50E-04	2.75E-05	6.99E-07	8.39E-06	4.50E-05	2.55E-05

The site was selected as the center of a polar grid and the grid was divided into 16 equally spaced sectors with the outermost radius extending to 80 km. Each sector was divided further into 10 elements to reasonably account for the site specific population distribution. The population and weather data of 1992 around the site are used in the calculation of health effects.

Evacuation and temporary relocation are considered as emergency response actions. These actions are to mitigate the effects of a release of radioactivity during a severe accident and are designed to reduce radiation exposures, public health effects, and economic impacts from an accident. Individuals are assumed to evacuate to a safety zone, i.e., beyond 16 km from the site at a speed of 1.8 m/sec which is a standard assumption used in NUREG-1150 studies[8]. The relocation of individuals is allowed in three ways, i.e., hot-spot relocation, normal relocation, and long-term relocation, which are assumptions based on guidance given from default values suggested in MACCS, and also used in the NUREG-1150 studies. Other parameters that enter the calculational process, such as protection factors for inhalation or skin exposure, resuspension, cloud and other shielding factors, and the specific input required for deriving chronic effects, are assumed to be the default values recommended in the MACCS User's Guide[9].

3.2 Calculation of Overall Health Effects

The health effects modeled in MACCS are classified as early and chronic health effects. Both health effects are calculated from doses to specific organs using dose conversion factors. Early health effects such as fatalities and injuries are estimated using nonlinear dose response models, and chronic health effects such as mortality and injuries resulting from radiation induced cancers are estimated using a linear-quadratic, zero threshold, dose response model. MACCS models the early fatalities and cancer fatalities that would be caused by the radiation exposure in the population using models that are described in detail in NUREG/CR-4214[10]. According to the model, the total cases of a specific health effect are calculated by multiplying the average individual risk by the number of people who receive a similar dose that leads to the risk.

The calculation of overall health effects were made based on the assumptions and parameter values mentioned above. According to the results, the values of early fatalities and total latent cancer fatalities are small relative to the total number of individuals, and the total latent cancer fatalities are larger than the early fatalities. This is due to the time span for the calculation, i.e., the calculated latent cancer fatalities occur over several decades. The individual early fatality risk and individual latent cancer fatality risk are 7.52×10^{-8} per year and 2.45×10^{-7} per year, respectively. These values are below the safety goal of the USNRC. However, these values are one or two order of magnitudes larger than the results of the Surry, Zion, and Sequoyah plants calculated in the NUREG-1150 studies. This can be due to the weather patterns at the site of the YGN 3&4 nuclear power plants. According to the analysis of the meteorological data of 1992 at the site, the most frequent wind direction is west-north-west. The western part of the site is a marine area and the eastern part of the site is a populated region. Therefore, many individuals may be in the direct pathway of the radioactive plume.

4. Results and Discussion

4.1 Formation of Scenarios

The basic scenarios were first made by using the results of the relative influences of source term release parameters and meteorological data on health effects. The source term release parameters used in the formation of basic scenarios are release height, heat content of the plume, release time, and warning time. Only the early health consequences are considered because the information obtained through the research will be used in developing the optimum emergency response strategies during the emergency phase which begins immediately after the accident and could last up to seven days following the accident. According to the results of Jeong and Ha[1], early fatalities and the resulting early fatality risk decrease as the release height and heat content increase.

The values of the early health effects show a maximum at 2 hours of release time and then decrease rapidly due to radioactive decay during the time between the reactor shutdown and the start of the release. As warning time increases, the values of early health effects increase. Jeong and Ha[2] have shown that the values of early health effect show maximum at the stable atmospheric condition with low wind speed and a heavy rainfall rate(about 50 mm/hr).

The basic scenarios listed in table 3 were made by considering the above mentioned characteristics of the relative influences of release parameters and meteorological data on early health effects. The parameter values of Scenario-1 in Table 3 are composed of values that show maximum values of early health consequences. Therefore, one can use the parameter values of Scenario-1 in order to obtain the most conservative results if the exact values of the release parameters and meteorological data are not available. As the number of the Scenario increases, the impact of the release parameters and meteorological data on early health consequences decreases. Finally, the parameter values of Scenario-4 are those within the range of available data that show minimum values of early health consequences.

Table 3. The Basic Scenarios and the Parameter Values

Parameters / Scenario	Release Height (m)	Heat Content (MW)	Release Time (hr)	Warning Time (hr)	Wind Speed (m/sec)	Rainfall Rate (mm/hr)	Atmospheric Stability Class
Scenario-1	0	1	2.0	3.0	2	50	F
Scenario-2	20	10	1.0	2.0	4	30	E
Scenario-3	40	20	0.5	1.0	6	10	D
Scenario-4	60	30	4.0	0.5	10	0	B

The seasonal scenarios are listed in Table 4. The values of the four source term release parameters of Scenario-1 through -4 for each season are the same values as the basic scenarios. However, the meteorological data such as wind speed, rainfall rates, and atmospheric stability are the values assumed to be representative for each season as mentioned in the atmospheric dispersion and meteorological data. The Scenario-5 of each season is the case that has the same parameter values of Scenario-1 of each season except for the rainfall rates. In these scenarios, the rainfall rate is zero. According to the analysis of the meteorological data of 1992 at the YGN 3&4 nuclear power plants site, the number of hours that rainfall occurred among the 8,760 hours is only 440 hours, which is about 5% of the total data. Therefore, we added Spctrum-5 for each season in order to compare the results for the cases with and without rainfall rates.

4.2 Results and Discussion

The offsite consequences of an accidental release of radioactive material from a nuclear reactor are health effects and economic impacts. Human health effects are classified as early, late, and genetic effects. We consider only the early health effects in order to obtain the basic insights used in developing optimum emergency response strategies. The early health effects are the fatalities and injuries that result from substantial radiation exposures incurred during short time periods, usually within weeks, though up to one year for pulmonary effects. Early fatalities that result from substantial exposures are caused by impaired functions of red bone marrow, the lungs, and the gastrointestinal tract. Early injuries are generally defined as radiation induced effects that require medical treatment.

Table 4. The Seasonal Scenarios and the Parameter Values

Parameters / Scenario	Release Height (m)	Heat Content (MW)	Release Time (hr)	Warning Time (hr)	Wind Speed (m/sec)	Rainfall Rate (mm/hr)	Atmospheric Stability Class
Spring-1	0	1	2.0	3.0	3.0	9.4	E
Spring-2	20	10	1.0	2.0	3.0	9.4	E
Spring-3	40	20	0.5	1.0	3.0	9.4	E
Spring-4	60	30	4.0	0.5	3.0	9.4	E
Spring-5	0	1	2.0	3.0	3.0	0.0	E
Summer-1	0	1	2.0	3.0	3.4	50.0	D
Summer-2	20	10	1.0	2.0	3.4	50.0	D
Summer-3	40	20	0.5	1.0	3.4	50.0	D
Summer-4	60	30	4.0	0.5	3.4	50.0	D
Summer-5	0	1	2.0	3.0	3.4	0.0	D
Fall-1	0	1	2.0	3.0	3.6	9.0	C
Fall-2	20	10	1.0	2.0	3.6	9.0	C
Fall-3	40	20	0.5	1.0	3.6	9.0	C
Fall-4	60	30	4.0	0.5	3.6	9.0	C
Fall-5	0	1	2.0	3.0	3.6	0.0	C
Winter-1	0	1	2.0	3.0	4.0	11.4	E
Winter-2	20	10	1.0	2.0	4.0	11.4	E
Winter-3	40	20	0.5	1.0	4.0	11.4	E
Winter-4	60	30	4.0	0.5	4.0	11.4	E
Winter-5	0	1	2.0	3.0	4.0	0.0	E

Among the several early health consequences, early fatalities, early injuries, the centerline early fatality risk between two specified spatial intervals, and the population weighted early fatality risk within 8 km from the site are considered in the estimation of the variation of health effects. The centerline early fatality risk is calculated for hypothetical individuals located directly under the Gaussian peak of the air and ground concentrations. The population weighted early fatality risk is obtained by calculating the early fatalities in a certain region and then dividing by the total population in the region.

The variations of early health consequences based on the basic scenarios are listed in Table 5. As shown in Table 5, the early health consequences except early injuries considered in this study show maximum values in the case of Scenario-1, and then decrease as the number of the Scenario increases. The early injuries are much larger than the early fatalities. These facts are attributed to the time span for calculation and the atmospheric dispersion. Early fatalities are incurred during short time periods, usually within weeks. However, early injuries due to pulmonary effects are incurred up to one year. The atmospheric dispersion increases due to the atmospheric stability and high wind speed as the number of the Scenario increases. Also, as the release height and heat content of the plume increase, the area affected by the radioactive plume is increased due to atmospheric dispersion. Therefore, the number of people affected by the radioactive plume increases in spite of low concentrations.

In the case of Scenario-4, all values of the health consequences are zero an although equal amount of radioactive material is released to the atmosphere. From this fact, we can figure out that the source term release parameters and meteorological data have a great impact on the offsite health consequences. Therefore, relatively exact values of release parameters and meteorological data should be provided in order to accurately predict accident consequences. One can use the parameter values of Scenario-1 to obtain conservative results if one cannot obtain the exact values of release parameters and meteorological data.

The centerline early fatality risks between two specified intervals in Table 5 show that the early fatality risk decreases rapidly as the distance from the site increases. Therefore, actions such as evacuation should be taken to protect the workers and the general public. Also, the warning time, which is the time after accident initiation at which the offsite alarm is rung, must be short so that evacuation can begin as soon as possible to protect the surrounding population. The population weighted risk which accounts for the population distribution shows similar trends to other health consequences.

Table 5. The variation of health effects based on basic scenarios

Health Effects / Scenario	Early Fatalities	Early Injuries	Early Fatality Risk (0.0–1.6 km)	Early Fatality Risk (1.6–3.2 km)	Pop. Weighted Early Fatality Risk
Scenario-1	43.4	720	1.00E+00	1.58E-02	1.08E-03
Scenario-2	38.4	806	1.00E+00	7.18E-03	9.59E-04
Scenario-3	0.496	899	2.66E-02	0.0	1.24E-05
Scenario-4	0.0	0	0.0	0.0	0.0

The variation of early health consequences based on seasonal scenarios considering the four distinct seasonal characteristics of Korea is shown in Table 6. The results for the scenarios of each season show similar trends as those of the basic scenarios. In the Fall, all the values of the early health consequences are minimum. This is attributed to the weather condition of the Fall. The most frequent atmospheric stability of the Fall is slightly unstable(C), while the most frequent atmospheric stability classes of other seasons are neutral(D) or slightly stable(E). Therefore, the concentration of radioactive material is relatively low in the Fall, although the area affected by the radioactive plume is increased due to atmospheric dispersion. In the Summer, the early fatalities and the resulting early fatality risk show a maximum value due to the large rainfall rate. In the case of high rainfall rates, all materials washed out from the radioactive plume will be deposited onto the ground. This would produce very high ground concentrations in the spatial elements onto which deposition would occur instead of spreading over many spatial elements, and it is likely that large exposures are delivered over short time periods. Therefore, there are more early fatalities and less early injuries in the Summer than other seasons.

The results of Scenario-5 for each season show less early fatalities and more early injuries than those of Scenario-1. The early fatality risk of Scenario-5 for each season is also less than that of Scenario-1 for each season. This is attributed to the plume depletion due to wet deposition because the Scenario-5 of each season has the same parameter values without rainfall as Scenario-1. That is, the radioactive plume is spread over much more spatial elements because of the lack of rain. Therefore, the radionuclide concentration is lower and the area affected by the radioactive plume is larger than the case of Scenario-1.

Table 6. The variation of health effects based on seasonal scenarios

Health Effects / Scenario	Early Fatalities	Early Injuries	Early Fatality Risk (0.0–1.6 km)	Early Fatality Risk (1.6–3.2 km)	Pop. Weighted Early Fatality Risk
Spring-1	35.0	1464	1.00E+00	1.23E-02	8.75E-04
Spring-2	36.1	1502	1.00E+00	1.86E-02	9.00E-04
Spring-3	10.7	136	6.10E-01	0.0	2.67E-04
Spring-4	0.0	0	0.0	0.0	0.0
Spring-5	13.6	2122	7.60E-01	0.0	3.39E-04
Summer-1	48.1	617	7.93E-01	0.0	1.20E-03
Summer-2	51.2	642	1.00E+00	0.0	1.28E-03
Summer-3	45.2	572	1.00E+00	0.0	1.13E-03
Summer-4	0.0	0	0.0	0.0	0.0
Summer-5	2.51	1992	1.41E-01	0.0	6.26E-05
Fall-1	2.09	365	7.82E-02	0.0	5.21E-05
Fall-2	3.41	414	1.23E-01	0.0	8.51E-05
Fall-3	2.18	413	7.78E-02	0.0	5.45E-05
Fall-4	0.0	0	0.0	0.0	0.0
Fall-5	0.0	596	0.0	0.0	0.0
Winter-1	28.2	1298	9.98E-01	7.14E-03	7.05E-04
Winter-2	30.3	1331	9.99E-01	1.09E-02	7.57E-04
Winter-3	18.9	1226	8.94E-01	0.0	4.71E-04
Winter-4	0.0	0	0.0	0.0	0.0
Winter-5	4.41	1832	2.95E-01	0.0	1.10E-04

5. Conclusions

The variations of health effects resulting from the severe accidents of the YGN 3&4 nuclear power plants were examined based on scenarios considering the release parameters and meteorological data. We have made basic scenarios based on the relative importance of the source term release parameters and meteorological data on offsite health effects. We then investigated the variation of health effects resulting from the severe accidents of the YGN 3&4 nuclear power plants from scenario to scenario by using MACCS code. Also, we have investigated the seasonal variation of health effects based on scenarios considering seasonal characteristics because we have four distinct seasons in Korea.

The results show that although an equal amount of radioactive material is released to the atmosphere, there are large differences in the consequence analysis from scenario to scenario. Therefore, the exact value of release parameters and meteorological data are necessary in order to estimate the accident consequences accurately. The variation of average individual early fatalities versus distance shows that the early fatality risk decreases rapidly as the distance from the site increases. Therefore, evacuation is a very effective emergency response action in order to protect the population. There are large differences in health effects from season to season. In the fall, the early fatalities and early fatality risk show minimum values due to atmospheric instability. The early fatalities show a maximum value in the Summer due to a large rainfall rate. It is necessary to consider seasonal characteristics in developing emergency response strategies because the seasonal variation of health effects is distinct. The information obtained through this research will be very useful in developing optimum emergency response strategies for reducing offsite risks from the viewpoint of accident management.

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