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Review

Radioactivity release from the Fukushima accident and its consequences: A review

Yang-Hyun Koo*, Yong-Sik Yang, Kun-Woo Song

Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon 305-53, Republic of Korea

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ABSTRACT

The Fukushima accident in March 2011 caused by the massive earthquake and tsunami led to hydrogen explosion, core meltdown, and the subsequent release of huge radioactivity both into the atmosphere and the Pacific Ocean. In the case of volatile fission products such as ^{137}Cs and ^{131}I, the release fraction of the core inventory of the units 1–3 into the atmosphere is estimated to be 1.2–6.6% and 1.1–7.9%, respectively. As for gaseous fission product ^{133}Xe, it is estimated that nearly 100% of the core inventory might have been released into the atmosphere. In addition, about 16% of the ^{137}Cs inventory flowed into the sea when the contaminated water used for cooling the decay heat of the units 1–3 overflowed the reactors. Therefore, even though almost three years have passed since the accident, it is still having a tremendous impact not only on Japan but all over the world as well.

This paper reviews the Fukushima accident from the viewpoint of radioactivity release and dispersion in the environment and its effect on public health, economy, energy policy, international relationship, and LWR fuel development.

1. Introduction

After the Fukushima accident occurred in March 2011, extensive studies have been performed so far to understand the accident, most of them focusing on a specific aspect of the accident. In this paper, based on the extensive literature, both an overall picture of the accident progression from the viewpoint of radioactivity release from the reactor core into the environment and the consequences of the accident on public health, economy, energy policy, international relationship, and light water reactor (LWR) fuel development have been reviewed.

This paper is structured as follows: In Section 2, characteristics of major fission products such as volatile ones and noble gases that are most abundantly produced by fission and also important in terms of radiological health impact are described, including how they are transported around the globe once released into the environment. In Section 3, radioactivity release and its distribution in Japan and around the world are reviewed: how much radioactivity inventory was available in the units 1–3 at the time of the accident, what fraction of the inventory was released into the atmosphere during the accident duration, and how the released radioactive materials were transported, dispersed and deposited on the various parts of the world. In Section 4, the consequences of the accident are described from the viewpoint of impact on public health, economy, energy policy, international relationship, and LWR fuel development.

2. Release and transportation characteristics of fission products in the Fukushima accident

2.1. Chemical characteristics of fission products

As shown in Table 1, fission products (FP) can be classified into five groups in terms of their volatility and chemical activity (Pontillon et al., 2010): 1) volatile FP including noble gases, 2) semi-volatile FP, 3) FP that are low volatile, 4) non-volatile FP, and 5) actinides. Among the five groups, the first one of volatile FP (Cs and I) and noble gases (Xe and Kr) are most important in terms of radiological consequence, because they have very strong chemical activity and relatively short half-life (except for ^{137}Cs with a half-life of 30 years), and are also easily dispersed in the environment (Grambow and Poinssot, 2012). Furthermore, the fission yields of these elements are much higher than others (Dauer et al., 2011): they correspond to the two peaks of fission yield in a bimodal distribution that represents the fission yield as a function of atomic mass numbers.

Hence, regarding volatile FP and noble gases, the combination of these two factors, the high probability for easy release from fuel

* Corresponding author. Tel.: +82 42 868 8728; fax: +82 42 864 1089.
E-mail address: yhkoo@kaeri.re.kr (Y.-H. Koo).

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Table 1
Classification of fission products (FP) (Pontillon et al., 2010).

Group	Major elements	Characteristics for leakage and transport	Leakage rate (>2350 °C)
Volatile FP (including noble gases)	Xe, Kr, I, Cs, Sb, Te, Cd, Rb, Ag	- High volatility - Very easily leaked from fuel pellet - Move very long distance in the environment	100%
Semi-volatile FP	Mo, Ba, Rh, Pd, Tc	- Medium volatility - Easily leaked from fuel pellet - Move long distance in the environment	50–100%
Low-volatile FP	Ru, Ce, Sr, Y, Eu, Nb, La	- Low volatility - Difficult to be leaked from fuel pellet - Move short distance in the environment	3–10% (for some nuclides: 20–40%)
Non-volatile FP	Zr, Nd, Pr	- No volatility - Very difficult to be leaked from fuel pellet	Not measured
Actinides	U, Pu	- Different leakage features depending on nuclides - Move short distance in the environment	U: at most 10% Pu: less than 1%

and high fission yield, contributes greatly to environmental impact for severe accidents. In addition, the release of volatile and gaseous FP from the fuel during a core meltdown event is effectively instantaneous and once released from the reactor they are easily dispersed in the atmosphere.

2.2. Release characteristics of fission products

2.2.1. Release from fuel into the primary system (reactor pressure vessel and primary containment vessel)

UO_2 fuels that are being used in current LWRs are designed to work very well under normal operating conditions, mainly due to UO_2 pellet's high melting temperature (2865 °C), its capability for retaining fission products, and zirconium alloy cladding's good corrosion resistance and mechanical properties.

On the other hand, UO_2 fuel behavior under accident conditions is very poor; zirconium alloy cladding reacts rapidly with steam at around 1200 °C (Hofmann, 1999), producing a very large amount of hydrogen that would lead to explosion. Furthermore, about 50% inventory of noble gases and volatile fission products (Cs and I) are released outside of UO_2 pellet when fuel temperature is above 1650 °C (McKenna and Glitter, 1988) and nearly 100% are released for fuel temperature higher than 2350 °C (Pontillon et al., 2010).

Therefore, in the Fukushima accident, 50–100% of the core inventory would have been released from the fuel into the interior of both reactor pressure vessel and primary containment vessel due to overheat and subsequent meltdown. While noble gases would have been released into the atmosphere when release pathways between the reactor interior and the atmosphere had been available, volatile fission products would have been present inside the reactor as the mixture of gas state and aerosol. When cooling water was pumped into the reactor to reduce the heat, some fraction of Cs and I would have been dissolved in the coolant since they are soluble in water to a certain degree–27% for ^{137}Cs (Grambow and Poinssot, 2012; TEPCO, 2011)–and also deposited in pipes and reactor internals such as core support structures and baffles. And it is sure that corium, the mixture of fuel pellets, zircaloy cladding and other structural materials created during core meltdown, would also have retained some amount of Cs and I.

At the earlier stage of the Fukushima accident, the damaged reactors were cooled by a process known as "feeding and bleeding", by which considerable amounts of radioactivity was released into the atmosphere. In this process, cooling water–sea water at first and fresh water later – was fed into the reactor, generating steam due to the decay heat transfer from the fuel to the water. The resulting steam increased the pressure inside the reactor pressure vessel and containment to a point where no more water could be pumped in. Then to allow more cold water to be put into the core for continuous cooling of the fuel, steam pressure was lowered by venting the radioactive steam into the atmosphere, which is called bleeding.

2.2.2. Release from the primary system into the sea

Once core cooling capability was restored by using fire engine pumps, another serious problem was developed. Injected water

Table 2
Summary of source terms released into the atmosphere from units 1–3.

		^{133}Xe	^{131}I	^{137}Cs
Half life, $t_{1/2}$		5.2 day	8.0 day	30.2 yr
Decay constant ($0.693/t_{1/2}$), (1/s)		1.54×10^{-6}	1.00×10^{-6}	7.27×10^{-10}
Inventory	Isotope number	7.80×10^{24}	6.40×10^{24}	$(1.05–1.13) \times 10^{27}$
	Activity (Bq)	1.20×10^{19}	6.40×10^{18}	$(7.60–8.20) \times 10^{17}$
	Mass (kg)	1.7	1.4	238.8–257.0
Source term into the atmosphere, Bq (release into the ocean not included)	Activity (Bq)	$(0.60–1.90) \times 10^{19}$	$(0.7–5.0) \times 10^{17}$	$(1.0–5.0) \times 10^{16}$
	Mass (kg)	0.85–2.7	0.015–0.11	2.9–17.0
	Fraction (%)	50–159[a]	1.1–7.9	1.2–6.6

[a] The source term for ^{133}Xe could have been higher than the core inventory of units 1–3 at the time accident, because additional ^{133}Xe might has been released into the atmosphere, which was formed by the decay of ^{133}I with half-life 20.9 h (Stohl et al., 2012b) during the time interval between when the reactors were shut down by the earthquake and when major emissions of radioisotopes took place due to three hydrogen explosions and venting (Stohl et al., 2012a).

that came in contact with the damaged fuel became highly contaminated with radioactivity, including Cs and I that were released from the damaged fuel. Because coolant circulation was not possible, the discharged water from the reactor had to be stored separately. However, because of the limited storage capacity, TEPCO had to release into the sea about 9000 m^3 of contaminated water that was kept in the storage facility together with radioactivity retained in it (57×10^{10} Bq) until waste water treatment system and coolant circulation had been established later (Blandford and Ahn, 2012).

It is reported that, of the total radioactivity released from the units 1–3 into the environment, more than 80% of it flowed into the sea (Hoeve and Jacobson, 2012; Christoudias and Lelieveld, 2013), implying that 4 times more radioactivity was released to the sea than to the atmosphere. According to Table 2, a best-estimate source term of ^{137}Cs, defined as the fraction of ^{137}Cs inventory released into the atmosphere, is about 4%, ranging from 1.2 to 6.6%. Therefore, this would mean that a best-estimate release fraction of the ^{137}Cs inventory that flowed into the sea when the contaminated water overflowed the reactors is about 16%.

2.2.3. Release from the primary system into the atmosphere

When release pathways were established by either hydrogen explosion or "feeding and bleeding", noble gases and volatile fission products present in the core in the form of gas or aerosol would have been mostly released only into the atmosphere and not to the sea. Especially, regarding radioactive noble gas such as ^{133}Xe which is insoluble in water, it has been reported that nearly 100% of the core inventory of units 1–3 was released into the atmosphere until 15 March 2011 (World Health Organization, 2012; Nuclear and Industrial Safety Agency, 2011), which is supported by an evaluation (Stohl et al., 2012a) that the entire ^{133}Xe inventory was released between 11 and 15 March 2011. In other cases, it is claimed that the entire ^{133}Xe inventory of units 1–3 and additional ^{133}Xe produced by the decay of ^{133}I during the accident duration, which amounts to 59% of the core inventory that was available just after the accident, was released into the atmosphere (Stohl et al., 2012a,b).

As shown in Table 2, the release fraction of ^{137}Cs into the atmosphere is 1.2–6.6% of the core inventory of the units 1–3. It is estimated that 1.1–7.7% of the inventory of ^{131}I was released into the atmosphere.

2.2.4. Distribution of the core inventory of the units 1-3 among the cores, primary systems, atmosphere and the sea

Based on the information given above, Fig. 1 shows how the core inventory of the units 1–3 for a volatile radioactive isotope ^{137}Cs was distributed in the reactors after meltdown, what fraction of the inventory was released into the atmosphere and the sea, and how much of the radioactivity released into the atmosphere deposited in both the Japanese land and other areas.

As shown in Fig. 1, the best-estimate release into the atmosphere was 4% of the core inventory (Morino et al., 2011) and 16% flowed into the ocean (Dauer et al., 2011; Hoeve and Jacobson, 2012; Christoudias and Lelieveld, 2013; Stohl et al., 2012a; NTN News, 2011). In addition, of the 4% inventory of ^{137}Cs released into the atmosphere, only 0.8% was deposited in the Japanese land and the other 3.2% was transported to the sea or other areas of northern hemisphere.

2.3. Transportation characteristics of fission products

As was described in Section 2.1, most of the radionuclides released into the environment during the Fukushima accident can be classified into three categories: noble gases, gases originated from volatile fission products, and aerosols (Mathieu et al., 2012a). Therefore, it is very likely that they would have been released into the atmosphere mostly in gas and some particulate form, and released to the sea mainly in liquid and possibly some particulate form (Dauer et al., 2011). While noble gases are unique in that they neither react with other species nor are deposited on the ground (Mathieu et al., 2012a), Cs and I have very different release and transport characteristics. Since Cs has a low volatility and partitions into ambient aerosol particles, it is rapidly attached to airborne particles (aerosols) (Sportisse, 2007; Masson et al., 2011) and thus is highly subject to washout removal by rain from the contaminated air (Masson et al., 2011).

While Cs is mainly found in particulate form, iodine is either in gaseous form or attached to atmospheric aerosols; it is usually assumed that the gaseous fraction of iodine is 80% (Morino et al., 2011; Chen et al., 2007). For the two forms – gaseous and particulate – of iodine in both the Fukushima site and Europe after the Fukushima accident, the average fraction of gaseous ^{131}I of the total ^{131}I was measured to be about 80% as shown in Fig. 2, suggesting that ^{131}I remains mainly in its gaseous form during transport (Hoeve and Jacobson, 2012; Masson et al., 2011), largely irrespective of traveling distance from the place where it was released. And the measured fraction of gaseous iodine is consistent with previous assumptions.

Partitioning between gaseous form and particles and the size distribution of aerosols strongly affect dry deposition and wet scavenging processes of rainout and washout (Sportisse, 2007). And the removal of these compounds from the atmosphere is governed by the dry and wet deposition processes (Christoudias and Lelieveld, 2013). A conceptual model for the transport of Fukushima-derived radioactive clouds at the mid-latitudes of the

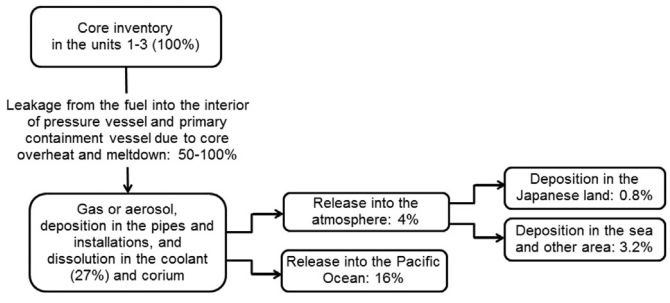


Fig. 1. Release and dispersion of ^{137}Cs in the Fukushima accident in terms of the core inventory of units 1–3 (Dauer et al., 2011; Hoeve and Jacobson, 2012; Christoudias and Lelieveld, 2013; Stohl et al., 2012a; Morino et al., 2011; NTN News, 2011).

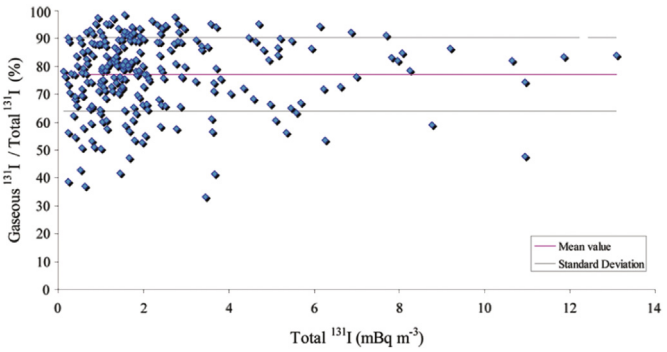


Fig. 2. The ratio of gaseous ^{131}I/total ^{131}I in the atmosphere of Europe following the Fukushima accident (Masson et al., 2011).

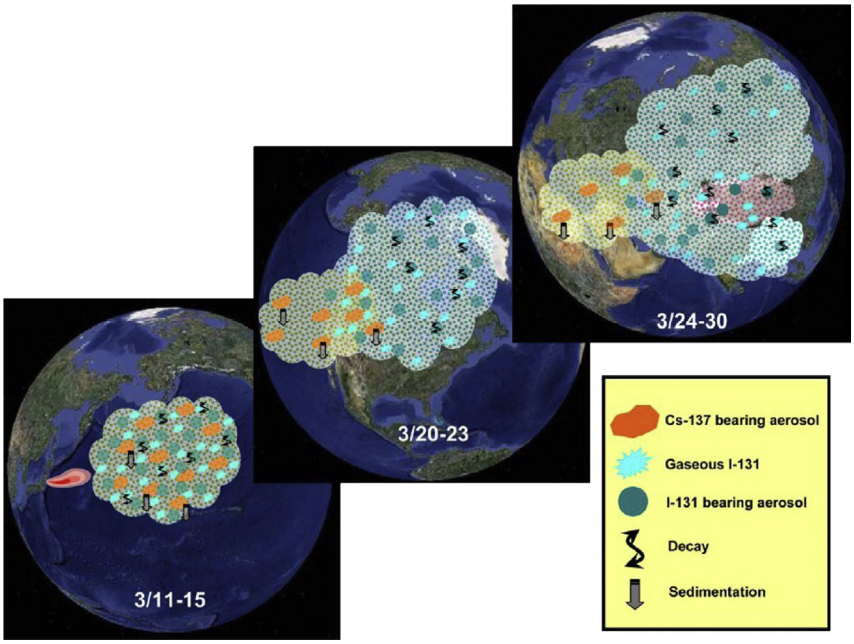


Fig. 3. A conceptual model for the transport of Fukushima-derived radioactive clouds, focusing at the mid-latitudes of the northern hemisphere (Hsu et al., 2012).

northern hemisphere was proposed as shown in Fig. 3 (Hsu et al., 2012), illustrating the atmospheric transport of volatile fission products of ^{131}I and ^{137}Cs. Fig. 3 shows that ^{137}Cs airborne particles in radioactive clouds decrease with traveling distance from Fukushima, because they would be easily removed by the wet scavenging processes in the atmosphere. On the other hand, since the aerosol fraction of ^{131}I in the radioactive clouds would be only about 20% based on the fact that gaseous fraction of ^{131}I is around 80% (Hoeve and Jacobson, 2012; Masson et al., 2011), the amount of ^{131}I that would be eliminated by the wet scavenging processes would be small and thus ^{131}I would remain mainly in its gaseous form during transport.

2.4. Deposition characteristics of fission products

The distribution and behavior of radioactive substances in contaminated region, especially around Fukushima, are very important in evaluating the health risk of people living in the area and assessing its usage for plant cultivation. Specifically, knowledge of the initial depth distribution of fallout radionuclides in soil is a key factor, because it can serve as a starting point for evaluating human dose by both internal and external exposure, as well as planning for soil decontamination.

Several measurements were made to reveal the vertical profile of radioactive cesium and iodine along the depth of contaminated soil (Kato et al., 2012; Ohno et al., 2012; Fujiwara et al., 2012; Yoshida and Takahashi, 2012; Tanaka et al., 2012). The maximum concentration was found at the surface of soil for all radionuclides and the concentrations decreased exponentially with depth. While there are some differences in the profiles depending on the kind of soil and site where measurements were made on soil samples collected on 28 April 2011, more than 70% of radioactive cesium and iodine were present in the uppermost 2 cm layer and about 90% or more deposited within 5 cm of the soil surface. Fig. 4 shows one example of the distribution of radioactive cesium and iodine along the depth of soil, indicating that most of them are present near a few centimeters from the surface (Kato et al., 2012).

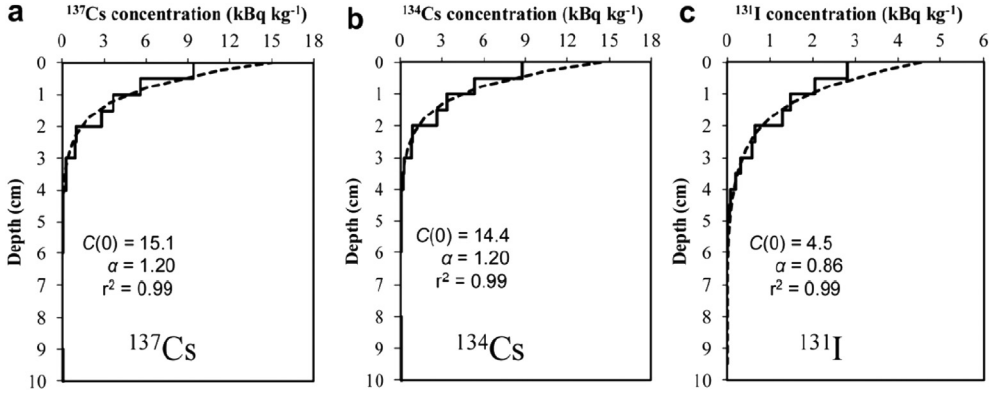


Fig. 4. Depth distribution of a) ^{137}Cs, b) ^{134}Cs and c) ^{131}I concentrations. Solid line is the measured depth distribution of radionuclide, and the dotted line is a fitting result (Kato et al., 2012).

Table 3
Inventory and source terms released into the atmosphere from units 1–3.

	^{133}Xe	^{131}I	^{137}Cs	References
Inventory at the time of the accident, Bq	1.2×10^{19}	–	7.6×10^{17}	(Stohl et al., 2012a)
	–	6.4×10^{18}	8.2×10^{17}	(Kirchner et al., 2012)
Source term to the atmosphere, Bq (release to the sea not included)	1.5×10^{19}	–	3.7×10^{16}	(Stohl et al., 2012a)
	–	0.7×10^{17}	1.7×10^{16}	(Hoeve and Jacobson, 2012)
	1.1×10^{19}	1.6×10^{17}	1.5×10^{16}	(World Health Organization, 2012)
	1.1×10^{19}	1.6×10^{17}	1.5×10^{16}	(Nuclear and Industrial Safety Agency, 2011)
	$(1.4–1.9) \times 10^{19}$	–	–	(Stohl et al., 2012b)
	–	1.5×10^{17}	1.2×10^{16}	(IAEA, 2011)
	–	5.0×10^{17}	1.0×10^{16}	(IAEA, 2012)
	–	1.6×10^{17}	1.5×10^{16}	(Nuclear Emergency Response Headquarters, 2011)
		2.0×10^{17}	2.2×10^{16}	(Lou Brandon, 2012)
	–	1.5×10^{17}	1.3×10^{16}	(Chino et al., 2011)
	–	3.8×10^{17}	5.0×10^{16}	(Austrian Central Institute, 2011)
	0.6×10^{19}	1.9×10^{17}	2.0×10^{16}	(Mathieu et al., 2012a,b)
	–	$(1.9–3.8) \times 10^{17}$	1.2×10^{16}	(Winiarek et al., 2012)
	–	$(1.0–2.0) \times 10^{17}$	$(1.0–2.0) \times 10^{16}$	(Akahane et al., 2012)
	–	4.0×10^{17}	1.0×10^{16}	(Achim et al., 2012)
	–	2.0×10^{17}	1.3×10^{16}	(Kobayashi et al., 2013)

3. Accident analysis

3.1. Inventory of the units 1–3

The inventory of three radioisotopes, ^{133}Xe, ^{131}I, and ^{137}Cs, that were available for release in the units 1–3 of the Fukushima Daiichi nuclear power plant at the time of accident is given in Table 3: 1.2×10^{19} Bq for ^{133}Xe (Morino et al., 2011), 6.4×10^{18} Bq for ^{131}I (Kirchner et al., 2012), and $7.6–8.2 \times 10^{17}$ Bq for ^{137}Cs (Stohl et al., 2012a; Kirchner et al., 2012). These values were calculated based on the amount of fuel and estimated burnup in each unit when the accident took place.

3.2. Source term to the atmosphere from the units 1–3

Studies shown in Table 3 have been made to investigate what number of radioisotopes and what fractions of the inventory were released to the atmosphere – source term – during the accident duration (Hoeve and Jacobson, 2012; World Health Organization, 2012; Nuclear and Industrial Safety Agency, 2011; Stohl et al., 2012a,b; Mathieu et al., 2012a,b; IAEA, 2011, 2012; Nuclear Emergency Response Headquarters, 2011; Lou Brandon, 2012; Chino et al., 2011; Austrian Central Institute, 2011; Winiarek et al., 2012; Akahane et al., 2012; Achim et al., 2012; Kobayashi et al., 2013). Since direct measurement of the source term was impossible, it was derived in most cases by the inverse modeling which combines the measurements of gaseous and volatile fission products at the Comprehensive Nuclear-Test-Ban Treaty Organization stations located around the world with the atmospheric conditions during the transport of the fission products. The inverse modeling is a top-down approach which determines the source term by optimizing the agreement between the measured data and model calculations (Stohl et al., 2012a).

In simulating radionuclide dispersion in the atmosphere, depending on the positions and time of the measurements of released radioisotopes from the Fukushima nuclear power plant, atmospheric dispersion model, including the transport of the radioisotopes around the globe and meteorological data, it is inevitable that the source terms from these studies differ from one another. For example, several inverse modeling methods have been used to simulate the radionuclide dispersion from the Fukushima accident: EMAC (Christoudias and Lelieveld, 2013; Lelieveld et al., 2012), FLEXPART (Stohl et al., 2012a), SPEEDI and WSPEEDI (Morino et al., 2011; Kobayashi et al., 2013), IDX (Mathieu et al., 2012a), and MM5 (Achim et al., 2012). Different meteorological data were also used to determine the transportation of radioactive plume and its scavenging processes in the atmosphere. The sources of the meteorological data for different studies were as follows: the European Centre for Medium Range Weather Forecast (ECMWF) and the National Centers for Environmental Prediction (NECP) Global Forecast System (GFS) (Stohl et al., 2012a; Achim et al., 2012), ECMWF and the Meteo-France based on the ARPEGE model (Mathieu et al., 2012a), and the Grid Point Value (GPV) (Chino et al., 2011).

Thus it is easily expected that, even if the same measured data would be used, different combination of dispersion model and meteorological data would produce different result for the source term. However, as shown in Table 3, the fact that differences among the studies are within an order of magnitude suggests that the methods used for the Fukushima accident analysis are generally effective in deriving the source term.

The source term shown in Table 2 could be considered rather small in terms of mass for the three radioisotopes: their upper values are only 0.11 kg for ^{131}I, 2.7 kg for ^{133}Xe, and 17 kg for ^{137}Cs. However, since the numbers of isotopes are tremendously huge and, at the same time, these radioisotopes exist as single atoms or attached to airborne particles, they can be transported very easily by winds. So it should be noted that, once they are released into the atmosphere, their consequences are enormous from the viewpoint of the public health, economy, and social impact.

There were some claims that significant fraction of spent fuel rods stored at the spent fuel pool of unit 4 had been destroyed by earthquake and hence large amount of ^{137}Cs may have been released to the atmosphere from this pool (Stohl et al., 2012a; Kirchner et al., 2012). However, it turned out that most of the spent fuel rods were intact and there was almost no radioactivity release from the spent fuel pool of unit 4 into the environment (Oura, 2012). Therefore, it is assumed in this paper that the source term was originated only from the cores of unit 1–3, and not from the spent fuel pool of unit 4.

3.3. Radioactivity in Japan and the Pacific Ocean off Fukushima

According to the recommendations of the International Commission on Radiological Protection that the initial action levels of human dose for emergency exposure situations should be set in the range of 20–100 mSv (ICRP, 2008), evacuation radius was finally expanded to 20 km from the Fukushima plant after the initial

hydrogen explosion and radioactivity release. People who were living in area located between 20 and 30 km from the reactor were ordered to stay inside buildings or were suggested to evacuate (Nuclear and Industrial Safety Agency, 2011).

Fig. 5 shows the distribution of soil activity concentration, as of 2 July 2011, due to ^{134}Cs and ^{137}Cs particulates within 80 km of the Fukushima Daiichi nuclear power plant (The National Diet, 2012). It is noted that soil contamination level of $\geq$40 kBq/m^2 for beta- and gamma-emitters has been suggested by IAEA (IAEA, 2005, 2006) as a threshold contamination level after the Chernobyl accident. The reason given by IAEA (2006) is that at this level the human dose during the first year after the major accident was about 1 mSv, implying that the soil contamination level of 40 kBq/m^2 would correspond to about 1 mSv/yr in terms of human dose, which is the limit of exposure for the public. Therefore, for example, if someone had lived in the red area with a soil contamination level higher than 3000 kBq/m^2, radiation exposure would have exceeded around 75 mSv/yr during the first year after the accident. On the other hand, people living outside of 80 km from Fukushima where the soil contamination level was lower than 10 kBq/m^2 would have received radiation exposure less than 1 mSv/yr.

In addition, it is shown in Fig. 5 that ^{137}Cs activity levels higher than 1000 kBq/m^2, indicated in red and yellow color, extend about 40 km from the Fukushima Daiichi plant especially to the northwest direction (The National Diet, 2012). This is explained by the combination of the following three factors (Stohl et al., 2012a): 1) the highest emission of the radioactivity that occurred during 14–15 March 2011, 2) direction of winds during this period that transported the emission to the northwest of Fukushima, and 3) precipitation that took place over the Fukushima area by ^{137}Cs washout during the transportation of the Cs-bearing radioactive plume.

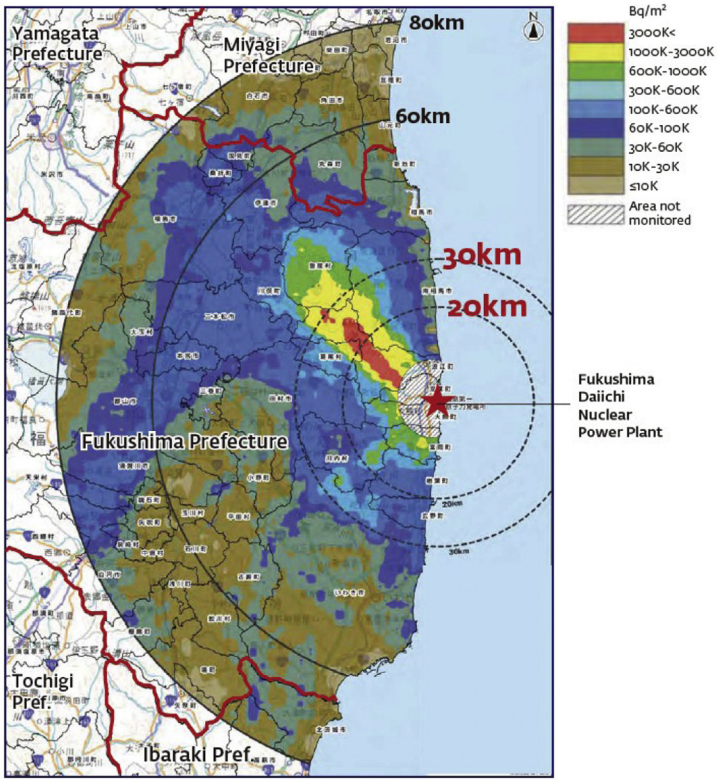
Before the accident, ^{137}Cs concentration level in seawater off the eastern Japan was 1–3 Bq/m^3 (Nakanishi et al., 2010). After the accident, however, measured concentrations in a 30 km perimeter from the Fukushima Daiichi plant exceeded 10^4 Bq/m^3 (10 Bq/l) and reached 6.8 $\times$ 10^7 Bq/m^3 (68,000 Bq/l) in the immediate vicinity less than 500 m from the plant in early April 2011 (Bois et al., 2012). According to a simulation (Behrens et al., 2012), due to dispersion by ocean currents and dilution, peak radioactivity in the seawater off Fukushima would be decreased to 10 Bq/m^3 during the first two years after the accident, followed by a gradual decline to 1–2 Bq/m^3 over the next 4–7 years.

3.4. Radioactivity in the world

Fig. 6 shows how ^{137}Cs released from the Fukushima plant was dispersed and deposited in the northern hemisphere (Stohl et al., 2012a). While high concentration of ^{137}Cs arrived in western North America on 17 March 2011, as for Europe, the first air mass relatively poor in ^{137}Cs was reached on 22 March 2011 due to the precipitation associated with rainout and washout during its transportation (Sportisse, 2007). Fig. 6 indicates that, except for the area near the Fukushima plant, the soil contamination of ^{137}Cs in the world was well below the IAEA's threshold contamination level of 40 kBq/m^2 (IAEA, 2006).

4. Consequences of the accident

The consequence of nuclear accidents is not just confined to radiological health problem in the area where the accidents occur; it could also have a very serious impact on economy and energy policy. Furthermore, depending on the amount of radioactivity released into the environment and dispersion to other countries, a



Map showing accumulated cesium-137 ▶
From data collected by MEXT on July 2, 2011

Fig. 5. Distribution of soil activity concentration due to ^{134}Cs and ^{137}Cs within 80 km of the Fukushima Daiichi nuclear power plant. Considering radioactive decay, the activity concentrations in the graph were corrected to July 2, 2011 (The National Diet, 2012).

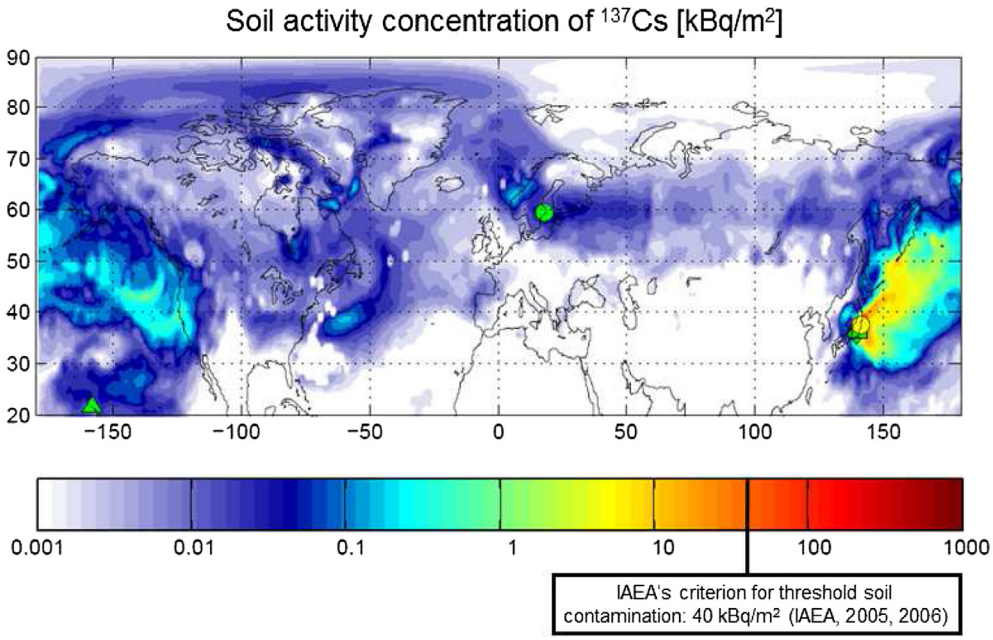


Fig. 6. Soil activity concentration of ^{137}Cs until 20 April 2011 in the northern hemisphere (Stohl et al., 2012a).

severe nuclear accident would cause very difficult international and diplomatic conflicts between the nation where the accident occurs and neighboring countries that would be affected by the accident.

4.1. Impact on public health

Just after the Fukushima accident, in order to mitigate the radiological health impact that would be induced by three hydrogen explosions, core meltdowns, and the ensuing release of huge radioactivity into the environment, more than 200,000 inhabitants from the vicinity of the site and potentially affected areas were forced to evacuate from their homes early in the accident (Dauer et al., 2011). Tens of thousands of people are still staying in temporary residences (Yoshisa and Kanda, 2012), without knowing when they can return because there is no clear plan yet for allowing displaced residents to go their homes (Brumfiel and Fuyuno, 2012). At the moment, while no one is officially reported to be dead so far by excessive exposure to radiation (Terra Daily, 2013; Srinivasan and Rethinaraj, 2013), there were nearly 600 non-radiological deaths that were indirectly caused by fatigue or aggravation of chronic illness due to the disaster and mandatory evacuation (Hoeve and Jacobson, 2012).

Iodine isotopes are chemically active and affect the thyroid gland when ingested or inhaled (World Health Organization, 2012). So, after a severe nuclear accident, the biological hazard of radioactive iodine is significant for relatively short-term period. And due to its long half-life of up to 30 years, radioactive cesium isotopes dominate projections for additional cancers for extended period of time (World Health Organization, 2012). Yet significant uncertainties remain about the long-term public health consequences of the nuclear accident.

Since there is no clear consensus on the long-term health effects of exposure to low level radiation (The National Diet, 2012), maybe it is too early to estimate the full public health damage induced by the Fukushima accident. Some studies have been made to quantify the worldwide health effects of the accident. Using a linear no-threshold (LNT) model of human exposure, Hoeve and Jacobson (2012) estimated that, mostly in Japan, radiation from the Fukushima accident may eventually cause a best estimate death tolls of about 130 (ranging from 15 to 1100) by cancer-related diseases. On the other hand, considering the effect of additional gamma ray dose from land contaminated with ^{134}Cs and ^{137}Cs (half-lives of 2 and 30 years, respectively), Beyea et al. (2013) predicted that a mid-range estimate for the number of future mortalities is closer to 1000 rather than 130, which is almost an order of magnitude larger than that of Hoeve and Jacobson (2012).

4.2. Impact on economy and energy policy

According to TEPCO that operated the Fukushima Daiichi nuclear power plant, the cost of clean-up for decades including compensation to victims and resettlement after the Fukushima accident may reach up to a colossal figure of US$ 125 billion (Nuclear Power Daily, 2012). Other sources' estimates (Reuters and Japan; News on Japan, 2013) could be even as high as US$ 250 billion over the next 10 years, including US$ 54 billion to buy up and decontaminate all land within 20 km of the Fukushima plant, US$ 8 billion for compensation payments to local residents whose jobs or home lives have been affected, and up to US$ 188 billion to scrap the plant's reactors (News on Japan, 2013). However, the cost required for this effort would be virtually impossible to predict accurately and are very likely to increase with time.

The Fukushima accident has had a great influence on the energy policy of many countries that were operating nuclear reactors or had plans for constructing new ones. About one and half year after the accident, the Japanese government announced an energy plan to phase out nuclear power by 2040 considering strong public opinion against nuclear energy (Wall Street Journal, 2012; Financial Times, 2012; BBC, 2012). However, the plan faced the intense opposition of business groups and communities whose economies depend on local nuclear power plants. Furthermore, it has also been questioned by other countries such as the US, the UK and France due to an impact that Japan's decision would have on the way nuclear energy is perceived in the world (Times, 2012). Finally, a government panel working on a draft of the long-term energy plan of Japan has urged the country to continue to use nuclear power,

abandoning a policy of phase-out (Business Line, 2013; The Voice of Russia, 2013).

Before the Fukushima accident, Germany was pursuing to extend the lives of the existing nuclear reactors while retaining the fundamental idea of the phase-out of nuclear power. However, shortly after the accident, the government reversed its policy on nuclear energy, shutting down eight reactors almost immediately and deciding to phase out the country's nuclear industry entirely by 2022 (Glaser, 2012). Switzerland also decided to abandon nuclear power by 2034, and Italy gave up its plan to construct new nuclear power plants through a referendum (Hayashi and Hughes, 2013). On the other hand, some countries such as the US, the UK, France, Russia, South Korea, and China took measures to strengthen nuclear safety in the wake of the accident (Zhou, 2012), and their policies on nuclear energy do not seem to be influenced greatly by the disaster (Thomas, 2012).

4.3. Impact on international relationship

Severe nuclear accident involving core meltdown and the ensuing release of large amounts of radioactivity into the environment poses a global risk, as was observed both in the Chernobyl and Fukushima accidents. This is closely correlated with the characteristics of volatile fission products including fission gases which are very mobile and hence, once massively released into the atmosphere when fuel is damaged by core meltdown (Burns et al., 2012), can be easily transported to any places in the world. This implies that radionuclides released from a reactor accident anywhere on the Earth would not just be deposited locally but globally. It took only 18 days for the Fukushima radioactive clouds to spread around the northern hemisphere (Hsu et al., 2012).

Recently, computer simulations revealed that on average only 8% of the ^{137}Cs airborne particles are expected to deposit within an area of 50 km around the accident site and about 50% of the airborne particles would be deposited outside a radius of 1000 km. Furthermore, about 25% would spread even further beyond 2000 km (Lelieveld et al., 2012). This study clearly indicates that, as was observed in the Chernobyl accident, reactor accidents are likely to cause radioactive contamination well beyond the national borders. Therefore, depending on the degree of contamination, this could lead to very difficult international and diplomatic conflicts between the nation where a severe accident occurs and neighboring countries that would be affected by the accident. As for the Fukushima accident, because of the geographic location of the nuclear power plant – at the beach of the Pacific Ocean – and Fukushima's meteorological conditions, including wind direction that mostly flows towards the Pacific Ocean, more than 80% of the radioactivity released from the crippled reactors flowed into the sea (Hoeve and Jacobson, 2012; Christoudias and Lelieveld, 2013). So fortunately only about 20% of the released radioactivity from the Fukushima accident (0.8% of the core inventory as shown in Fig. 1) was deposited over the Japanese land, keeping the exposed population relatively low.

However, this would not be always the case. Especially in Europe and Asia where many countries are located in a relatively small area with lots of nuclear power plants operating, a severe accident could lead to the huge contamination of the neighboring countries, raising a very complicated problem related to both the legal and economic liability of the nation where the accident took place.

4.4. Impact on LWR fuel development

After the Fukushima accident, worldwide efforts have been made to enhance the safety of nuclear power plants, including thorough investigation of the safety of existing nuclear reactors – stress tests – and subsequent provision of recommendations both in the European Union (European Commission, 2012) and US (US NRC, 2011). However, implementation of the recommendations in the existing reactors is usually difficult and costly, and even if it were done, safety risk of the reactors would not be likely eliminated completely (Lyman, 2012, 2008; Cooper, 2012). Furthermore, it is still possible that some or many of the safety-related systems would not function as designed (Blandford and Ahn, 2012) under certain situations that might not have been expected when evaluating nuclear reactor safety, which is the so-called beyond design basis accidents. In addition, not equipment failures but human errors, which might be practically very hard to predict, could lead to severe accidents (Taebi et al., 2012). In this respect, several countries including the USA, France and South Korea (Shannon Bragg-Sitton et al., 2013; Koo et al., 2014; Brachet et al., 2013) has started to develop accident tolerant fuel that could prevent accidents or mitigate the consequences of nuclear accidents. It is considered that two of the most important characteristics that the accident tolerant fuel must possess are as follows (Gulliford, 2012): 1) hydrogen production through the steam oxidation of cladding at high temperature must be minimized so that hydrogen explosion could be avoided or mitigated and also time to melting could be extended, and 2) ability of fuel pellet to retain fission products, especially volatile ones such as Cs and I which cause public health problem once released into the environment, should be increased to the maximum degree achievable.

5. Conclusions

The Fukushima accident in March 2011 caused by the massive earthquake and tsunami led to hydrogen explosion, core meltdown, and the subsequent release of huge radioactivity both into the atmosphere and the Pacific Ocean. In the case of volatile fission products such as ^{137}Cs and ^{131}I, the release fraction of the core inventory of the units 1–3 into the atmosphere is estimated to be 1.2–6.6% and 1.1–7.9%, respectively. As for gaseous fission product ^{133}Xe, it is estimated that nearly 100% of the core inventory might have been released into the atmosphere. Furthermore, about 16% of the ^{137}Cs inventory flowed into the sea when the contaminated water used for cooling the decay heat of the units 1–3 overflowed the reactors.

Due to this radioactivity release into the environment, the Fukushima accident has had a tremendous impact not only on Japan but all over the world as well. As for the impact on public health, since there is no clear consensus on the long-term effects of exposure to low level radiation, analysis results for the consequences of the accident vary very widely. Depending on the studies, best estimate number of mortalities of the accident ranges from 130 to 1000.

Nuclear energy policy of many countries has also been affected. Shortly after the accident, Germany reversed its policy on nuclear energy, shutting down eight reactors almost immediately and deciding to phase out the country's nuclear industry entirely by 2022. Switzerland also decided to abandon nuclear power by 2034, and Italy gave up its plan to construct new nuclear power plants. In the case of Japan, about one and half year after the accident, the Japanese government announced an energy plan to phase out nuclear power by 2040. However, Japan is recently reconsidering to abandon the phase-out policy and then to continue to use nuclear power. On the other hand, while some countries such as the US, the UK, France, Russia, South Korea, and China took measures to strengthen nuclear safety in the wake of the Fukushima accident, their policies on nuclear energy do not seem to be influenced greatly by the disaster.

Since radioactive material knows no national boundary, depending on the location of the accident and the amount of radioactivity released into the environment, very complicated

international problems could take place between the nation where an accident occurs and neighboring countries that would be affected by the accident. For example, as for Cs radioisotopes which exist as single atoms or attached to airborne particles in the atmosphere and hence can be transported very easily by winds, it is estimated that 50% of the airborne particles would be deposited outside a radius of 1000 km from a nuclear power plant where a severe accident occurs and about 25% would spread even further beyond 2000 km. As for the Fukushima accident, fortunately because the nuclear power plant is located at the beach of the Pacific Ocean and wind mainly flows towards the sea at the plant, most of the released radioactivity deposited in the Japanese land or flowed into the sea.

Public's perception on nuclear energy has been aggravated worldwide after the Fukushima accident. However, considering the scarcity of natural energy resources and global warming that could arise by greenhouse effect, nuclear energy needs to play an important role continuously for the sustainable development of the world. For this purpose, nuclear safety should be strengthened significantly than ever before. However, since practically no reactor design can insure against all contingencies in advance and the possibility always exists that unexpected severe events could occur, accident tolerant fuel which can prevent severe accident or mitigate the accident's consequences are strongly required. This is why several countries are actively developing the accident tolerant fuel.

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