Radioactive release during nuclear accidents in Chernobyl and Fukushima

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Abstract. Nuclear accidents that occurred in Chernobyl and Fukushima have initiated many research interests to understand the cause and mechanism of radioactive release within reactor compound and to the environment. Common types of radionuclide release are the fission products from the irradiated fuel rod itself. In case of nuclear accident, the focus of monitoring will be mostly on the release of noble gases, I-131 and Cs-137. As these are the only accidents have been rated within International Nuclear Events Scale (INES) Level 7, the radioactive release to the environment was one of the critical insights to be monitored. It was estimated that the release of radioactive material to the atmosphere due to Fukushima accident was approximately 10\% of the Chernobyl accident. By referring to the previous reports using computational code systems to model the release rate, the release activity of I-131 and Cs-137 in Chernobyl was significantly higher compare to Fukushima. The simulation code also showed that Chernobyl had higher release rate of both radionuclides on the day of accident. Other factors affecting the radioactive release for Fukushima and Chernobyl accidents such as the current reactor technology and safety measures are also compared for discussion.

1. Introduction

Nuclear accident does not commonly occur, but when it happens, it will raise worldwide interest especially on the safety aspect. There are many factors affecting the plant operation and leads to failure such as human error, reactor design, and natural disaster. The age-profile of the NPP may also indicate whether the safety evaluation is satisfactory and in-line to protect from the latest potential threat.

The fission products released to the environment or source term is originated from the irradiated fuel rod in the reactor core. Depending on the half-life of radionuclide, this factor will determine how long it will stay in the radioactive plume and may dispersed towards the public area. However, some short half-lived radionuclides may be hazardous as well, for example; Iodine-131 (\textit{I}-131) because iodine is naturally absorbed by thyroid and food chain. For long half-lived radionuclides, this may be a great concern as it will require additional effort such as decontamination and relocation for a longer term.

The Chernobyl and Fukushima nuclear accidents are now remained the most catastrophic accident in the nuclear history. Although the cause of the accident and the effects are different from each other, it is still trigger the question whether having a nuclear power plant in one’s country is a good source of
energy when the safety issues are still a concern. Both accidents were rated Level 7 by International Nuclear Events Scale (INES) which describes the accident to be serious enough to require a country to implement countermeasures to protect the public from the health and environmental effects of radiation, but it does not mean that these effects have occurred.

Radionuclides I-131 and Cs-137 were chosen as the primary release in this work. The radioactive release caused by the accidents was analyzed by referring to the previous reports which have used computational code systems to model the release rate for both accidents. While comparing the results as both showed different aftermath accident consequences, discussions are made to enlighten the issue.

1.1. Chernobyl Nuclear Accident
On 26th April 1986, operators were preparing to test the backup cooling system in reactor Unit 4. This test allows power to be provided in the event of a station blackout. However, the routine safety drill went horribly wrong. During the test, almost all of the control rods were removed. The reactor became unstable due to large positive coefficient of reactivity under certain conditions and the faulty actions of the operators for switching off the emergency safety systems of the reactor [1].

Technicians began to lose control of coolant flow as the lower transitions joints that link the zirconium fuel channels in the core to the steel pipes that carry the inlet cooling water weakened, causing the temperature in the reactor core to be extremely increased. Fuel rods started to melt, exposing zirconium (Zr) to react with hydrogen in steam (H₂O), thus resulted in an explosion. It blew up the roof top of the building including the top of the reactor core vessel, spilling out eight tons (8 Tons) of radioactive debris.

Information on the details of accident including the radioactive release on that time is available in a meeting report by IAEA [2]. The radioactive release from this accident occurs continuously for over 10 days. Although the release rates recorded were varying, the highest release rate was on the day of the explosion, which bared the inside of reactor directly to the atmosphere. After 10 days, the release decreased abruptly, indicating the end of intense release period [3]. The radioactive release was affecting greatly to the reactor neighbouring regions in European part of the former Soviet Union.

1.2. Fukushima Nuclear Accident
A great earthquake with a magnitude of 9.0 in East Japan awakened a 15-metre tsunami and causing three Fukushima reactors to be disabled. When the earthquake hit the coast, the seismic sensors triggered the insertion of the control rods to stop the fission reaction. However, the off-site power supply was lost, activated the diesel-generator supplying electricity to a backup system needed for core cooling. The tsunami waves arrived less than an hour after the earthquake and went over the sea wall, thus flooding the lower parts of building. The emergency diesel generator had stopped functioning which then resulted in heat in the core to highly increase.

The three reactor units were unable to maintain their cooling system and water circulation functions. Despite all the hard work from engineers to bring back the backup system online, the heat trapped in the core vessel started to cause the water evaporated into steam and the fuel rod began to melt after reaching 2,300 °C. Just like Chernobyl case, the zirconium from the cladding of the fuel rod started to react with hydrogen resulted in the explosions in reactor unit 1 and 3. For reactor unit 4, sources of flammable gas remained unknown as the spent fuel in the spent fuel pool was still covered with water. Explosion occurred in reactor unit 2 was reported due to lower suppression area.

The core meltdown scenario was almost the same for all three units, except that it happened on different dates. Temperatures above 2000°C in reactor core may not only cause melting of UO₂, but also the zircaloy cladding and steel [4]. The melted fuel rod when mixed with other materials in the core vessel will form a quenched meat, named corium. Some volatile fission products such as Cs and I were released during melting process, but the less volatile fission product and the actinides were still remained in the corium as it cools down. Therefore, the corium may still contains the radionuclides and leads to a long-term radiotoxicity in the reactor core [5].
2. Methodology
In this paper, the results from the previous reports using System for Prediction of Environment Emergency Dose Information (SPEEDI) were referred. It is a type of computer-based decision support system developed by Japanese Atomic Energy Research Institute (JAERI) for real-time dose assessment [6] and predictions of environmental radioactivity [7] in radiological emergencies. SPEEDI is used for domestic local range accidents and involved in a national scale emergency response programme. However, Chernobyl accident necessitated the expansion of the prediction area of SPEEDI to evaluate the long-range transport of airborne radioactivity due to a severe nuclear accident in a foreign country.

The worldwide version of SPEEDI, better known as WSPEEDI was then developed to predict the radiological impact on Japanese people in case of nuclear accident occurs in neighbouring country. As detailed explanation on both systems are already reported in other literatures [6][8][9], a summary of description for SPEEDI and WSPEEDI has also been outlined by [10]. For comparison purpose, we will look into the results using SPEEDI only for both Chernobyl and Fukushima accidents.

SPEEDI flow of computational codes is described in figure 1. The first step in using this SPEEDI is to insert the information such as the location of nuclear accident site. This system has characteristic data of nuclear reactor sites in Japan such as longitude, latitude and stack height. Then, it will predict the meteorological condition automatically, whenever the observed data are made input. The WEADUS2 code will forecast the wind speed and wind directions at the measuring points. The output data file generated by this code has both observed data and forecasted data. Other codes involve in main calculations are WIND04, PRWDA and CIDE. WIND04 code calculates the wind fields by using a three-dimensional mass-consistent model that is influenced by terrain. PRWDA code is used to simulate the diffusion of airborne and CIDE to evaluate the dose [11].

When SPEEDI was used in 1986 to predict the release rate from Chernobyl accident, the system had a limitation in terms of topographical data. SPEEDI was only equipped with topographical data of Japanese nuclear power plant. According to the report [7], the application of SPEEDI was continued in this case by assuming a flat terrain, as the objective region is almost flat. The radioactive release was assumed to start at 25th April 1986 with a height of 1000 m for 12 hours from the start of the release and 200 m after the first 12 hours. During Fukushima accidents, there were some difficulties in estimating the time of the release. Therefore, the explosive sound around the suppression chamber of Unit 2 was reported and marked as the starting point to record the release rate [10]. This was also supported by the extremely increased dose rate measured at the main gate of the plant.

![Figure 1. The flow of computational codes in SPEEDI.](image)

3. Results and Discussion
The activity for the release of Cs-137 and I-131 release during Chernobyl are $2.3 \times 10^6$ Ci and $50.0 \times 10^6$ Ci respectively are shown in figure 2. These values were significantly higher than that of Fukushima which are $0.41 \times 10^6$ Ci and $4.3 \times 10^6$ Ci respectively. In Chernobyl, two explosions were reported occurred during the accident. The first one was the initial steam explosion followed by a
second explosion happened after two to three seconds, possibly caused by the build-up hydrogen due to zirconium-steam reactions. A number of fires started as a result from the ejected fuel, moderator and structural materials. The destroyed core was exposed and lead to the radioactive release directly to atmosphere.

Figure 2. The release activity of radionuclide Cs-137 and I-131 during Chernobyl and Fukushima accidents [13].

Most of the released were made up of short physical half-lives, making the long-lived radionuclides in smaller group. Hence, short-lived radionuclides released by the accident have already decayed. However, I-131 with half-life of eight days was raising concern towards the public. Current estimation of I-131 deposition was required to improve thyroid dose reconstruction [12]. After the initial period, Cs-137 also became a problem as it is in the form of salts, making it highly soluble with water thus increase the probability of water contamination.

However, in Fukushima, most of the radioactivity released from the reactor was captured in the water inside the reactor building [13]. The explosions from three reactors were signaling that a loss of coolant had occurred. This had caused the fuel temperature increasing up to 1,000 °C and the zirconium alloy cladding to oxidize when reacted with steam. The oxidation process created the hydrogen gas which then leaked out to the ceiling of the building, mixed with air and then came the blast. Even though the ceiling of the containment blew off, the reactor vessel was still remained intact.

The estimated release rate of Cs-137 and I-131 in table 1 was reported by using SPEEDI. The simulation process was done by the same researchers for both accident but on different reports, therefore they had credible experience in handling the model. Although there was a large time gap in between both accidents, the release rate will be discussed in terms of technical issues occurred.

| Radionuclide | Release rate on the day of accident \(10^3 \text{ Ci} / \text{hr}\) |
|--------------|---------------------------------------------------|
|              | Chernobyl (26 April 1986) | Fukushima (12 March 2011) |
| Cs-137       | 5.6                                | -                      |
| I-131        | 2000                               | 0.621                  |

Chernobyl was reported to have a release rate of Cs-137 and I-131 which were \(5.6 \times 10^3 \text{ Ci}\) and \(0.02 \times 10^3 \text{ Ci}\) respectively. Within the first 24 hours from the explosion started, half of the noble gas inventory has been discharged [7]. The higher release of Chernobyl when compared to Fukushima was still mainly caused by the major exposure of the reactor core. The explosion also caused the core debris to be dispersed and started multiple fires on the roofs of the reactor building and the machine
These areas were covered with highly flammable tar. However, it is still unclear the fires were originating from the reactor cavity during the first 20 hours after the explosion.

In Fukushima, there was no detection of Cs-137 but only for I-131 which was $0.621 \times 10^3$ Ci. Cs-137 was only detected on March 15th, the third day after the first explosion. It was reported that the cause of undetected Cs-137 was the dust sampling missed to capture the plumes [10]. The release of I-131 was probably occurred during primary containment vessel venting [15] in order to reduce the pressure inside the reactor. The steam vented was believed to contain small amount of radioactive material. The first hydrogen explosion which happened a few hours later at Unit 1 might as well had cause the release to be increasing.

The results of the radioactive release during Chernobyl and Fukushima accidents can also be used to initiate various further studies. These data are crucial in deposition studies, estimating atmospheric dispersion locally and globally and exposure pathways. As both accidents were rated Level 7 by INES, a detailed research can also be a guideline for other countries with NPP to prepare with an updated and comprehensive emergency plan. Although nuclear accidents may reach to the catastrophic level if it goes beyond human control, it is still recorded as low number of accidents in the industry.

4. Conclusion

This paper is aimed at discussing on the radioactivity release during nuclear accidents in Chernobyl and Fukushima. The release rates focusing on Cs-137 and I-131 were estimated by referring to the previous reports using SPEEDI computer code system. The radioactive release and the release rate from Chernobyl accident were significantly higher than that of Fukushima accident. Both accidents were rated level 7 by INES scale for the major release of radioactive material with widespread health and environmental effects. Chernobyl accident which mainly caused by human error can be avoided if only the operators did not turn off their emergency backup system. The exposed core had resulted in great radioactive release and consequently, higher exposure dose to public. Although Fukushima accident was not prophesized to be this worst as it was affected by high-magnitude earthquake and tsunami, the backup system did not last long enough to keep the core cooled. It was very unfortunate for such accidents to occur but the lesson learned should be taken to improvise the current reactor technology towards better nuclear power generation.

5. References

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