The Fukushima Accident – Past, Present, and Future

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1. Introduction

The accident at the Fukushima Dai ich Nuclear Power Plant (FDNPP) in 2011 resulted in a melting of core fuels, reactor vessel failure and significant amount of radiological releases to the environment. It took several years to start investigations in the Primary Containment Vessel (PCV) area. Still, there is no direct information on the locations of reactor vessel failure and fuel debris. It is expected that it will require another 30-40 years for the decontamination and decommissioning of the FDNPP.

This paper introduces status and outcome of domestic and international collaborations for the better understanding of accident progressions in the FDNPP and for the decontamination and decommissioning efforts for the damaged reactors. Also, technical issues raised during last 9 years are discussed to forecast the future of the FDNPP.

2. Analyses and Reviews of Current Progress

2.1 Understanding of Severe Accident Progression

There has been an OECD/NEA project of BSAF [1] for better understanding of accident progressions in the FDNPP accident. As exact initial and boundary conditions of accident in unit 1, 2, and 3 of FDNPP were not identified, the efforts were forensic nature that the analyses were designed not only to predict the core melt progression and radiological releases but also to investigate the probable scenarios. Here, investigations on unit 2 are explained as an example.

In unit 2, reactor core isolation condenser (RCIC) were operated and effective in removing the decay heat during almost 3 days that it delayed fuel damage. The importance of safety system using the steam driven turbine as RCIC in the case of station black out condition was highlighted. Since APR1400 employed turbine driven auxiliary feed water system, this safety system is expected to be effective in removing the decay heat during the station black out accident.

Fig. 1 shows a comparison of reactor pressure vessel (RPV) pressure calculated MELCOR code and measured data [2] during 5 days. Yet, it was difficult to estimate the status of the molten core in the RPV and possibility of reactor vessel failure by the computer codes as plant data such as water injection rate to the RPV was uncertain. A measurement on the status of molten core was made by using cosmic rays of muon. It was shown that for the unit 1, reactor core was empty that all the molten core was judged to be discharged outside the reactor vessel and relocated in the pedestal floor area of PCV. In the case of Unit 2, some of the molten core is still in the reactor vessel.

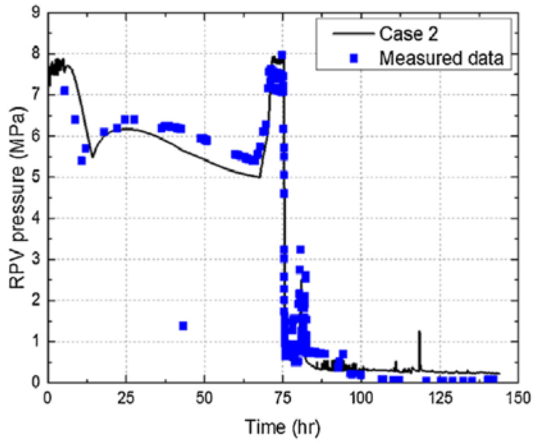

Fig.1 RPV pressure for FDNPP unit 1 [2]

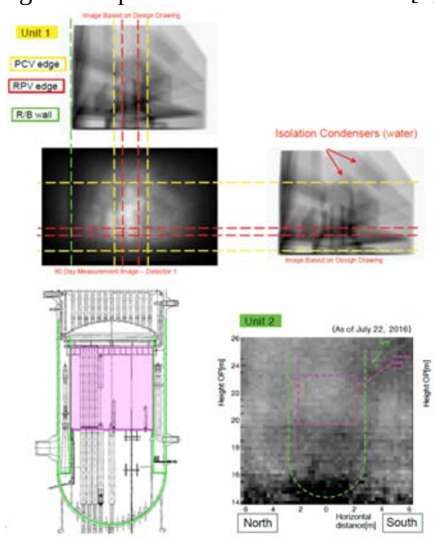

Fig.2 Status of Molten Core for unit 1 and 2[3]

By combining the results of computer code predictions and measurement data such as muon image, it was possible to estimate the status of reactor vessel, fuel debris and PCV. Fig.3 shows a conceptual picture end state of unit 2 [1].

Also, radiological releases were calculated and compared with the measurement data for each unit.

Fig.4 illustrate distribution of Cs in the major components and environmental releases in unit 1 [4].

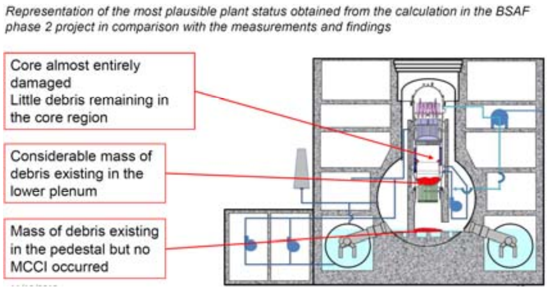

Fig.3 End state of FDNPP unit 2 [1]

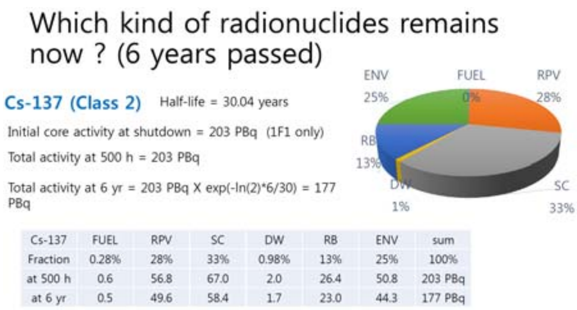

Fig.4 Distribuition of Cs in unit 1

2.2 Radiological Releases

The radiological releases to the atmosphere and ocean were of interest for the public safety including the food consumption and environmental contamination. Atmospheric radiological releases for the FDNPP is compared with those of Chernobyl in Table 1. It is shown that the releases from the FDNPP is much smaller than those of Chernobyl except the noble gases.

Table 1. Radiological Releases from the FDNPP [5]

Radionuclides		FDNPP		Chernobyl	
		Release	Initial Inventory	Release	Initial Inventory
Noble gas	^{133}Xe	6000 - 12000	12100	6500	7300
	^{85}Kr	6.4 – 32.6	83.7	33	33
Volatile FPs	^{137}Cs	7- 20	700	~85	290
	^{131}I	100 - 400	6020	~1760	3100
Low volatile FPs	^{90}Sr	3.3 x 10^{-3} – 0.14	522	~10	200
	^{106}Ru	2.1 x 10^{-6}	2240	> 73	2000
	^{140}Ba	1.1 - 20	11200	240	5300
Others	^{144}Ce	0.011	5920	~50	3300
	^{238}Pu	2.4 x 10^{-6} – 1.9 x 10^{-5}	14.7	0.015	1.00
	^{241}Pu	3.3 x 10^{-7} – 1.2 x 10^{-3}	819	~ 2.6	170

FDNPP accident is unique in terms of release to the water. Most of the species including Cs, I, Sr, actinides were released to the water which was injected into the reactor core in 100 tons/day since 2011. Conceptual picture of release pathways to the contaminated water is shown in Fig.5. Due to the underground water, the huge amount of contaminated water had to be stored at the site, some of contaminated water from which only Cesium was removed during first years, was stored at the site. And some of the contaminated water was leaked into the ocean resulting in an issue of fish consumption.

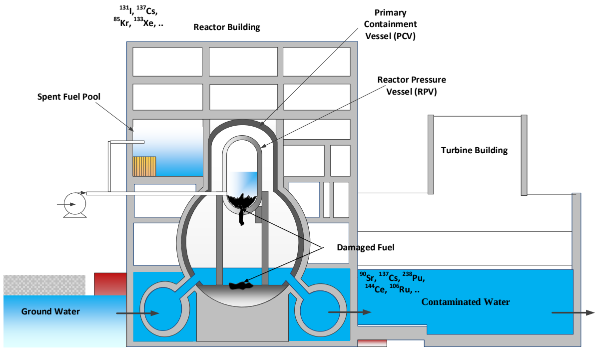

Fig. 5. Release pathways to the contaminated water.

2.3 Status of Decommissioning Effort

Due to the high radiation, workers and robots had only limited access to the plant that removal of first fuel debris would start after 3-4 years.

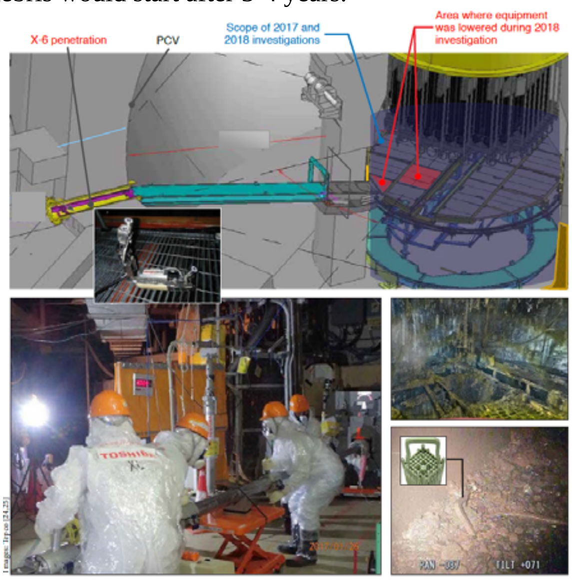

Fig. 6. Access to the PCV

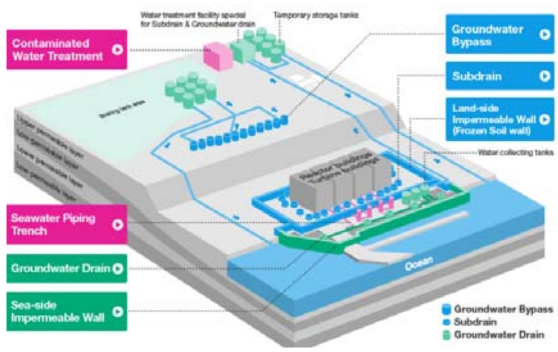

Fig.7 Measures for the isolation of contaminated water

In years 2018, only limited access to the PCV was possible as shown in Fig.6. Still it was not possible to determine the locations of reactor vessel failure and fuel debris. One of the main problem is isolating the contaminated water. The measures taken for the isolation of contaminated water is shown in Fig.7.

2.4 OECD/NEA Fukushima projects

There are OECD/NEA projects related to the FDNPP. The first one was BSAF, which was carried out during 2012-2018 to simulate the core melt progression and radiological releases in the FDNPP. The project indicated that current computer codes are able to predict the FDNPP scenarios. Different modeling employed in different code resulted in a variation of predictions, such as amount of hydrogen generation, and molten core material and radiological consequences. Using code predictions and recent measurement data, it was possible to determine the end state of each unit.

TCOFF project is being carried out during 2017 – 2019 to determine the thermodynamic equilibrium phases for the molten corium and fission products. Cesium rich micro balls and effect of B_4C control rod material on the accident progression was of interest. KAERI was active in the project by providing the results of FDNPP specific corium experiments, which gave an insight for the morphology of corium in the RPV and PCV. Fig.8 shows that corium at FDNPP specific composition can results in a stratified corium layer, where upper layer is rich in metal and lower layer was rich in oxide [6]. Equilibrium phases for the corium is important bot in the aspect of understanding the core melt progression and estimating the end state of fuel debris, which is important for determining the strategies for the fuel debris handling and defueling.

OECD/Pre-ADES will be carries out during 2018-2020. The purpose of this project is to assess the technical difficulties and suggest solutions for handing the fuel debris, such as critical control, determining fuel debris handling tools, control of radioactive aerosols, methods of physical and chemical analyses of samples.

Lastly, ARC-F project has started in year 2019, which is a follow up of BSAF-project. In this project, revised analyses of accident progression in FDNPP will be carried out including hydrogen combustion and explosion analysis. Also, all the data from the FDNPP will be compiled and analyzed in this project.

The purpose of these projects aligned for the better understanding of core melt progression and providing solutions for the technical issued to be encountered during the decommissioning process. The technical expertise of USA from TMI-2, Russia from Chernobyl, other countries using sim-corium test facilities such TROI and VESTA at KAERI [7] are expected to give meaningful contributions for the decommissioning of FDNPP.

3. Conclusions

It was necessary to improve the understanding of the accident progression in the FDNPP accident to obtain insights for the better safety of the nuclear power plant. Also, it is necessary to identify technical issues provide and solutions for the decommissioning efforts for the FDNPP, which will be carries out in 30-40 more years. To meet these needs, international collaborations initiated by OECD/NEA including BSAF, TCOFF, Pre-ADES, ARC-F have been carried out and will be continued.

Thanks to the efforts from the TEPCO, Japanese government, and international collaborations, the accident progression in the FDNPP was mostly understood. However, due to the high dose rate and flooded condition in the plant, direct evidences for the reactor vessel failure location and status of fuel debris in the RPV and PCV were not obtained. Only limited access to the PCV was possible in 2018. The thermodynamic phase distribution of molten core in the RPV and PCV was identified as one of the major phenomena which has to be investigated more.

Acknowledgement
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