Accident Progressions and Radiological Releases in the Fukushima Accident

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1. Introduction

Even six years after the accident, the status of damaged core in the Fukushima Daiich Nuclear Power Plant (FDNPP) is still unknown. It would take another 20-30 years for the decommissioning of the nuclear power plant. Recent investigations indicated that the reactor vessels of unit 1, 2, and 3 were breached and damaged fuel debris were located both in the reactor and in the Primary Containment Vessel (PCV) [1, 2, 3]. Forensic analyses by severe accident computer codes and results of investigations including the use of robots and muon rays revealed the damage status of the plant [4,5]. Radiological consequences of the Fukushima accident have been investigated by both forward method predicted by the severe accident analysis code and inverse method based on the terrestrial and oceanic measurements of the concentrations of radio-isotopes coupled with transport analysis supported by weather data and oceanic current data [4,6].

2. Accident Progressions and Radiological Releases

Compared to the previous severe accidents of TMI and Chernobyl, more systematic investigations has been made. Knowledges on the accident progressions and radiological releases in the accidents at FDNPP enables us to better understand the severe accident phenomenology and environmental impact.

2.1 Accident Progressions

The reactors in the FDNPP are boiling water reactors, whose typical configuration can be seen in Fig.1. The nuclear fuels in the core are heated up accompanying the oxidation of cladding and hydrogen generation, and finally molten during the progression of the severe accident due to a depletion of coolant in the reactor vessel. The depletion of coolant in the FDNPP was caused by a complete loss of safety systems due to a complete loss of electric power, which was resulted from an unprecedented tsunami subsequent to an earthquake [7]. Though the accident progressions in units 1, 2, and 3 of FDNPP were different, they all resulted in a melting of substantial amount of fuels in the core. The damages of nuclear fuel occurred within 1 – 3 days after the initiation of the accident in the FDNPP.

The damage was more significant than expected that the core was molten and it attacked the reactor vessel. Therefore, the damaged fuel debris are located both inside the reactor and in the floor of the Primary Containment Vessel (PCV) in all units of 1, 2, and 3.

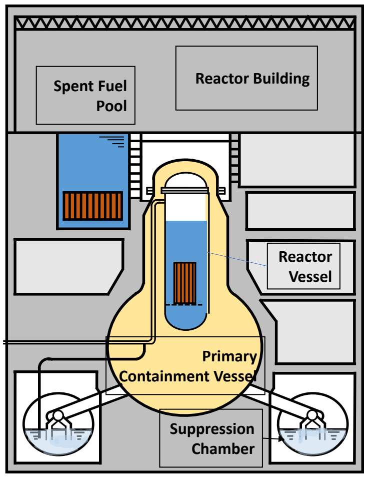
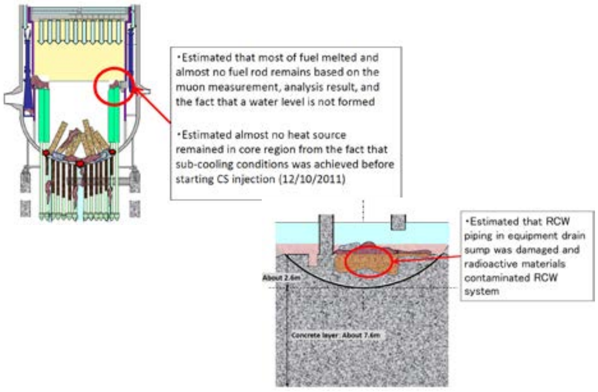


Fig. 1. A typical configuration of a BWR

Recent investigations enabled to sketch conceptual pictures of the core melt progression as shown in Figures 2, 3, and 4. The locations of fuel debris investigated by muon rays indicated that most of molten fuel was relocated outside of the reactor vessel in cases of unit 1 and 3, while some of the fuels are inside the reactor vessel in case of unit 2.



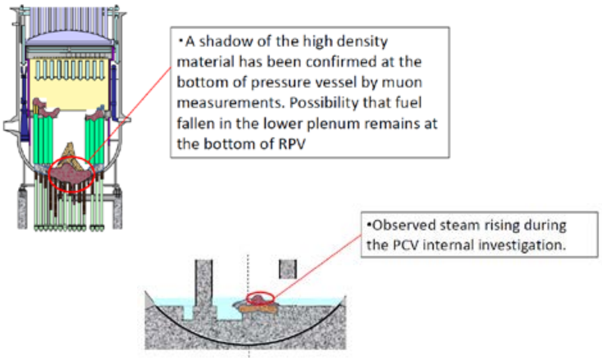
- Estimated that most of fuel melted and almost no fuel rod remains based on the muon measurement, analysis result, and the fact that a water level is not formed

- Estimated almost no heat source remained in core region from the fact that sub-cooling conditions was achieved before starting CS injection (12/10/2011)

- Estimated that RCW piping in equipment drain sump was damaged and radioactive materials contaminated RCW system

Fig. 2. Conceptual picture of core damage in Unit 1 [1]

In case of unit 1, most of the fuels in the core is molten and it resulted in a failure of the reactor vessel and relocation of molten core material into the pedestal area of PCV. Due to the molten core concrete interaction, it is suspected that the liner of PCV is damaged due to an ablation of concrete by the molten core [1].

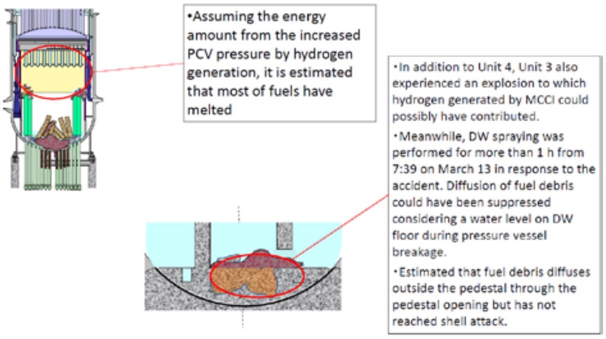


•A shadow of the high density material has been confirmed at the bottom of pressure vessel by muon measurements. Possibility that fuel fallen in the lower plenum remains at the bottom of RPV

•Observed steam rising during the PCV internal investigation.

Fig. 3. Conceptual picture of core damage in Unit 2 [2]

In case of unit 2, damages to the core was minimal among three units. Investigations by muon cosmic ray indicated that significant amount of fuel is located in the lower part of the reactor vessel [2].



•Assuming the energy amount from the increased PCV pressure by hydrogen generation, it is estimated that most of fuels have melted

•In addition to Unit 4, Unit 3 also experienced an explosion to which hydrogen generated by MCCI could possibly have contributed.

•Meanwhile, DW spraying was performed for more than 1 h from 7:39 on March 13 in response to the accident. Diffusion of fuel debris could have been suppressed considering a water level on DW floor during pressure vessel breakage.

•Estimated that fuel debris diffuses outside the pedestal through the pedestal opening but has not reached shell attack.

Fig. 4. Conceptual picture of core damage in Unit 3 [3]

In case of unit 3 as it resulted in a hydrogen explosion both in unit 3 and unit 4, it is believed that there were significant amount of molten core concrete interaction which generated substantial amount of combustible gas including hydrogen and carbon mono-oxide in addition to the hydrogen generation caused by an oxidation of claddings of nuclear fuels [3].

The analyses of accident progressions among different computer codes and different institution show wide variations due to the differences in the modeling of severe accident phenomenology and use of different boundary conditions. As an example, the amount of hydrogen generation and temperature of steam were totally different among different computer codes [4]. Also, it has to be noted that a use of different boundary conditions was inevitable since there are still uncertainties in the amount of water injection, operator actions, and amount of damages to the PCV and reactor vessel, which would determine the size of vent area [4].

Investigations by Japanese government are still going on and planned for the FDNPP [8] that accident progressions in the FDNPP will be understood more clearly. Correct understanding of severe accident progressions would certainly contribute to the strengthening of the nuclear reactor safety against the unexpected severe accident.

2.2 Radiological Releases

The radiological releases from the damaged fuel to the atmosphere and into the cooling water in case of FDNPP has been analyzed by many investigators [9, 10, 11, 12]. While atmospheric releases mostly occurred during the first week of the accident, continuous releases of radionuclides from the damaged fuel into the cooling has led to an accumulation of contaminated water in the PCV and turbine building during last six years. The conceptual pictures of release paths to the atmosphere and to the ocean are illustrated in Figs. 5 and 6.

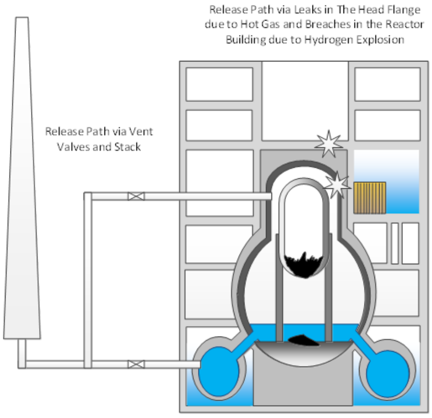


Fig. 5 Paths for the atmospheric release

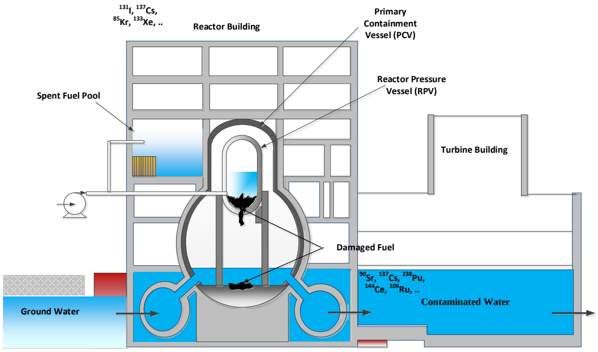


Fig. 6 Releases of radiological materials in the form of contaminated water

It can be seen that volatile FPs such as Cs and Iodine and noble gases were mainly released to the atmosphere. Terrestrial measurements indicate that atmospheric releases of volatile and less volatile Fission Products (FPs) in the FDNPP were much smaller than those of Chernobyl accident as indicated in Fig.7.

Long lived FPs and actinides are of concern for the release into the cooling water, because we have to remove and manage those radioactive materials. Fig. 6 indicates that there are release paths for those isotopes from the damaged fuel into the ocean and ground through the leaks generated during the earthquake and subsequent damages.

An analysis of contaminated water indicated that there has been a significant release of radionuclides of long half-life and low volatile fission products from the damaged fuel into the cooling water. It was pointed out that the amount of dissolution of cesium into the water is equivalent to 34% of the initial inventory while the amount of cesium released to the atmosphere is about 2% of initial inventory in the fuel of FDNPP's three reactors [10]. This observation clearly indicates that the release mechanism for radionuclides from the cold damaged fuel into the water was quite different from that of the atmospheric release.

It was found that there were periods of higher ^{90}Sr radioactivity concentrations than that of ^{137}Cs in the water samples taken from the ocean near the FDNPP. Considering the observation that the radioactivity concentration of ^{90}Sr was 10 times higher than that of ^{137}Cs in the contaminated water, it is suggested that contaminated water has leaked into the ocean [11].

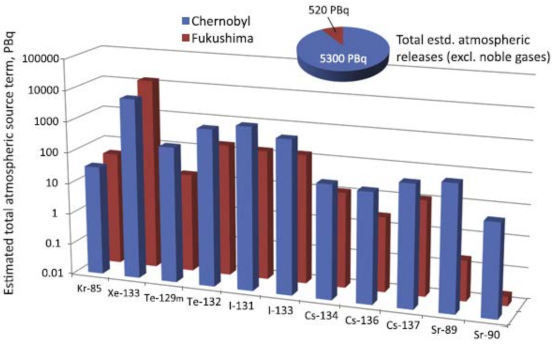


Fig. 7 Comparison of Atmospheric releases [9]

3. Conclusions

Investigations on the accident progressions and radiological releases from the FDNPP during last six years enabled us to draw a conceptual picture of the accident progressions, though decommissioning of the plants would take another decades. The amount of core damage was more substantial than expected that the reactor vessels were damaged for all units of 1, 2, and 3. In case of unit 1 and 3, it is suspected that there were significant amount of molten core concrete interaction. The atmospheric releases of FPs were much smaller than those of Chernobyl. On the other hand, the amount of releases into the cooling water, which has been injected into the reactor to remove decay heat during last six years, was substantial that about 34% of initial inventory of ^{137}Cs was released into the cooling water. The observation that there were periods of higher ^{90}Sr radioactivity concentrations than that of ^{137}Cs in the water samples taken from the ocean near the FDNPP, it is suggested that contaminated water has leaked into the ocean. This aspect calls for an attention on the proper management of contaminated water during the decommissioning process in coming decades.

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