



Review

Perspectives on a Severe Accident Consequences—10 Years after the Fukushima Accident

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Abstract: Scientific issues that draw international attention from the public and experts during the last 10 years after the Fukushima accident are discussed. An assessment of current severe accident analysis methodology, impact on the views of nuclear reactor safety, dispute on the safety of fishery products, discharge of radioactive water to the ocean, status of decommissioning, and needs for long-term monitoring of the environment are discussed.

Keywords: Fukushima accident; nuclear reactor safety; severe accident analysis; safety of fishery products; discharge of radioactive water; decommissioning



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1. Introduction

Nuclear experts and scientists represented by the International Atomic Energy Agency (IAEA) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reported that a severe accident consequences of the Fukushima accident do not significantly challenge the health of the general public or environmental contamination. IAEA [1] reported that “the release of radionuclides, and the corresponding doses to nonhuman biota occupying areas of high deposition in Japan, was much lower than in areas around Chernobyl.” United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [2] reported that “the doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or low. No discernible increased incidences of radiation-related health effects are expected among exposed members of the public or their descendants.”

However, certain countries became reluctant in building new nuclear power plants and pursued other alternatives such as regenerative energy soon after the Fukushima accident. Germany made a drastic decision to fade out nuclear power plants by year 2022 [3]. In the year 2017, new president in Korea announced that Korea would halt plans to build new nuclear power plants and would not extend the lifespans of existing ones [4]. Before the Fukushima accident, strict regulation was enforced only for a design basis accident, while regulation for a severe accident was minimal. The risk of severe accident was considered to be residual. There was little practice of enforcing back-fit on operating reactors to prevent or to mitigate severe accident. After the Fukushima accident, the safety of the nuclear power plant has been significantly improved in a global scale ranging from an establishment of formal regulation for a severe accident to strengthening the mitigation measures for unexpected accidents and natural hazards.

In Japan, strong regulation on nuclear reactor safety was enforced by the Nuclear Regulatory Agency (NRA) soon after the Fukushima accident. The NRA stated that a “so-called “safety myth” had critically impeded efforts for nuclear safety in Japan before the accident at Fukushima Daiichi nuclear accident; however, more stringent regulations have been developed with an underlying assumption that severe accidents could occur at any moment [5].” United State Nuclear Regulatory Commission (USNRC) strengthened the regulation for better safety by employing various measures: adding capabilities to

maintain key plant safety functions following a large-scale natural disaster, updating evaluations on the potential impact from seismic and flooding events, new equipment to better handle potential reactor core damage events, and strengthening emergency preparedness capabilities [6].

New regulations for a severe accident adopted in global nuclear community allows only a fractional amount of radiological release at a low probability. As an example, Japanese Nuclear Regulatory Agency [5] requires that the frequency of an accident that causes discharging ^{137}Cs over 100TBq should be reduced to not exceed one in one million reactor years. The amount of 100TBq of ^{137}Cs is less than 1% of the release from the Fukushima accident, such that radiological impact would be minimal. Therefore, it is fair to say that the current fleet of nuclear power plants is at least better than before.

The probability argument element in the new regulation for a severe accident is based on a cost-benefit analysis [7]. An expert in the nuclear sector would easily accept that it will be extremely unlikely to experience another severe accident in his or her lifetime. However, nuclear experts and the public have different perceptions for nuclear risk. Recent studies shows that experts perceive radiological risks differently from the general public. Experts' perception of medical X-rays and natural radiation is significantly higher than in the general population, while for nuclear waste and an accident at a nuclear installation, experts have lower risk perception than the general population [8]. The public needs to be convinced to understand the views from the nuclear expert.

The different views among nuclear experts and the public raised several issues, which called for international attention after the Fukushima accident. Prominent issues include uncertainties of severe accident analysis, more emphasis on nuclear safety, decommissioning of Fukushima nuclear power plant, discharge of radioactive water, and safety of fishery products. The author revisited these issues in a broader view where both the public and the expert engaged to provide perspectives on severe accident consequences.

2. Severe Accident Analysis Methodology

To investigate the accident progression and radiological releases in the Fukushima accident, there were research efforts on an international scale, such as the Nuclear Energy Agency of the Organization for Economic Development (OECD/NEA) project of Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF) [9]. The state-of-the-art computer codes including ASTEC [10], MELCOR [11], MAAP [12] were employed to predict and interpret the accident progression, including core damage, reactor vessel failures, and radiological releases to the environment in three units of the Fukushima Daiichi nuclear power plant (FDNPP). Progression of core damage and resulting radiological releases were analyzed for unit 1, 2, and 3 of the FDNPP [13–18]. Yet, it had to be forensic in nature because initial and boundary conditions for the accident progression, such as responses of various components of the nuclear power plant at off-design conditions and net effects of operator actions cannot be confirmed [17,18]. The behavior of the components in the off-design conditions of high temperature, pressure, and radiation experienced during a severe accident were uncertain [9,13–18].

Atmospheric dispersion calculations for the radiological releases to the environment during weeks after the accident were performed, but the results were not consistent with the measured terrestrial deposition pattern due to incomplete weather data and uncertain release histories from each unit [19].

Physical models for a severe accident phenomena had to accompany uncertainties because they handled the behavior of complex system, which consists of multi-phase (liquid, vapor, droplet, aerosol) and multi-component (water, molten fuel at various compositions of different materials, non-condensable gas) subsystems with complicated geometric configuration in a wide range of pressure and temperature. Therefore, the correlations employed for the fluid flow and heat transfer in a severe accident analysis code have model parameters to allow a range of predictions. As degradation of core fuels and neighboring materials at high temperature near 3000 K experiences phase change, it has to handle

thermodynamics of multi-component system of UO_2 , Zr, ZrO_2 , stainless steel, and B_4C [20]. In addition, phenomenon-specific model parameters such as flame speed for the hydrogen combustion calculation, range of the size of aerosols for fission product transport, size particulate debris bed for heat transfer, and melting temperature of composite materials are allowed to have a range [10–12].

Therefore, the accident progression and radiological releases were predicted with uncertainties. Recently, systematic approaches to handle these uncertainties in the phenomenological and physical modellings of a severe accident analysis have been developed [21,22], which enabled handling of the uncertainties in a rigorous statistical manner [23]. Typical uncertainty calculation included sensitivity studies on sequence related parameters such as primary safety valve stochastic number of cycles until failure-to-close, in-vessel accident progression related model parameters such as Zircaloy melt breakout temperature, molten clad drainage rate, and ex-vessel accident progression related model parameters such as hydrogen ignition criteria, chemical form of iodine, aerosol dynamics shape factor, containment convection heat transfer coefficient [21].

Using Monte–Carlo or Latin hypercube sampling methods, about 300–1000 calculations were performed for a typical scenario, such as station black out (SBO), whose accident progression is similar to that of Fukushima. Widespread radiological release was observed between calculated median, mean, and 95th percentile curves [21,22]. These analyses results are integrated with the MACCS (MELCOR Accident Consequence Code System) [24] analyses to predict latent cancer fatality (LCF) risk statistics. MACCS models atmospheric transport and deposition of radionuclides, emergency response, exposure pathways, early and latent health effects to the population.

The above methodology required a significant number of MELCOR and MACCS calculations up to 300–1000; however, it became feasible with recent advances in the computer hardware. Severe accident consequence analyses with rigorous uncertainty quantification would not only increase the confidence and accuracy of the results of radiation exposures to the public and health effects, but it also would help communication with the public or scientists in other fields.

3. Views on the Nuclear Reactor Safety

The continued investigations on the status of the damaged reactors of the FDNPP confirmed that molten fuels discharged out of the reactor vessel, and they were relocated on the floor of the primary containment vessel and interacted with the concrete structure of the floor in all three units. Cosmic muon radiography was utilized to visualize the presence of the reactor fuels in the reactor vessel [25]. The reactor vessel failed, and a mixture of steam, fission products, and hydrogen gas was released out of the primary containment vessel. This type of severe accident consequence is different from that of Three Mile Island (TMI) [26] with negligible radiological releases to the environment, where reactor vessel failure was prevented, although a significant amount of core was molten.

The radiological releases in the Fukushima accident consist of atmospheric release and direct release of contaminated liquid into the ocean. Atmospheric releases are in the form of gas and aerosols transported to the land and sea by the wind and rainfall.

The numbers reported by UNSCEAR [2] can be considered as representative values. The total releases to the atmosphere of ^{131}I and ^{137}Cs ranged generally between 100–500 PBq and 6–20 PBq, respectively. The releases of less volatile radionuclides (e.g., ^{90}Sr and ^{239}Pu) were negligible. The total releases of ^{131}I and ^{137}Cs to the atmosphere are 120 and 10 PBq, respectively. Releases of radionuclides into the Pacific Ocean occurred directly and indirectly. They comprise: (i) direct releases in the first three months amounting to about 10 to 20 PBq of ^{131}I and about 3 to 6 PBq of ^{137}Cs ; (ii) deposition of radionuclides on to the ocean surface following their release to, and dispersion in, the atmosphere, amounting to about 60 to 100 PBq of ^{131}I and 5 to 8 PBq of ^{137}Cs .

While the amount of atmospheric release was about 1/10 of the one in the Chernobyl accident, the amount of direct release to the ocean was in the same order as that of Cher-

nobl. Atmospheric release consisted of noble gases such as Xe, Kr, cesium and iodine, mainly in the form of aerosols. As half-life of ^{137}Cs is about 30 years and transported by the wind and finally deposited on the terrestrial land and ocean, we are highly concerned about this species. Although noble gases such as Xe and Kr were released more than in the Chernobyl accident, they would be fully dispersed into the atmosphere in the form of gas. To protect the public in the contaminated area, decontamination efforts for the soil and plant were carried out in a massive scale. In addition, foods are screened with proper regulatory limits to prevent consumption by the public.

Fortunately, no casualty due to radiation was reported. However, there were large numbers of casualties due to relocation-related stress in the Fukushima accident. The Fukushima mental health and lifestyle survey disclosed that the Fukushima accident caused severe psychological distress in the residents from evacuation zones [27]. The effects of a major nuclear accident on societies are diverse and enduring. One of important issue for the future would be the establishment of counter measures for the potential relocation due to major nuclear accidents. The countermeasures should include disaster management, long-term general public health services, mental and psychological care, behavioral and societal support, in addition to efforts to mitigate the health effects attributable to radiation [27].

After the Fukushima accident, IAEA compiled an effort to assess the safety of the FD-NPP in various aspect including relation to external events, failure to maintain fundamental safety function, treatment of beyond design basis accidents, accident management provisions and implementation, regulatory programs, human and organizational factor [28]. Song and Kim [29] also discussed the issues on the nuclear reactor safety raised by the Fukushima accident.

The safety of nuclear power plants has been significantly improved after the Fukushima accident on a global scale due to efforts such as the EU-stress test [30], new regulations adopted in Japan [5], strengthening of the mitigation features in the United States [4], such that that we can claim that the current fleet of nuclear power plants is at least better than before. However, the comment from the director general of IAEA on the nature of Fukushima accident [31] below gives us a warning. "A major factor that contributed to the accident was the widespread assumption in Japan that its nuclear power plants were safe that an accident of this magnitude was simply unthinkable. This assumption was accepted by nuclear power plant operators and was not challenged by regulators or by the Government. As a result, Japan was not sufficiently prepared for a severe nuclear accident in March 2011."

The chance of a severe accident accompanying large release of radionuclides cannot be denied, although the probability of occurrence is low. However, the consequences would be limited by new engineering safety features imposed after the Fukushima accident in many countries. It is fair to say that there is a possibility of nuclear accident with large radiological releases but with limited casualties due to radiation. New regulations for a severe accident adopted in global nuclear community allows only a fractional amount of radiological releases at low probability. However, as there are uncertainties in the modeling of severe accident phenomena, the limits of 100 TBq of ^{137}Cs and the frequency [5] had to be properly estimated with proper confidence levels, considering the uncertainties. As there has been little practice in the new regulatory frame yet, extensive efforts need to be pushed to guarantee the safety of the nuclear power plant.

4. Dispute on the Safety of Fishery Products

The impact on the health of the population by consumption of fishes caught near the Fukushima and open sea were of interest among international community. For food consumption and trade, there is an international guideline on the concentration limit of radionuclides in foods. The joint WHO/FAO Codex Alimentarius Commission [32] was in place reflecting the knowledge gained after the Chernobyl accident. The limits on 20 radionuclides are set based on a reference level of 1 mSv/year with an assumption that 550 kg of food is consumed per year with 10% of the food supply being contaminated. This

is consistent with the exposure limit for the general public at 1 mSv/y above background set by the International Commission on Radiological Protection. Natural and man-made radiation may derive from different sources, but both affect us in the same way.

On 17 March 2011, the Ministry of Health, Labor and Welfare (MHLW) of Japan established a provisional regulation level for the radionuclides in the food to consider the consequence of Fukushima accident [33]. Soon after, on 1 April 2012, the standard was revised, where a maximum limit of 100 Bq/kg was established for radiocesium in general foods, revising the previous value of 500 Bq/kg [33,34]. It is equivalent to not exceeding a committed effective dose of 1 mSv/year.

Because of concerns from the public about the unprecedented large radiological releases to the ocean from the Fukushima accident, where significant amounts of direct release of contaminated water was reported [1,35,36], imports of fishery products were restricted in certain countries directly after the Fukushima accident. Until the year 2019, 23 countries continued to restrict imports of Japanese fishery products [37].

Meanwhile, there were efforts to estimate the risk of sea food consumption on health, although there were limited data on the radioactivity concentration of various radionuclides in the sea, seabed, and marine biota. Povinec and Hoirose [38] reported the total effective dose commitment from ingestion of radionuclides in fish, shellfish and seaweed caught in coastal waters off Fukushima. It was estimated to be 0.6 ± 0.4 mSv/y. The individual effective dose commitment from consumption of radioactive-contaminated fish caught in the open Pacific Ocean was estimated to be much lower 0.07 ± 0.05 mSv/y [38]. Mathew. P. Johansen also [39] reported similar results.

There are huge numbers of samples for inspecting Cs by Fishery Agency of Japan [40]. However, there has been less than 100 samples of fish inspected for other radionuclides such as Sr and Pu until year 2015 [40]. It was mainly due to the difficulty of inspecting beta emitters. Considering the fact that significant amount of Sr was released directly into the ocean and the potential for the release of other radionuclides, more samples of fish should have been taken for inspection of Sr and other radionuclides.

The import ban on fishery products imposed by Korea was strict. Then, Japan initiated a trade complaint at the World Trade Organization (WTO) in 2015, arguing that radioactive levels for the food were safe with guideline levels of 100 Bq only for cesium; however, Korea's measure is without scientific basis. Japan challenged these measures as more restrictive than necessary under the Sanitary and Phytosanitary Measures (SPS Agreement).

The WTO panel agreed with Japan in year 2018, but this ruling was largely reversed by the Appellate Body in year 2019. The panel accepted Korea's appropriate level of protection (ALOP), which included both quantitative and qualitative elements. However, the Appellate Body found that the panel only addressed the quantitative aspect of Korea's ALOP and reversed decision on that basis. South Korea claimed that the environment where the fish Japan exports inhabit should be taken into consideration in evaluating ALOP, and the appellant body deemed that the lower panel failed to discuss the matter sufficiently [37].

Article 5.33 of the report of Appellate Body [41] stated "having accepted Korea's formulation of its ALOP, it was incumbent on the Panel to assess whether the alternative measure proposed by Japan, namely, testing whether the cesium content of food products exceeds 100 Bq/kg, would achieve Korea's ALOP by maintaining levels of radioactivity that exist in the ordinary environment, and as low as reasonably achievable, below the 1 mSv/year radiation dose limit. The Panel, however, did not explicitly integrate the various elements of Korea's ALOP to account for all of these elements in assessing the level of protection that would be achieved by Japan's alternative measure . . . the Panel did not consider all relevant conditions, including territorial conditions with potential to affect products that have not manifested in products but "are relevant in light of the regulatory objective and specific SPS risk at issue". Consequently, the Panel erred by focusing on product test data to the exclusion of territorial conditions that could differently affect the potential for contamination.

The decision from the WTO reflects the view of the public, who have interest in both quantitative and qualitative ALOP.

5. Discharge of Radioactive Water to the Ocean

Figure 1 illustrates the conceptual picture of the current state of the Fukushima Daiich Nuclear Reactor Units 1, 2 and 3. With various efforts to isolate the plant from the ground water, it was not successful that more than 100 tons of ground water is flown into the plant every day. Because of the need for cooling the damage core fuel to remove decay heat, more than 100 tons of water is also being fed into the reactor vessel every day since the accident. This configuration resulted in a large amount of contaminated water being accumulated at the Fukushima Daiich nuclear power plant site [42,43] during the last 10 years.

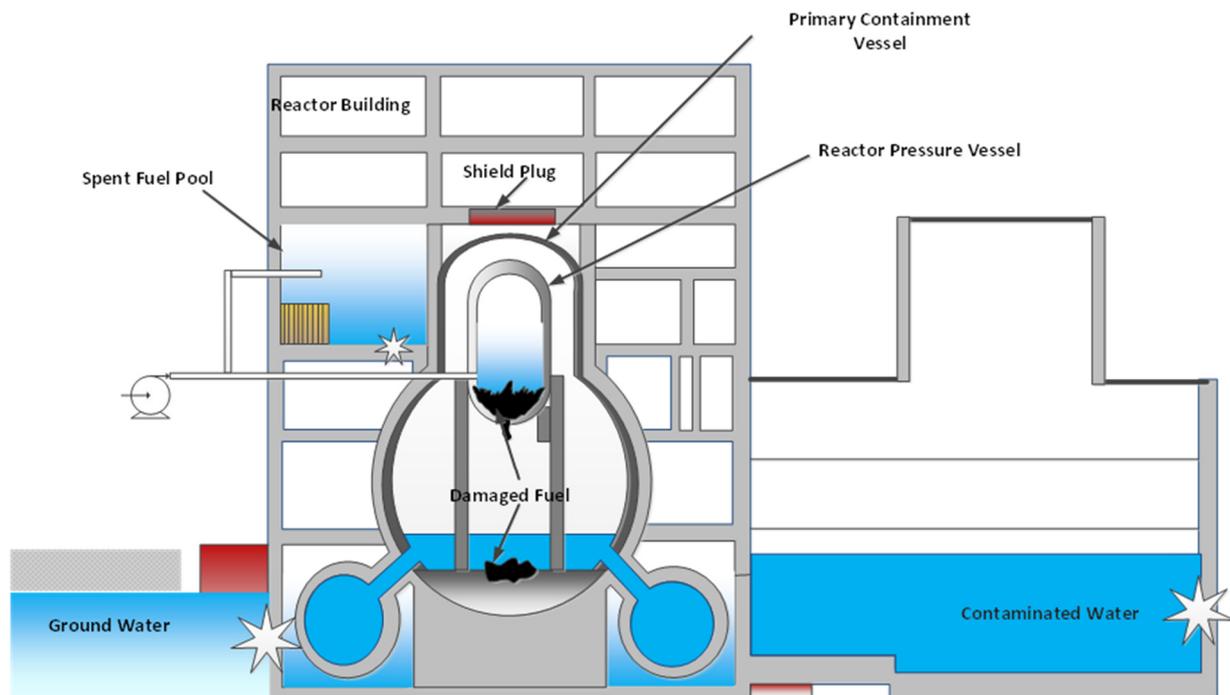


Figure 1. Current state of the Fukushima Dai ich nuclear reactor units 1, 2 and 3.

A significant amount of radionuclides is continuously dissolved into the coolant. As this situation was not experienced in previous nuclear accidents, the type and amount of radionuclides released to the water could not be properly predicted [44]. The radionuclides in the contaminated water was removed by an ALPS (advanced liquid processing system), which targeted to removed 62 radionuclides. It was intended that the processed water should contain radionuclides below the legal discharge limit [43]. The treated water exiting the ALPS was accumulated at the site, which reached 1,000,000 tons in year 2021 and occupied a large space. The worry about the accidental releases of the treated water due to natural disaster and need to establish space for upcoming decommissioning work, Japanese government announced a plan to discharge the water into the ocean [43]. It was faced with an objection from the people living near Fukushima and neighboring countries such as Korea and China [45].

Major concern was for the danger of radioactive water on the contamination of fisheries and marine ecosystem [46]. As admitted in the report from the Japanese government [43], the release plan had issues for public concern. About 70% of tanks contained radionuclides above the legal discharge limit in which Japan must treat the contaminated water before discharge. The reason for having a concentration above discharge limit could be either due to malfunction of ALPS or intrinsic functional problems of ALPS. In addition, they had to dilute the water to reduce the concentration of tritium, which cannot be

removed by ALPS. The bottom line of the Japanese argument is that a planned amount of annual discharge of radionuclides is below the current annual discharges from the operating reactors worldwide [43].

However, there are issues to consider in this argument. The planned discharge for the coming 30 years is about 30,000 ton per year, while the accumulation of treated water is also about 30,000 ton per year [43]. This means that the amount of contaminated water storage at the site would not decrease after the liquid discharge into the ocean. Unless the Japanese government purified 70% of contaminated water soon, the danger of accidental release does not decrease. However, the Japanese government did not initiate a massive purification process yet. The other point is inadequate consideration of delay in decommissioning process. Recently, the NRA approved the decommissioning plan for the Fukushima Daiichi plant taking 40 years [47]. Considering that Daiichi plant did not experience a severe accident, the decommissioning process for Fukushima Daiichi will take a longer time than Daiichi plant. The recent finding of huge amount of cesium under the shield plug, resulting in a high dose rate inadequate for the operators to work, would cause significant delays in the decommissioning process [48]. Therefore, there is an additional concern for the accumulation of contaminated water beyond 30 years.

The yearly discharge of the treated water at a concentration below the discharge limit would be acceptable in the regulatory point of view. However, there is still a big uncertainty on the effects of long durations of the release of treated water on the impact on the marine eco-system, which should be carefully investigated [46]. If there are other better methods than the discharge to the sea, it should be investigated further. It has to be remembered that selecting the discharge to sea option was based on the cost–benefit aspect. The economic gain using this option has to be compensated by the efforts to preserve precious marine eco-system, which has important value not only for the public but also for the scientist.

6. Status of Decommissioning

In 2011, the Japanese government announced a decommissioning plan for the Fukushima Daiichi nuclear power plant [49]. It mainly consists of (1) efforts for maintaining plant in an ongoing stable state, (2) a plan to reduce radioactive dosage in the power station as a whole and to mitigate sea water contamination, (3) a plan for fuel removal from the spent fuel pool, (4) a fuel debris removal plan, and (5) a plan for disassembly of reactor facilities and processing and disposal of radioactive waste. Tasks (1) and (2) are in good progress, which can be checked from the website of TEPCO (<https://www.tepco.co.jp/en/hd/decommission/progress/about/index-e.html>, accessed on 29 September 2021). Figure 2 shows the picture of unit 3 at the time of the accident and current shape. A cover is placed on the reactor building, and construction of various structures for the decommissioning is in place.

On 27 December of 2019, the Japanese government revised the road map for decommissioning [50], which is the fifth revision of the roadmap. Fuel removal from units 1 and 2 is postponed by up to ten years from the initial target of 2018, with further preparation needed to reduce radiation and clear debris and other risks. Fuel rod removal at the Fukushima Daiichi unit 1 reactor pool will begin sometime in 2027–2028, after debris is cleared away and a rooftop cover installed to contain radioactive dust. Fuel removal from the unit 2 pool is to begin in 2024–2026. Work at the unit 3 reactor pool began in April 2019 and all 566 assemblies will be removed by March 2021 [50,51].

There are new technical problems, which were not experienced in the TMI and Chernobyl, such as treating the contaminated water and removal of fuel debris from the damaged plant. As the problem of contaminated water was discussed above, we discuss the removal of fuel debris.

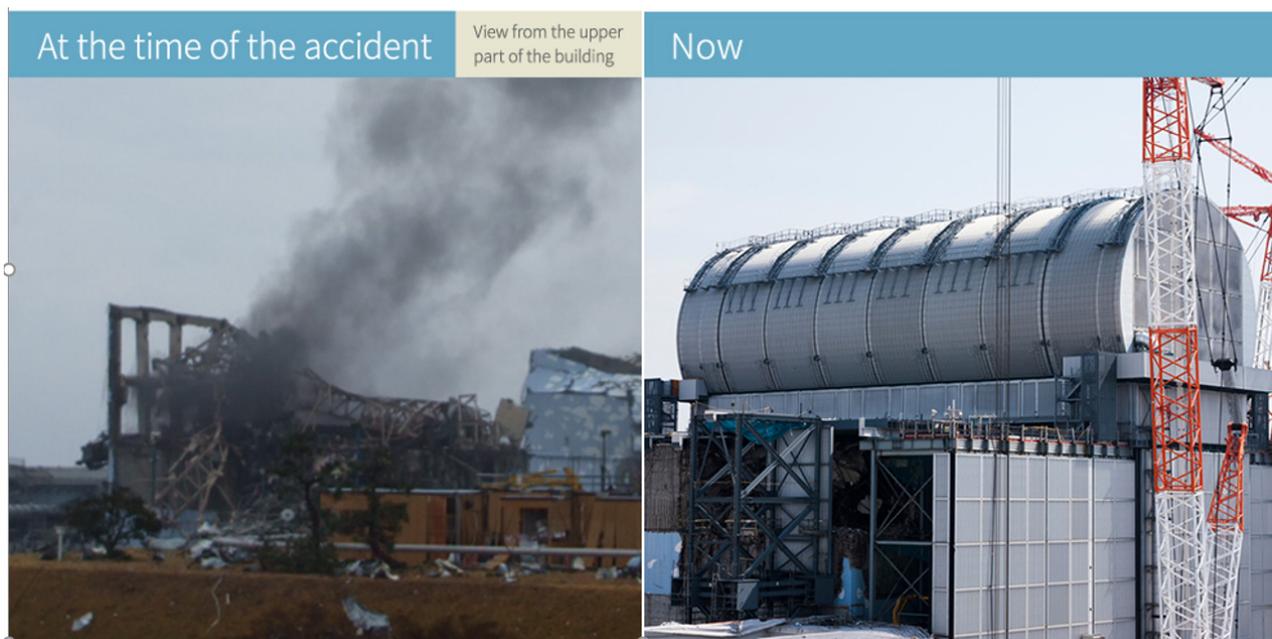


Figure 2. Status of decommissioning in Unit 3 (<https://www.tepco.co.jp/en/hd/decommission/progress/about/index-e.html>, accessed on 29 September 2021, Courtesy of TEPCO).

The most difficult task is removal of about 900 tons of fuel debris (nuclear fuels in the core damaged, initially molten and solidified later) from the three reactors. Information on the morphology and composition of fuel debris is important for the decommissioning process. Recently, the OECD/NEA project of the Preparatory Study on Analysis of Fuel Debris (PreADES) was launched. As part of the PreADES Tasks, relevant information such as experiences from the TMI and Chernobyl and sim-corium experiment were reviewed to provide graphical depictions of the debris end states at the damaged Daiichi units, which will provide a basis for suggesting future debris examinations [52]. However, as actual removal of fuel debris from the Fukushima site is only at small scale until year 2021, the information on the morphology and composition of fuel debris is little. In addition, the amount of fuel debris is much more than the amount dealt with in the decommissioning process for TMI and Chernobyl site.

Removal of fuel debris is scheduled to begin in 2021 at Fukushima Daiichi unit 2, where robotic probes have made progress. However, the robot has limited operability due to high radiation damage of the electronics. The removal of melted fuel was only a small amount suitable for physical and chemical analysis. The Japanese government hopes to gradually expand the scale of the removal to an engineering scale, which would require a significant amount of engineering development. The next decade is expected to be crucial for future progress [51].

Finally, there is a problem of waste management. There will be about 770,000 tons of solid radioactive waste by 2030 [51]. This will include contaminated debris and soil, sludge from water treatment, scrapped tanks and other waste. It will need to be sorted, treated and compacted for safe storage. The amount of radionuclides in the waste has to be assessed for nuclear waste management. Shibata et al. [53] estimated the radionuclide inventories in the secondary wastes from the water treatment system, the inventories remained in the reactors, and initial inventory in the core as shown in Table 1. The amount is the sum of radionuclides in the three reactors. The secondary waste mainly came from the water treatment system such as ALPS. The radionuclides can present in the reactor in the form of fuel debris and nuclide aerosols stuck on the reactor components and structures.

Table 1. Distribution of radionuclide inventory as of 13 March 2014 (unit Bq) [53].

Nuclides	Initial Inventory	Release to Atmosphere	Secondary Waste	Remained in the Reactors
⁵⁴ Mn	2.5×10^{13}	-	9.3×10^{11}	2.4×10^{13}
⁶³ Ni	4.0×10^{13}	-	6.1×10^{11}	4.0×10^{13}
⁹⁰ Sr	4.9×10^{17}	1.3×10^{14}	1.2×10^{17}	3.7×10^{17}
¹⁰⁶ Ru	2.9×10^{17}	2.6×10^8	1.8×10^{12}	2.9×10^{17}
¹²⁹ I	2.1×10^{11}	5.7×10^9	2.0×10^{11}	2.7×10^9
¹³⁴ Cs	2.6×10^{17}	1.5×10^{16}	1.0×10^{17}	1.4×10^{17}
¹³⁷ Cs	6.5×10^{17}	3.3×10^{16}	2.3×10^{17}	3.9×10^{17}
²³⁸ Pu	4.5×10^{15}	1.9×10^{10}	2.4×10^9	4.5×10^{15}

The inventory of Cs in the secondary wastes was one-third of initial inventory (II) and half of II of Cs remained inside the reactors. A quarter of II of ⁹⁰Sr were in the secondary wastes, and three quarters of II of ⁹⁰Sr remained inside the reactors. The ¹²⁹I inventory in the secondary wastes reached 94% of II. Most of ¹⁰⁶Ru, ¹²⁵Sb, and ²³⁸Pu likely remained inside the reactors. It is remarkable that a significant amount of radionuclides much larger than the release to the atmosphere is present in the form of secondary waste. For example, about 1/3 of II of Cs, which is 10 times bigger than the release to the environment, has been discharged to the water treatment system in the form of secondary waste such as sludge and depositions on filters. They had to be stored and managed properly and this effort should be continued in coming decades before completion of decommissioning. As shown in Table 1, most of the radionuclides are residing in the reactor. It would be present mainly in the fuel debris. The continuous dissolution of various radionuclides into the cooling water resulting in an accumulation of contaminated water will continue. More importantly, safe removal and storage of fuel debris in a proper place is a big scientific and engineering task that has to be solved in next decade.

With all these issues to solve, the completion of decommissioning would continue beyond 30–40 years.

7. Needs for Lon Term Investigation

The Chernobyl and Fukushima accidents provide unique opportunities on the investigation of radiological consequences and radiation effects on environment in a large scale that cannot be observed in the laboratory. Research on the long-term effects of Fukushima accident need to be continued in a comprehensive manner.

The Nuclear Regulation Authority (NRA) reported that a huge amount of radioactive materials apparently had attached to shield plugs of the containment vessels in the unit 2 and unit 3 reactors [48,54]. A shield plug, made of reinforced concrete, is circular in shape and measures about 12 m in diameter. It has a triple-layer structure, with each layer about 60 cm thick. It is placed above the containment vessel like a lid on the top floor of a reactor building. The location of the shield plug is shown in Figure 1. The shield plug blocks radiation from the reactor core at normal times. When the nuclear fuels need to be replaced, workers remove a shield plug to gain access to the interior of the containment vessel. The location of shield plug can be seen from Figure 1. According to NRA investigation [54], the estimated amount of Cs deposited below the shield plug is 0.16, 70, and 30 PBq for units 1, 2, and 3 respectively.

The amount of deposited radionuclides below the shield plug for units 2 and 3 is much bigger than the release to the atmosphere predicted by the severe accident code on radiological releases [1,2,8], and the phenomenon of accumulation of huge amount of radionuclides under the plug was never predicted. This is a surprise in terms of the current capability of severe accident analysis methodology. In addition, there should have been direct release paths from the reactor vessel to the primary containment vessel bypassing the suppression chamber other than reactor vessel breach. As we can see from Figure 1, the radionuclides released from the core fuels can be released to the primary containment

vessel only through the breaches in the reactor vessel and connected piping and system especially before the reactor vessel failure. Potential breach locations could be on the main steam lines, but it is not identified yet. It is noted that the radionuclides can reach the shield plug only after the leakage of the primary containment vessel head flange. Thus, it could have happened during the period when the primary containment vessel is at high pressure and temperature.

This new finding may be a challenge for a severe accident progression modeling and investigations on the long-term radiological consequences. In addition, this huge amount of radionuclides under the shield plug will certainly impede the decommissioning progress because the high dose rate would allow a short time window for the decommissioning work by the people or robot.

Cesium-rich microparticles (CsMPs) were found in the soils in addition to soluble forms of Cs near the Fukushima nuclear power plant and at a 170 km distance [55]. As these types of CsMPs were never found in previous nuclear accidents, there were investigations on the chemical composition and structure, formation mechanism and abundance levels [55–57]. As CsMPs are insoluble form, their transport in soil, water, plants and animals if ingested would be quite different from soluble form of Cs, such as CsOH. In addition, the fraction of Cs transported in the form of CsMPs during the Fukushima accident progression is an important question to be investigated.

Most CsMPs (with sizes of 2.0–3.4 μm) comprise SiO_2 glass matrices and ~ 10 nm sized Zn–Fe-oxide nanoparticles associated with a wide range of Cs concentrations. It is suggested that the nano-texture in the CsMPs records multiple reaction process steps during a meltdown in a severe FDNPP accident: melted fuel (molten core)–concrete interactions (MCCIs), incorporating various airborne fission product nanoparticles, including CsOH and CsCl, proceeded via SiO_2 condensation over aggregates of Zn–Fe oxide nanoparticles originating from the failure of the reactor pressure vessels [56].

Spatial distribution of the numbers (particles/g) and radioactive fraction (RF) of the CsMPs in surface soil, which is defined as the sum of the CsMPs radioactivity (in Bq) divided by the total radioactivity (in Bq) of the soil sample were reported [57]. Three regions of particular interest have been identified, where the number and RF of CsMPs were determined to be 22.1~101 particles/g and 15.4~34.0%, 24.3~64.8 particles/g and 36.7~37.4%, and 0.869~8.00 particles/g and 27.6~80.2%. These distributions seem to reflect the plume trajectories of material released from the FDNPP [57].

As surface soil was removed in most of the contaminated region for the decontamination, it would be rather difficult to thoroughly investigate the abundance of CsMPs. However, proper attentions need to be paid to answer the question of the contribution of CsMPs among total Cs release and their transport mechanism in the environment and health effect due to ingestion and/or inhalation, as Cs is the major radionuclides affecting the environmental contamination.

After the Chernobyl Nuclear Power Plant accident, researchers reported that game animals were contaminated. Gulakov et al. [58] reported that the average concentration of ^{137}Cs in the muscle tissue of wild boars remained as high as 37,000 Bq/kg, even at 22 years after the accident. Recently, the cesium in muscle samples were measured for the wild boars captured in Tomioka town located within 20 km of the FDNPP [59]. The results showed that 210 (98.6%) muscle samples exceeded the regulatory cesium limit (100 Bq/kg). Cesium levels ranged from 87.1–8120 Bq/kg fresh mass. In addition, a study was conducted to present a direct comparison of cesium concentrations in marine and freshwater fish inhabiting different water bodies in the Fukushima Prefecture, and to reveal plausible contamination mechanisms for each habitat [60,61]. The research showed that in contrast to marine demersal fish, which showed lower and less variable Cesium concentrations, freshwater fish showed higher and more site-specific variations for each species and habitat in 2015–2016.

The effective dose by unexpected consuming of wild boar meat or freshwater fishes would be negligible compared to 1 mSv/yr. However, these two findings clearly demon-

strate that comprehensive long-term monitoring is needed at least in the evacuation zone to identify risk factors affecting recovery from a nuclear disaster.

8. Summary and Conclusions

The issues related to the consequences of the Fukushima accident raised during the last 10 years are discussed. The topics include severe accident analysis methodology, views on nuclear reactor safety, dispute on the safety of fishery products, discharge of radioactive water to the ocean, status of decommissioning, and needs for long-term monitoring of the environment. Each topic was discussed with a broader view from both the expert and the public.

Severe accident analysis methodology: The accident progression and radiological releases analyses for the Fukushima accident had to be performed in a forensic nature with uncertainties including the functions of plant components at off design condition, uncertainties in the physical modeling, and incomplete weather data. A systematic and rigorous approach for handling the uncertainties in the phenomenological and physical modellings of severe accident progression is needed in the new regulatory frame to increase the confidence and accuracy.

Views on nuclear reactor safety: The safety of the nuclear power plant has been significantly improved after the Fukushima accident in a global scale that we can claim that the current fleet of nuclear power plants is at least better than before. Still, there is a chance of severe accident accompanying a large release of radionuclides, although the probability of occurrence is low. New regulations for a severe accident adopted in global nuclear community allows only fractional amounts of radiological releases at low probability compared to that of the Fukushima accident.

Safety of fishery products: Because of concerns from the public about the unprecedented large radiological releases to the ocean from the Fukushima accident, imports of fishery products were restricted in certain countries directly after the Fukushima accident. Because of the ban imposed by Korea, Japan initiated a trade complaint at the World Trade Organization (WTO) in 2015, arguing that radioactive levels were safe with guideline level of 100 Bq only for cesium and Korea's measure is without scientific basis. The panel agreed with Japan in year 2018, but this ruling was largely reversed by the Appellate Body in year 2019. The Appellate Body found that the panel only addressed the quantitative aspect of Korea's ALOP and reversed decision on that basis. The decision from the WTO reflects the view of the public, who have interest in both quantitative and qualitative ALOP.

Discharge of radioactive water: A large amount of contaminated water had to be accumulated at the Fukushima Daiich nuclear power plant site during last 10 years, including with various efforts to isolate the damaged plant from the ground water. The radionuclides in the contaminated water have been removed by ALPS (advanced liquid processing system). The treated water was accumulated at the site, which reached 1,000,000 tons and occupied a large space. A plan to discharge the water into the ocean was faced with an objection from the people living near Fukushima and neighboring countries. The yearly discharge of the radioactive water below the discharge limit is claimed to be acceptable in the regulatory and expert point of view. However, the effect of a long duration of release of treated water on the impact on the marine eco-system is a big concern from the public.

Status of decommissioning: On 27 December 2019, the Japanese government announced its fifth revision of the road map for decommissioning. Fuel removal from units 1 and 2 is now postponed by up to ten years from the initial target of 2018. The most difficult task is removal of about 900 tons of fuel debris from the three reactors. Removal of fuel debris is scheduled to begin in 2021 at Fukushima Daiichi unit 2, in small amounts, for physical and chemical analysis. The Japanese government hopes to gradually expand the scale of the removal to an engineering scale. The next decade is expected to be crucial to future progress. A significant amount of radionuclides much larger than the release to the atmosphere is present in the form of secondary waste. They had to be stored and managed properly and this effort should be continued in coming decades before completion of

decommissioning. Novel technical problems faced in the Fukushima decommissioning efforts are expected to cause a significant delay.

Needs for long-term investigation: (1) A huge amount of radionuclides recently found under the shield plug is expected to impede the decommissioning progress because the high dose rate would allow a short time window for the decommissioning work by the people or robot. (2) Cesium-rich microparticles (CsMPs) were found in the soils in addition to soluble form of Cs. As CsMPs are insoluble form, their transport in the soils, water, plant and animals, if ingested, would be different from soluble forms of Cs; the fraction of Cs transported in the form of CsMPs during the Fukushima accident progression is an important question to be investigated further. (3) In a large fraction of samples of the meat of wild boars living in Tomioka town, cesium above the legal limit was observed. In addition, a study on a direct comparison of cesium concentrations in marine and freshwater fish showed that freshwater fish showed higher cesium concentration above legal limit. These findings clearly demonstrate that a comprehensive long-term investigation is needed for the damaged nuclear power plants and for the environment, at least in the evacuation zone, to identify risk factors affecting recovery from a nuclear disaster.

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