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Environmental impact on the Korean peninsula due to hypothetical accidental scenarios at the Haiyang nuclear power plant in China

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1. Introduction

Recently, the potential environmental impact of nuclear power plant (NPP) accidents has accepted a lot of attention as there are over 440 operational NPPs in the world (IAEA, 2017). Moreover, the recent Fukushima Daiichi NPP accident in Japan caused by a tsunami after an earthquake on March 11, 2011, was not only a problem for Japan, but also an international issue due to the dispersion of radionuclides (Evangeliou et al., 2015; Masson et al., 2016). The environmental impact in Japan and other countries was investigated in several studies, focusing on the effect of long-distance atmospheric-dispersal of radionuclides (Srinivas et al., 2014; Keum et al., 2013). For the Fukushima accident, the assessments of health risk were performed by using atmospheric dispersion models and estimating the effective dose (WHO, 2013).

Environmental consequences of hypothetical accidents were used to evaluate the proposed location of an NPP to be constructed in the United Kingdom (McMahon et al., 2013). In Taiwan, the evacuation zone for a potential NPP accident has also been projected using models (Tang et al., 2016). After the Fukushima nuclear accident, the threat of NPP accidents became not only a regional issue, but also a global concern, indicating the necessity of NPP accident assessments in nearby countries. For example, in the flexRISK project, assessments of hypothetical severe NPP accidents across the European continent were conducted by using atmospheric simulations (Arnold et al., 2011).

In this respect, South Korea, China, and Japan are geographically close to each other. The environmental impact on South Korea after the Fukushima nuclear accident was insignificant. This was due to the dispersion of radionuclides across the Pacific Ocean by the westerly winds in the mid-latitudes, which averted direct radionuclide deposition on the Korean Peninsula (Lee et al., 2015). Unlike in Fukushima, NPPs in China are located on the west side of South Korea. In China, 17 NPPs are in operation and eight NPPs are under construction near the Yellow Sea and East China Sea (IAEA, 2017). In the case of hypothetical accidents at Chinese NPPs, the countries located in northeastern Asia might be directly affected by the dispersion of radionuclides through the westerly winds at mid-latitudes. The Haiyang NPP in China was selected as the case study in this research because it is the nearest NPP to the Korean Peninsula. The Haiyang NPP successfully completed its hydro test in July 2016 and will be set in operation soon. The environmental impact on the Korean Peninsula, in the case of a hypothetical accident at the Haiyang NPP in China, was analyzed using atmospheric dispersion modelling.

2. Methods

2.1. Location of Haiyang NPP and radiation monitoring

The Haiyang NPP is located to the west of the Korean Peninsula (36° 42′ 30″ N, 121° 23′ 0″ E). Typically, the wind flows from west to east due to the westerly winds at mid-latitudes throughout the year (Jeong and Joe, 2010), while some winds of inverse direction have been shown in summer following the East Asian summer monsoon (Chang, 2004; Ding and Johnny, 2005; Zhu et al., 2014). Fig. 1 shows the location of the Haiyang NPP in China and 12 radiation monitoring stations in South Korea. Considering the distance, 12 out of 15 radiation monitoring stations were selected for this research. Monitoring stations measure gamma and gross beta radioactivity of airborne dust,

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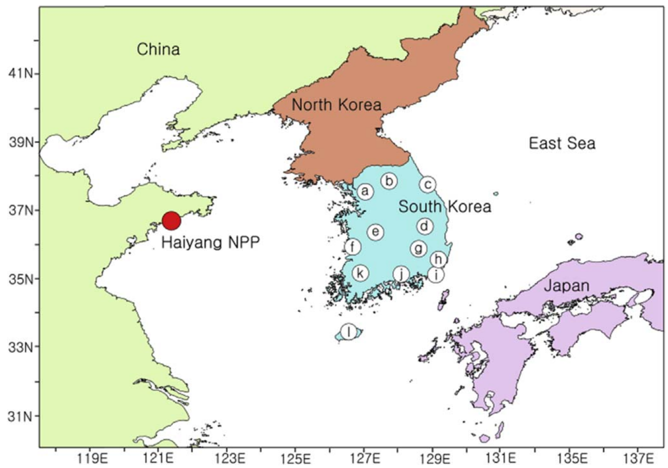

Fig. 1. Location of Haiyang NPP in China and the 12 monitoring stations in South Korea: ⓐ Seoul, ⓑ Chuncheon, ⓒ Gangneung, ⓓ Andong, ⓔ Daejeon, ⓕ Gunsan, ⓖ Daegu, ⓗ Ulsan, ⓘ Busan, ⓙ Jinju, ⓚ Gwangju, ⓛ Jeju.

radioactive fallout, precipitation, and tap water (KINS, 2015). After the Fukushima NPP accident in 2011, gamma-emitting nuclides (I^{131}, Cs^{134}, Cs^{137}) in airborne dust and Cs^{137} in soil were measured at the monitoring stations (KINS, 2011). In the case of any NPP accident in surrounding countries, these monitoring stations could also conduct radiological measurements of airborne dust and soil. The monitoring stations were selected to detect any environmental impact in Korea in the case of potential radionuclide contamination.

2.2. FLEXPART simulation

The Lagrangian particle dispersion model FLEXPART version 9.02 was used for atmospheric dispersal and transportation of radionuclides (Stohl et al., 1998, 1999). FLEXPART was originally developed to simulate the dispersion of radionuclides and it has been used for long-range transport modelling (Kim et al., 2012). FLEXPART simulates the transportation, diffusion, dry and wet deposition, and radioactive decay of nuclides. The meteorological data used in the simulations were obtained from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) wind fields. The GFS data had a global $0.5^{\circ} \times 0.5^{\circ}$ horizontal resolution and 26 vertical pressure levels. All the radionuclides, except noble gases and iodine, were assumed to have 2500 kg/m^3 density, 0.6 μm mean diameter, 0.3 μm logarithmic standard deviation, $1.0 \times 10^{-4}\ s^{-1}$ scavenging coefficient at 1 mm/h precipitation, and a factor of 0.8 rain dependency as shown in FLEXPART documentation (Stohl et al., 2011). Airborne iodine was assumed to be 20% in the particulate form and 80% in the gaseous phase, similar to that observed in the Fukushima accident (Masson et al., 2011; Ten Hoeve and Jacobson, 2012).

2.3. Release of radionuclides in the environment

The Haiyang NPP is an AP1000 pressurized-water reactor for electricity generation. An accidental scenario and knowledge of the reactor core inventory were needed to simulate emissions from the NPP. The accidental scenario determines the release fraction and time of radionuclides from the reactor core to the environment. In addition, knowing the reactor core inventory, we can estimate the release amount of radionuclides at the timing of the hypothetical accident. The accidental scenarios of large radionuclide emissions with containment bypass and of slight emissions with intact containment were selected for the environmental report from the Levy AP1000 NPP (Progress Energy Florida, 2009). The report includes the release fraction of radionuclides of six accidental scenarios. In the containment-bypass scenario, radionuclides are released directly from the reactor coolant system into the environment (Winters et al., 2004). The containment-bypass scenario has the largest emission fraction of radionuclides out of the six different scenarios. The intact-containment scenario releases radionuclides into the environment through nominal leakage. This scenario has the smallest emission fraction of fission products among the 6 scenarios of the report but the probability of accident is the most frequent. The probability of the containment-bypass scenario to occur is 1.05×10^{-8} per year, in contrast to an intact-containment scenario probability occurrence of 2.21×10^{-7} per year. The release duration of containment bypass and intact containment were assumed to be 7200 s and 12,000 s, respectively (Sholly et al., 2014). All radionuclides were assumed to be uniformly dispersed during the duration of the release.

The initial release height of radionuclides is an important input factor for the atmospheric simulation. Especially in the case of a nuclear accident, the rise of the hot plume from the NPP must be considered. In Stohl et al. (2012), three release heights of 0–50 m, 50–300 m and 300–1000 m was considered for dispersion of radionuclides in Fukushima accident. 0–50 m was used to consider the leakage through wall or roof opening and 50–300 m was used to consider the rise of hot thermal plume. 300–1000 m was used for the period of hydrogen explosions. However, 300–1000 m was not considered in this study because the explosion was not contained in the scenario although the large emission was assumed in the containment bypass scenario. Considering the large emissions without explosion, the fraction was conservatively assumed for 100% of 50–300 m height because 50–300 m was suggested for thermal plume rise. Because an intact containment would result in slight leakage with the smallest release fraction, a release height of 0–50 m was assumed for the intact-containment scenario.

The reactor core inventory was assumed to be shut down by the end of the three-region equilibrium cycle, after a constant operation of 2% above the full core thermal power, as in the AP1000 design document (Winters et al., 2004). Based on this core inventory and the above accidental scenarios, Table 1 shows the source term by radionuclide and accidental scenario. In the case of Cs^{137}, which was one of the major radionuclides emitted after the Fukushima accident, the amount of emissions from the containment-bypass scenario was found to be

Table 1
Level of source term according to each accidental scenario (Winters et al., 2004; Sholly et al., 2014).

Emission Source Term					
Nuclide	Accidental Scenario		Nuclide	Accidental Scenario	
	IC(Bq)[a]	BP(Bq)[a]		IC(Bq)	BP(Bq)
Xe^{131m}	1.04E+14	3.92E+16	I^{130}	1.63E+12	6.09E+16
Xe^{133m}	5.73E+14	2.16E+17	I^{131}	4.28E+13	1.60E+18
Xe^{133}	1.86E+16	7.03E+18	I^{132}	6.22E+13	2.33E+18
Xe^{135m}	3.79E+15	1.43E+18	I^{133}	8.84E+13	3.31E+18
Xe^{135}	4.75E+15	1.79E+18	I^{134}	9.68E+13	3.62E+18
Xe^{138}	1.62E+16	6.11E+18	I^{135}	8.26E+13	3.09E+18
Kr^{85m}	2.58E+15	9.73E+17	Cs^{134}	8.25E+12	1.95E+17
Kr^{85}	1.04E+14	3.92E+16	Cs^{136}	2.35E+12	5.56E+16
Kr^{87}	4.97E+15	1.88E+18	Cs^{137}	4.81E+12	1.14E+17
Kr^{88}	7.00E+15	2.64E+18	Cs^{138}	7.74E+13	1.83E+18
Ru^{103}	7.03E+13	2.40E+17	Te^{127m}	3.96E+10	7.95E+14
Ru^{105}	4.76E+13	1.63E+17	Te^{127}	3.06E+11	6.14E+15
Ru^{106}	2.31E+13	7.91E+16	Te^{129m}	1.35E+11	2.71E+15
La^{140}	9.16E+12	8.75E+14	Te^{129}	9.12E+11	1.83E+16
La^{141}	8.15E+12	7.79E+14	Te^{131m}	4.20E+11	8.43E+15
La^{142}	7.90E+12	7.55E+14	Te^{132}	4.14E+12	8.31E+16
Ce^{141}	3.55E+10	1.92E+13	Sr^{89}	3.82E+13	1.28E+16
Ce^{143}	3.31E+10	1.79E+13	Sr^{90}	3.29E+12	1.10E+15
Ce^{144}	2.68E+10	1.45E+13	Sr^{91}	4.75E+13	1.59E+16
Ba^{139}	7.90E+13	5.88E+16	Sr^{92}	5.11E+13	1.70E+16
Ba^{140}	7.59E+13	5.65E+16			

[a] IC: Intact containment, BP: Containment bypass.