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Review

Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts

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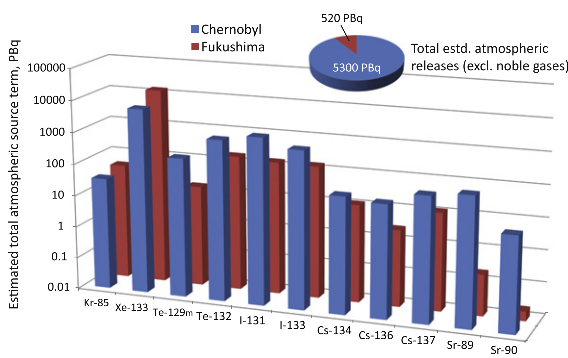
HIGHLIGHTS

- The environmental effects of Chernobyl and Fukushima are compared.
- Releases of radionuclides from Chernobyl exceeded Fukushima by an order of magnitude.
- Chernobyl caused more severe radiation-related health effects.
- Overall, Chernobyl was a much more severe nuclear accident than Fukushima.
- Psychological effects are neglected but important consequences of nuclear accidents.

GRAPHICAL ABSTRACT



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ABSTRACT

The environmental impacts of the nuclear accidents of Chernobyl and Fukushima are compared. In almost every respect, the consequences of the Chernobyl accident clearly exceeded those of the Fukushima accident. In both accidents, most of the radioactivity released was due to volatile radionuclides (noble gases, iodine, cesium, tellurium). However, the amount of refractory elements (including actinides) emitted in the course of the Chernobyl accident was approximately four orders of magnitude higher than during the Fukushima accident. For Chernobyl, a total release of 5300 PBq (excluding noble gases) has been established as the most cited source term. For Fukushima, we estimated a total source term of 520 (340–800) PBq. In the course of the Fukushima accident, the majority of the radionuclides (more than 80%) was transported offshore and deposited in the Pacific Ocean. Monitoring campaigns after both accidents reveal that the environmental impact of the Chernobyl accident was much greater than of the Fukushima accident. Both the highly contaminated areas and the evacuated areas are smaller around Fukushima and the projected health effects in Japan are significantly lower than after the Chernobyl accident. This is mainly due to the fact that food safety campaigns and evacuations worked quickly and efficiently after the Fukushima accident. In contrast to Chernobyl, no fatalities due to acute radiation effects occurred in Fukushima.

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1. Introduction

The accident at the Fukushima Daiichi nuclear power plant (NPP) was one of the biggest environmental disasters in recent years. In public perception, enhanced by media reports, parallels between the nuclear accidents of Fukushima (Japan, 2011) and Chernobyl (Ukraine, 1986) have often been drawn. Both accidents have been rated on the International Atomic Energy Agency (IAEA) International Nuclear and Radiological Event Scale (INES) as a “Major Accident” as INES 7. However, are the accidents as comparable as suggested by this rating? The nuclear accidents of Chernobyl and Fukushima exhibit some interesting similarities and differences, which warrant comparison. In this review, the main focus is on environmental consequences of both accidents, the causes of the accidents, the types and amounts of radionuclides released, the areas of contamination, the environmental media affected, and a brief discussion of the most relevant radiological aspects including food safety.

2. Causes of the accidents

The Chernobyl nuclear accident happened on 26 April 1986 in the course of a technical test in Unit 4 of the Chernobyl NPP. Inappropriate reactor operation at low power level led to “xenon-poisoning” of the reactor, which was not recognized properly by the reactor staff and caused improper operation of the reactor's control rods (Grishanin, 2010; Smith and Beresford, 2005). This operating error led to thermal destruction of the RBMK-1000 reactor by a sudden power excursion, which ultimately caused at least one (steam) explosion and ignition of the graphite moderators (Michel, 2006). Radionuclides released from the explosion included very short-lived fission products, which resulted in very high dose rates in the adjacent areas. After the initial peak release, further releases of radionuclides occurred over 10 days due to the graphite fire.

On 11 March 2011, the magnitude 9.0 East Japan Earthquake (also referred to as Tohoku Earthquake) occurred at 14:46 (local time) with an epicenter in the Pacific Ocean 130 km east of Sendai (Japan) and 163 km northeast of the Fukushima NPP (Thielen, 2012). The earthquake caused a devastating tsunami that reached heights of up to 40.5 m and caused massive destruction along the coast line. The tsunami rolled as much as 10 km inland (Hamada and Ogino, 2012), causing 15,854 confirmed fatalities and 3089 missing persons (as of 28 March 2012) (Hamada et al., 2012).

The Fukushima Daiichi NPP was operated by the Tokyo Electric Power Company (TEPCO) and consisted of six boiling water reactors with a combined power capability of 5480 MWe (Schwantes et al., 2012). The reactors were brought into operation between 1971 and 1979 and were protected by a 10 m sea wall (Lipscy et al., 2013). The tsunami, however reached as high as 14 m at the plant site. Three of the six reactors (Units 1, 2, and 3) were in operation at the time of the earthquake, but the first seismic signals of the earthquake triggered an automatic shutdown of the reactors. The tsunami reached the site of the NPP at 15:38. It flooded, damaged, and blocked the water intake buildings of the NPP and destroyed the diesel generators, leaving the main cooling systems inoperable due to a complete station blackout. This also included the cooling systems for the spent fuel pools of reactor Units 4, 5, and 6 (Thielen, 2012). Under these circumstances, the battery-driven reactor core isolation pumps remained the only method of cooling for the reactor pressure vessels. The reactor core isolation pump is driven by steam from the pressure vessel, and the steam is discharged into the reactor condensation chamber, while simultaneously pumping water from the condensation chamber into the vessel. However, there was no heat removal from the building via the condensation chamber, and the reactor core isolation pump eventually stopped functioning. After the loss of battery power or pump failure (Unit 1: 11 March; Unit 2: 14 March; Unit 3: 13 March), the reactors were left uncooled (Braun, 2011). At that time, the decay heat of the fission products was still in the range of 20 MW, which caused damage and partial meltdown of the fuel elements. Tanabe (2012) found that core damage started at 1200 K due to ballooning and bursting of the fuel cladding. Core material melting started at 1500 K. Kirchner et al. (2012) estimated that the temperature of the core, however, remained below 2670 K, so that refractory elements were mobilized only to a minor extent. At the temperatures reached, however, the redox-reaction between zirconium and water takes place (the reaction initiates at temperatures >1170 K and becomes autocatalytic >1570 K (Schwantes et al., 2012)), causing the formation of large amounts of hydrogen gas. During venting operations (Blandford and Ahn, 2012) for overpressure relief, both radionuclides and hydrogen gas were released into the service floor level of the reactor buildings, mixing with air. Three massive oxy-hydrogen gas explosions subsequently damaged Unit 1, 3, and 4 buildings. Unit 2 was damaged due to a hydrogen explosion in the condensation chamber.

In contrast to Chernobyl, Fukushima reactors were equipped with a concrete containment building. The explosions at Fukushima were solely of chemical nature (hydrogen explosions) and affected the reactor buildings but, based on the best available information, not the reactor pressure vessels or the reactors themselves. The release characteristics were distinct from the Chernobyl accident. Releases of only gas phase radionuclides occurred in the course of venting operations to relieve over-pressure inside the vessel, after approximately one day delay. In contrast to the uncontrolled, continuous releases of Chernobyl with peak releases in the very beginning, the venting operations at Fukushima NPP happened in pulses over a time span of more than a week, and were often conducted under advantageous weather conditions that transported approximately 80% of the radionuclides offshore (Morino et al., 2011).

3. Types and amounts of released radionuclides

The radionuclide source terms after releases from major nuclear accidents are obtained by model simulations with distinct assumptions and preconditions. This explains the variability of early estimates. For Chernobyl, a value of 5300 PBq ($1\ \text{PBq} = 10^{15}$ Bq) for the total activity released (excluding noble gases) has been established as the most cited source term in recent literature (UNSCEAR, 2000). Later, the release of refractory elements was adjusted to a 50% lower value. These changes are mostly academic in nature and neither dramatically influence the assessment of radiation doses nor the estimation of the