Turbulence, Heat and Mass Transfer 7

Lessons learned from the Fukushima Daiichi Nuclear Power Plant Accident

T. Narabayashi[1]

[1]*Division of Energy and Environmental Systems, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo 060-8628, Japan.*

E-mail: tnaraba@eng.hokudai.ac.jp

Abstract – Many lessons can be learned from the Fukushima Daiichi Nuclear Power Plant accident. First, if an isolation condenser (IC) continues to operate, the accident would be terminated soon. A reactor core isolation cooling (RCIC) steam turbine also stopped due to loss of battery power in Unit #2 and #3. suppression pool (S/P) temperature and pressure were so high that the accident management water injection took took too long time. After the loss of ECCS and IC core cooling, Containment Vessel pressure increased. Hydrogen explosion occurred after venting. The analysis results show that the depressurization of the reactor pressure vessel (RPV) started before RPV bottom failure. It is hoped that the lessons learned from this accident will help to improve the safety of nuclear power plants worldwide.

1. Introduction

On March 11, 2011, Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant (NPP) was hit by a tsunami caused by the Tohoku-Pacific Ocean Earthquake, resulting in nuclear accidents in Units #1 to #4. With the aim of improving the safety of NPPs worldwide, we summarize the lessons that have been learned following a thorough analysis of the event and make specific proposals for improving the safety of such facilities. The author has been involved in investigating the causes of the accidents and developing countermeasures for other NPPs in Japan as a member of the Committee for the Investigation of Nuclear Safety of the Atomic Energy Society of Japan [1], an advisory meeting member of NISA with regard to technical lessons learned from the Fukushima Daiichi NPP accidents, and a Safety Evaluation Member of NISA for the other NPPs in Japan [2].

2. Investigation of accidents

The Fukushima Daiichi NPP was hit by a tsunami caused by the Tohoku-Pacific Ocean Earthquake, resulting in nuclear accidents in Units #1 to #4. As shown in Fig. 1, other NPPs such as Fukushima Daini, Onagawa and Tokai Daini were also hit by the tsunami, but they were able to terminate operation and safely cool down. in the Fukushima Daiichi and Daini NPPs. The Fukushima Daini NPP shutdown safely even though Unit #1 was affected by flooding that occurred

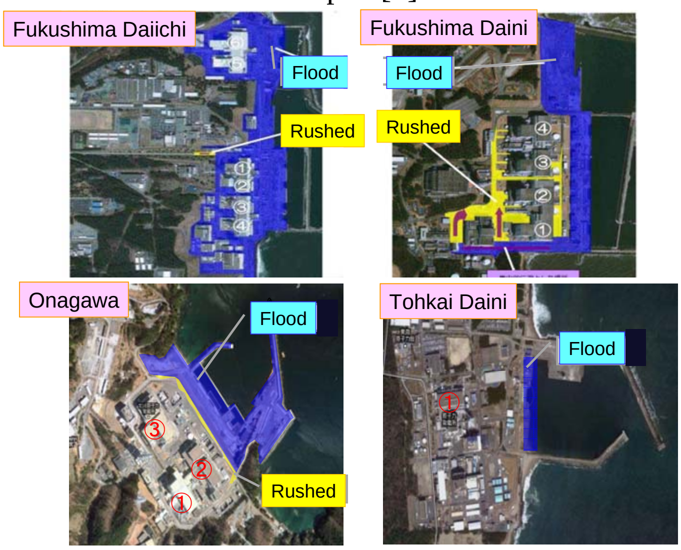


Fig. 1 Comparison of flooded area for each NPP [2].

through hatches and an emergency Diesel generator (EDG) air intake. The AC power was restored by changing the power cable and the seawater pump motors were replaced by bringing in new motors from the Toshiba Mie Works and Kashiwazaki-Kariwa NPP by helicopter. In the case of the Fukushima Daiichi NPP, Unit #5 was brought under control using EDG power from Unit #6.

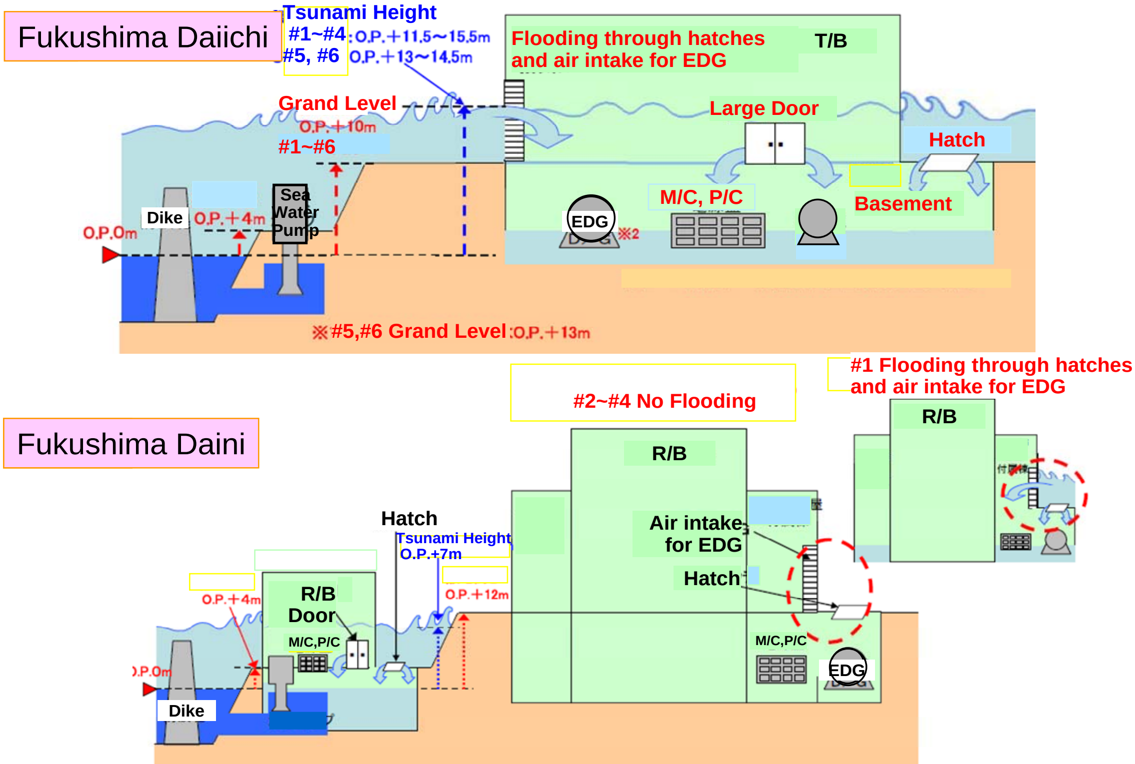
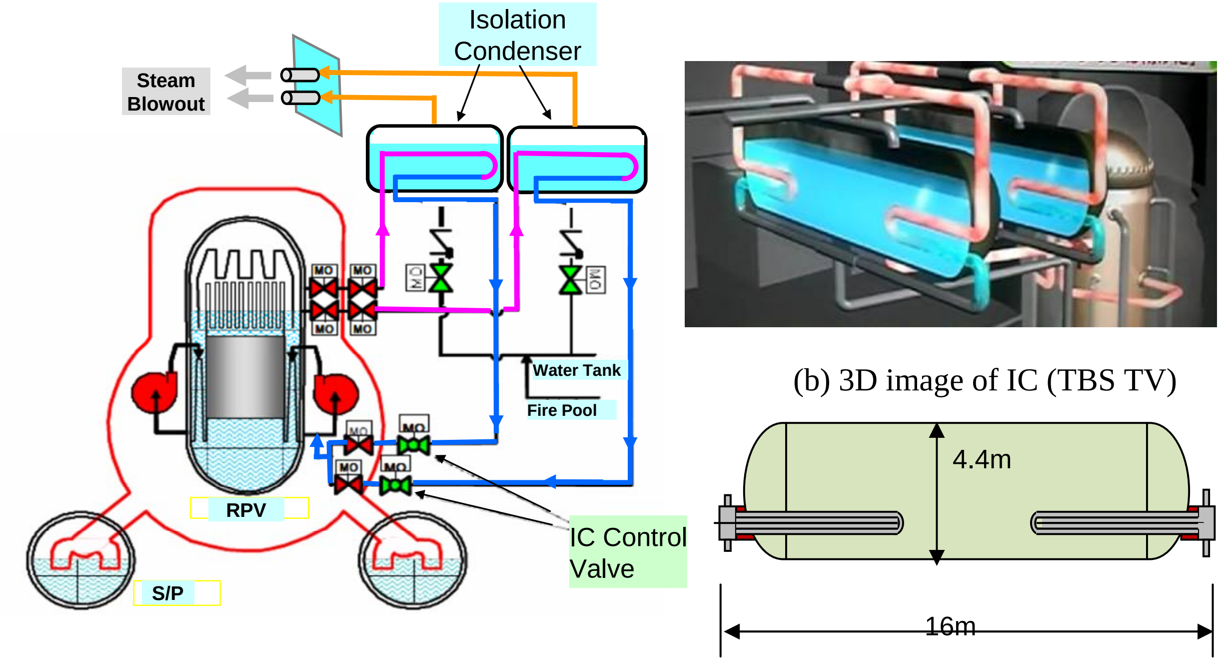


Fig. 2 Comparison of flood damage to emergency diesel generators for Fukushima Daiichi and Daini NPPs [2].

Table 1 Cause of station blackout for Units #1 to #4 in Fukushima Daiichi NPP [2]

	#1	#2	#3	#4	#5	#6
DG	A:NG B:NG (T/B B1)	A:NG (B1) B:OK (FP/B 1F)	A:NG B:NG (T/B B1)	A:NG (T/B B1) B:OK (FP/B 1F)	A:OK->NG B:OK->NG (T/B B1) Water Cooling	A:OK->NG (R/B B1) Water Cooling B:OK (DG/B 1F)
Metal-Crad Swich	NG (T/B B1)	NG (T/B B1)	NG (T/B B1)	NG (T/B B1)	NG (T/B B1)	Barely (R/B B2F)
Power Center	NG (T/B B1)	Barely (T/B B1)	NG (T/B B1)	Barely (T/B 1F)	Barely (T/B 2F)	Barely (R/B B2F)
DC Buttery	NG (C/B B1)	NG (C/B B1)	OK (T/B BM1)	NG (C/B B1)	OK (T/B BM1)	OK (T/B BM1)
ECCS RCIC	HPCI:NG IC:OK(FC)	NG RCIC:OK	HPCI:OK RCIC:OK	(No Fuels in RPV)	–	HPCS:OK (R/B B1)

Figure 2 shows a comparison of the flood damage to emergency diesel generators (EDGs) However, for Units #1 to #4, there was a complete loss of both AC power from the EDGs and DC power, and this was the main cause of the severe accidents that followed. In the case of Unit #1, DC battery power was lost in the main control room. This caused the MO isolation valves to undergo fail-close action, thereby cutting off the isolation condenser (IC), as shown in Fig. 3. It was a fail-dangerous system. If the IC had continued to operate, the situation would have soon been brought under control.



(a) IC system (c) IC tank structure

Fig. 3 Isolation condensers in Fukushima Daiichi Unit #1

After the loss of both the emergency core cooling system and the IC core cooling, the containment vessel (CV) pressure increased. The water level measurement drifted due to evaporation in the reference leg, as shown in Fig. 4. The radiation level increased at a turbine building (T/B). A hydrogen explosion occurred after suppresion chamber (S/C) wet venting.

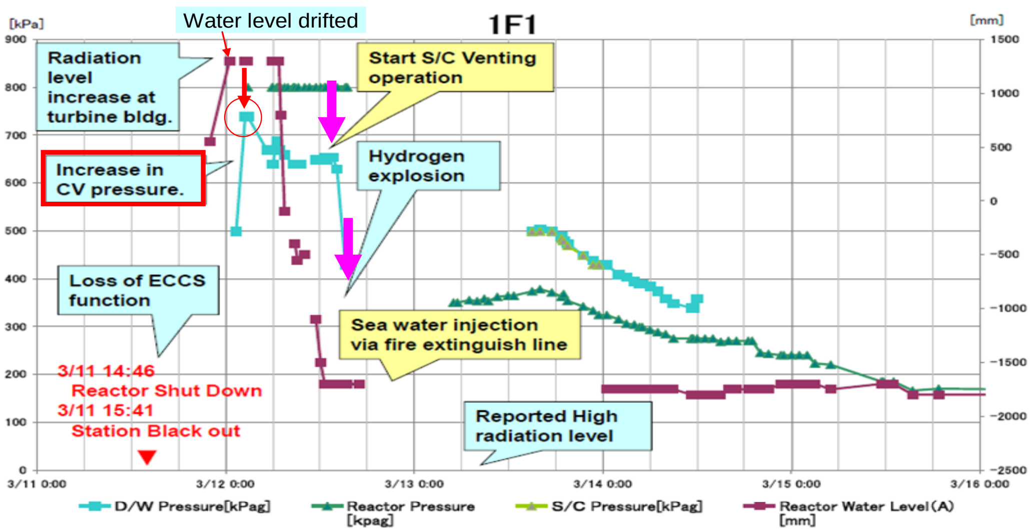
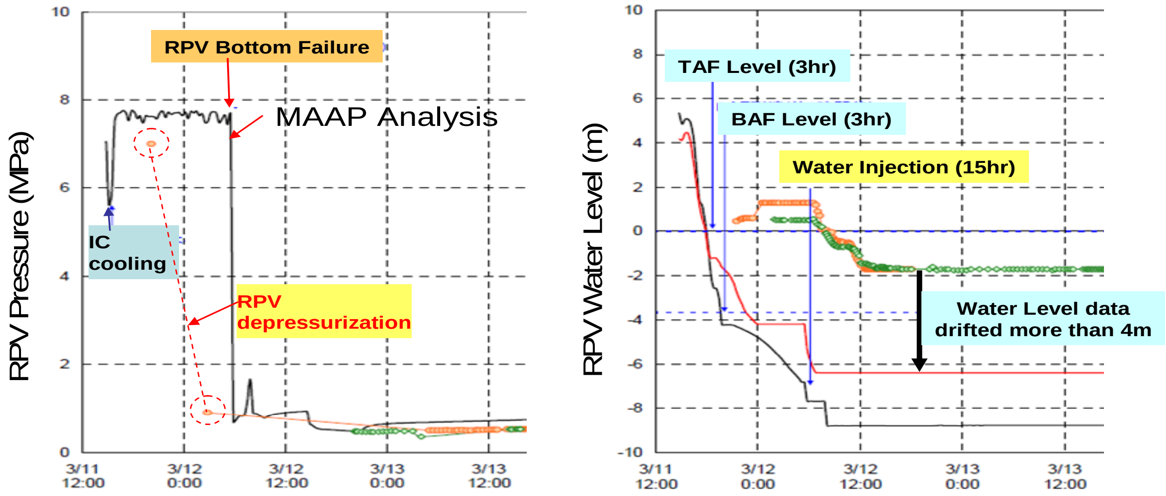


Fig. 4 Measured pressure in RPV and CV of Unit #1, and water level in RPV [3].



(a) Pressure in RPV (b) Water level in RPV

Fig. 5 MAAP analysis results compared with actual plant data for Unit #1 [2] .

As shown in Fig. 5(a), both the MAAP code analysis results and actual data suggest that depressurization of the RPV started before its bottom failed. This might have been caused by melted TIP tubes in the core or control rod drive (CRD) tubes. As shown in Fig. 5(b), the measured water level measurement drifted by more than 4 m due to water loss in the reference leg. This is likely to have been caused by the high-temperature superheated core. Water should have been supplied to the water level reference leg through the instrumentation piping.

In the case of Unit #2, reactor core isolation cooling (RCIC) continued to work for about 3 days. As shown in Fig. 6, after the loss of RCIC water injection, the water level in the RPV soon decreased. The safety relief valve (SRV) was opened and the drywell (DW) pressure increased to 650 kPa.

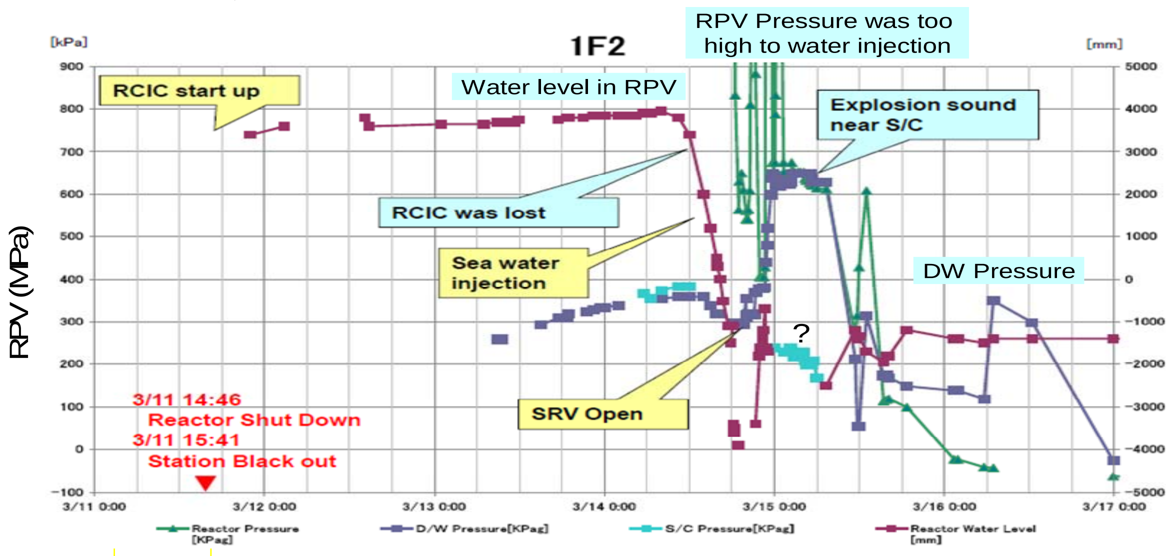


Fig. 6 Measured pressure in RPV and CV of Unit #2, and water level in RPV [3]

The RPV pressure was too high to allow water injection using a fire pump. This failure to promptly inject water soon after RCIC stopped in Unit #2 caused core damage and the generation of H_2, as shown in Fig. 7. A high-pressure discharge pump driven by a diesel engine should have been used.

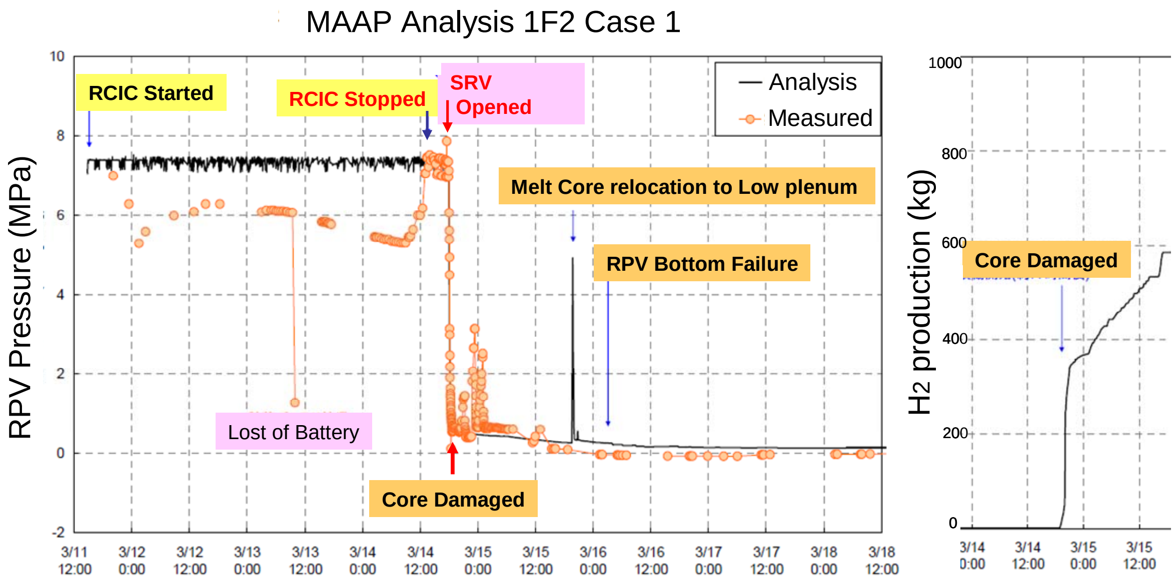


Fig.7 MAAP analysis results compared with actual plant data for Unit #2 [2] .

As shown in Fig. 8, H_2 detonations occurred after venting operations (#1, #3, #4). It was reported that an explosion was also heard near S/C. However, examination of the data showed it was due to a hydrogen detonation in the Unit #4 reactor building (R/B). Soon after the detonation, the Unit #2 DW pressure deceased.

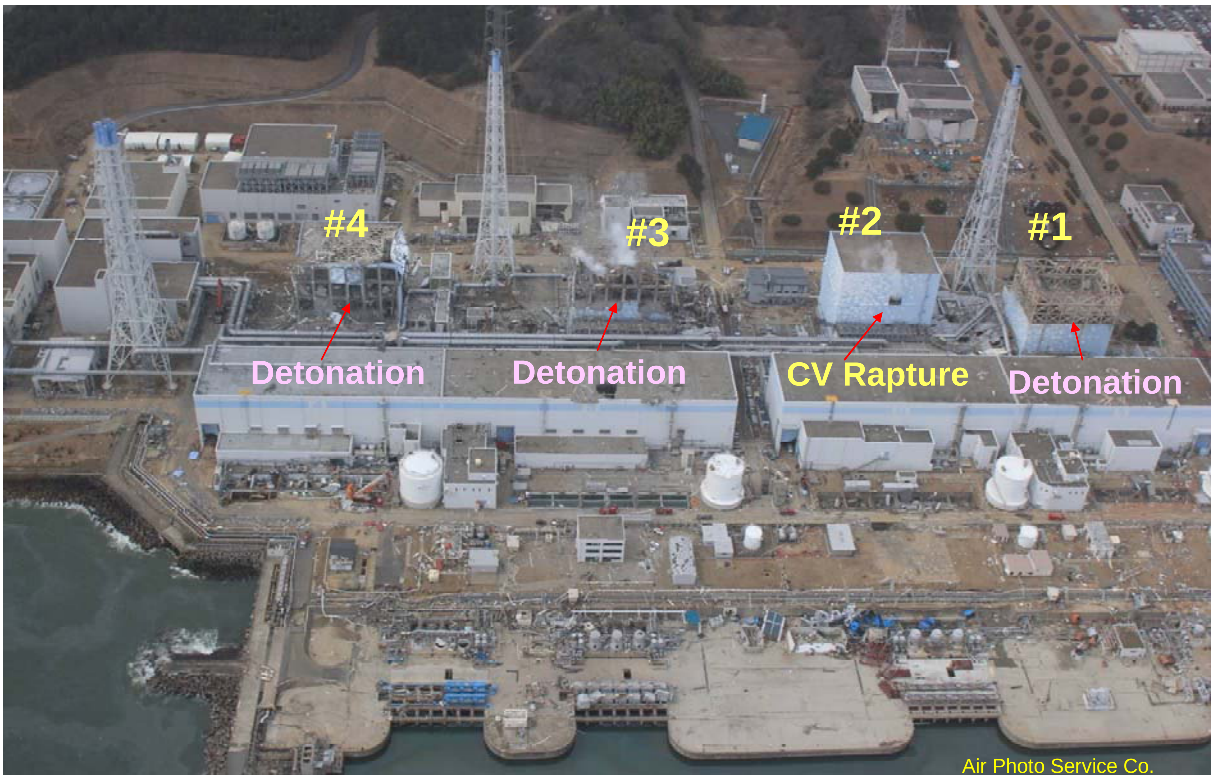


Fig. 8 H_2 detonations occurred after venting operations (Units #1, #3 and #4).

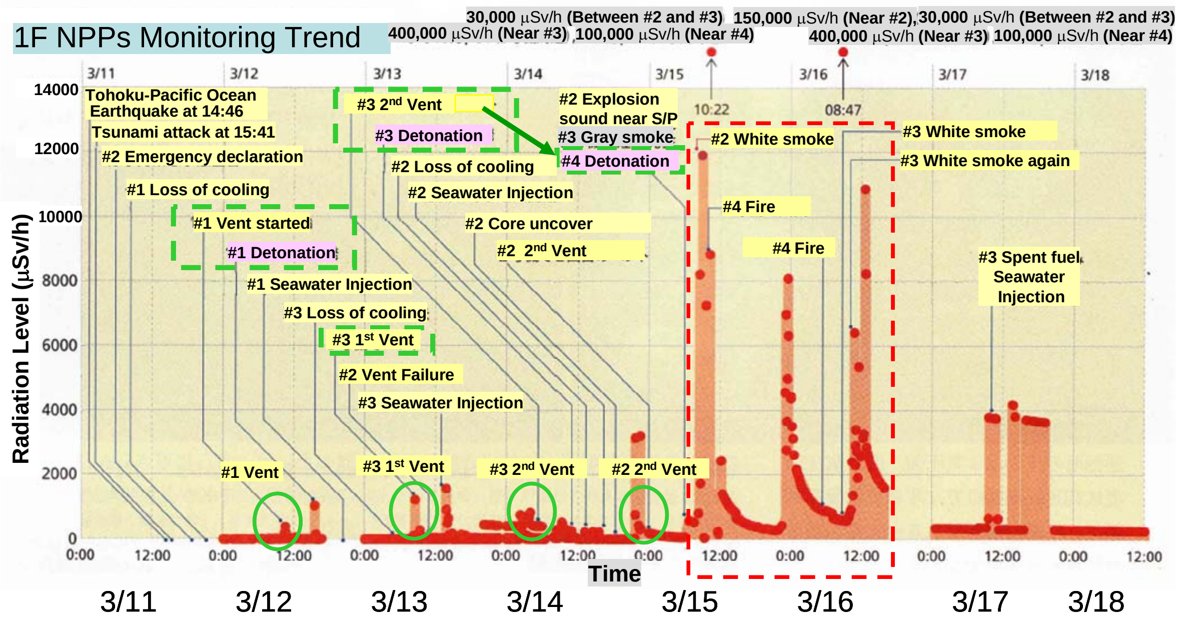


Fig. 9 Monitored radiation levels for Fukushima Daiichi Units #1, #2, #3 and #4 (Nikkei Science, July 2011)

Figure 9 shows the trend in monitored radiation levels for Fukushima Daiichi Units #1, #2, #3 and #4, which can be compared with the passage of events. The radiation level increased soon after the Unit #2 CV rupture on March 15. A loss of core cooling occurred due to the IC trip in Unit #1, and the RCIC steam turbine also tripped due to loss of battery power in Units #2 and #3. The suppression pool (S/P) temperature and pressure were so high that accident management water injection took a long time. This was the reason why the chain of severe accidents occurred in the Fukushima Daiichi NPP, as shown in Fig. 10.

Figure 11 shows that the CV top flange and hatches might act as leakage pathways. Hydrogen and FP flowed upwards by way of stairways and hatches. Although there was no fuel in the core of Unit #4, hydrogen flowed from Unit #3 through the stack line into Unit #4 and underwent reverse flow through the standby gas treatment system (SGTS) filters, as shown in Fig. 12. A strong detonation occurred in the Unit #4 reactor building on March 14.

As shown in Fig. 13, it was confirmed that the SGTS filters were contaminated and all the MO valves were open due to the fail-open design in Units #3 and #4.

The author pointed out to NISA that the added vent line might have acted as a means of hydrogen supply through the SGTS and HVAC lines, as shown in Fig. 14.

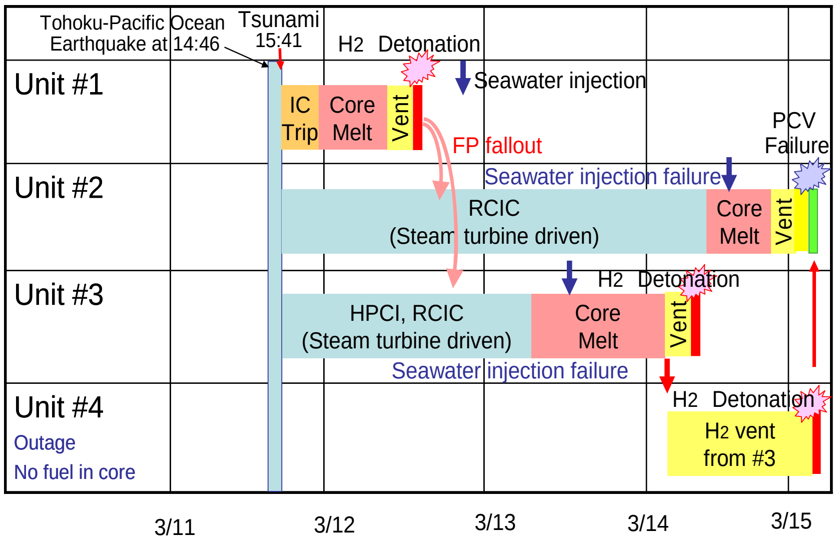
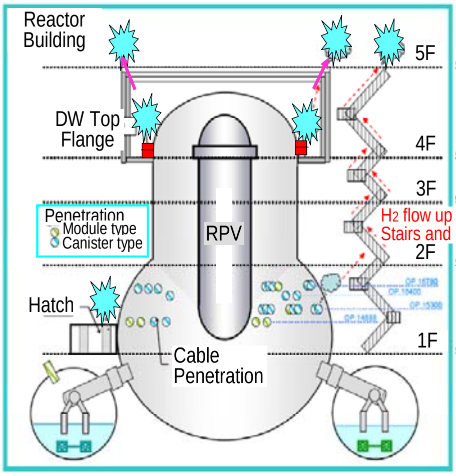


Fig. 10 Chain of severe accidents in the Fukushima Daiichi NPP



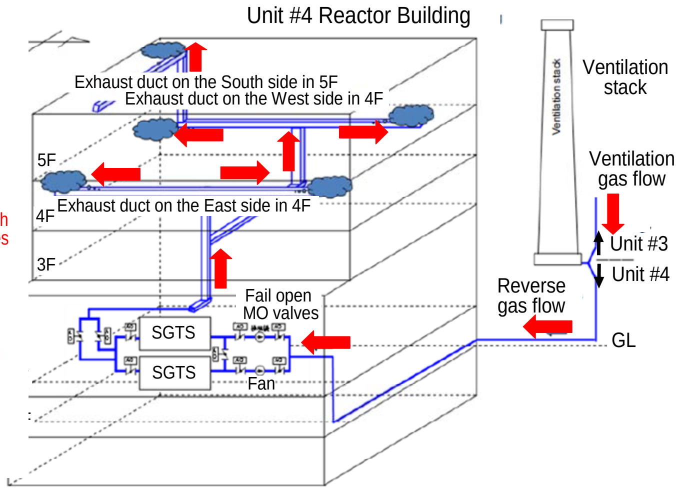
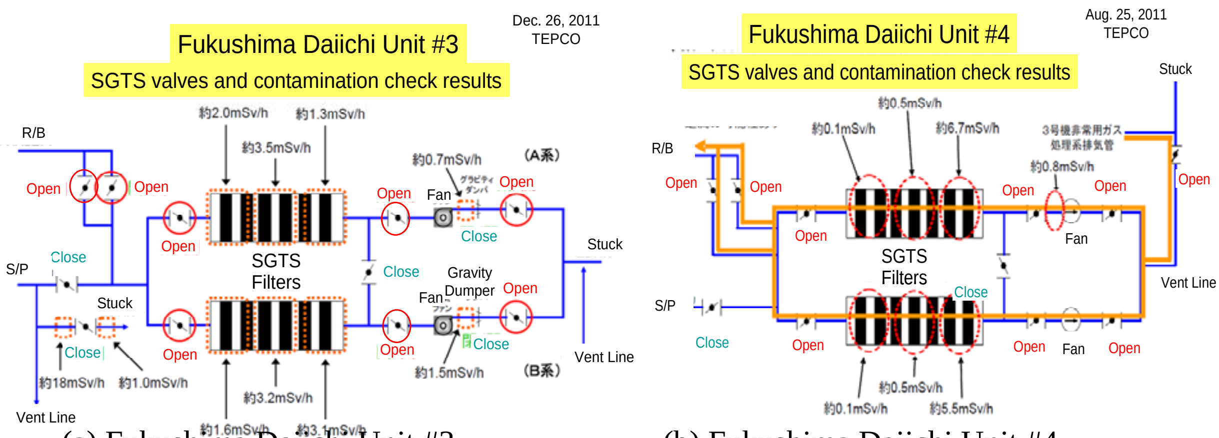


Fig.11 H2 leak path from DW　　Fig.12 H2 flow into unit #4 reactor building from unit #3



(a) Fukushima Daiichi Unit #3　　(b) Fukushima Daiichi Unit #4

Fig. 13 Results of SGTS valves open/close check and SGTS filter contamination survey [2]

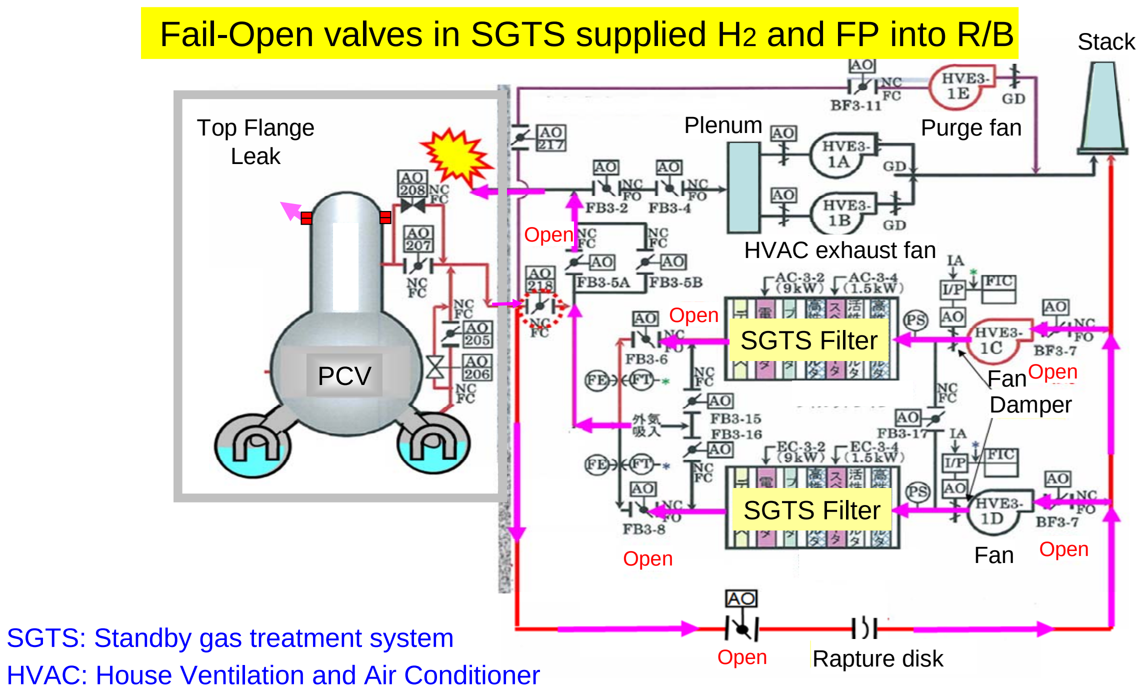


Fig. 14 Flow diagram of SGTS/HVAC and added vent system [2].

Hydrogen and FP flowed back into each room through the exhaust gas ducts. The vent lines of each NPP should have been independent from the SGTS/ HVAC line.

3. Countermeasures

3. 1 Filtered Containment Venting System

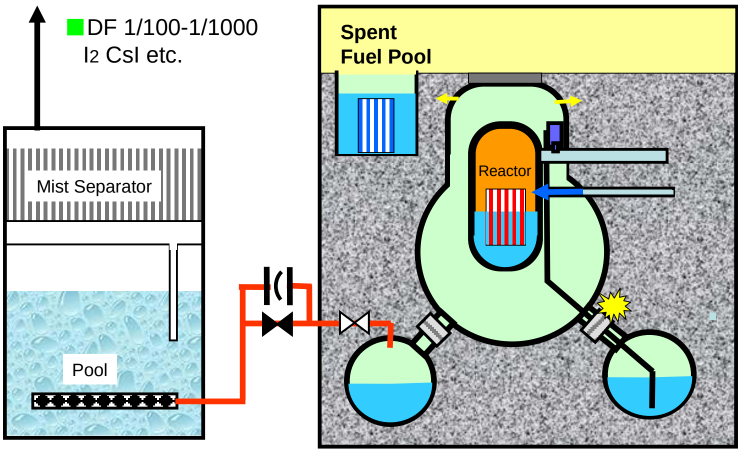


Fig.15 Filtered containment venting system

As shown in Fig. 15, after the Chernobyl NPP accident, countries such as France, Germany, Switzerland, Finland and Sweden decided to install a filtered containment venting system (FCVS) to protect against radioactive material exhaust, as shown in Figs. 16 and 17.

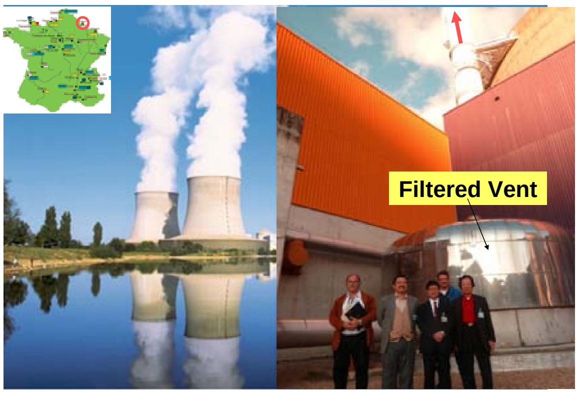


Fig. 16 Installed FCVS in Chooz NPP, France

Fig. 17 FCVS in Leibstadt NPP, Switzerland

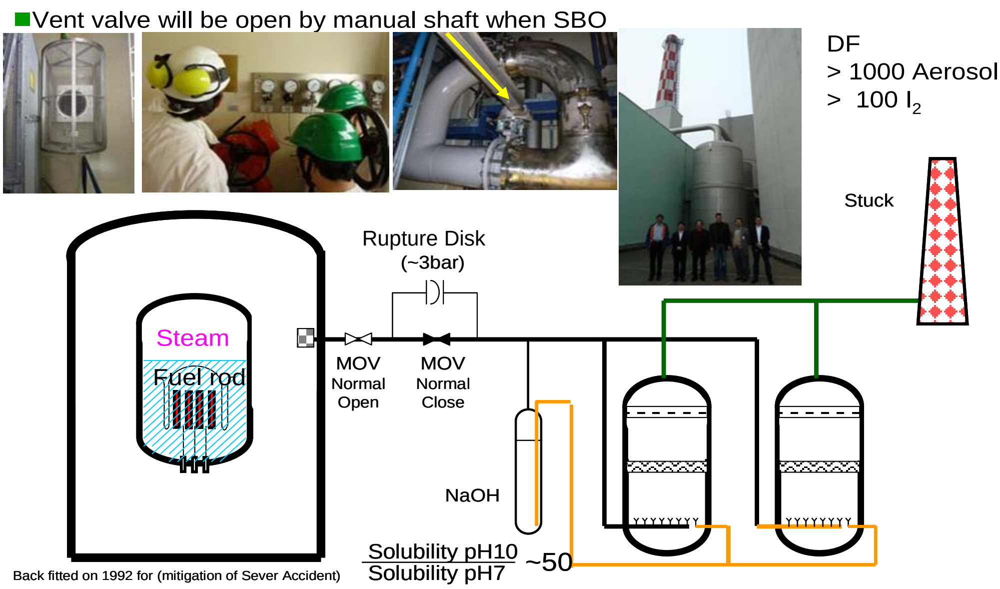


Fig. 18 Schematic diagram of FCVS in Leibstadt NPP

Figure 18 shows a schematic diagram of the FCVS installed in the Leibstadt NPP. A venting process is automatically carried out when the CV pressure reaches the set pressure for the rupture disk. An operator who wishes to vent early can easily open the vent valve using a hand wheel driven shaft. In the case of the Fukushima Daiichi NPP accidents, operators should have closed a large number of valves in the SGTS system and then opened the vent valve using an air compressor and connecting tubes, because of the station blackout condition. If a FCVS had already been installed in the Fukushima Daiichi NPP, environmental contamination by FP would be have been avoided. The decontamination factor is about 1000 for aerosols and about 100 for I_2.

3.2 Heat Sink and EDG

After the TMI-2 accident in 1979, Kernkraftwerk Leibstadt (KKL) back-fitted the Leibstadt NPP with additional CV cooling (Defense in Depth 3) and a mitigation system for severe accidents (Defense in Depth 4). The back-fitted system was named the special emergency heat removal (SEHR) system. The SEHR system was required by ENSI/ HSK in the late 70s, shortly after the start of the project planning, so it was the first back-fitting in the present design of KKL. Due to space limitations, only a single heat exchanger was installed for two SEHR trains and the heat removal power is a minimum of 36.3 MW (1% of the nominal power: decay heat). The system has two special EDGs and an underground well water heat sink. The system is able to cool both the core and the CV using the heat exchanger.

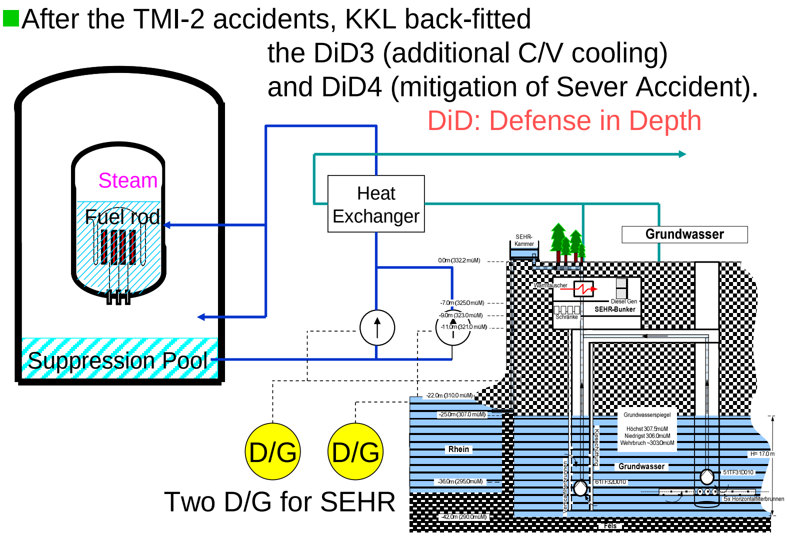


Fig.19 SEHR (Special Emergency Heat Removal) System

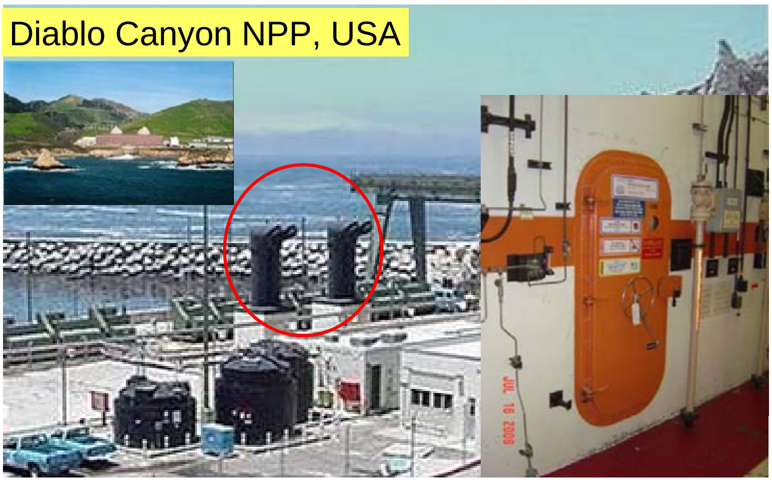


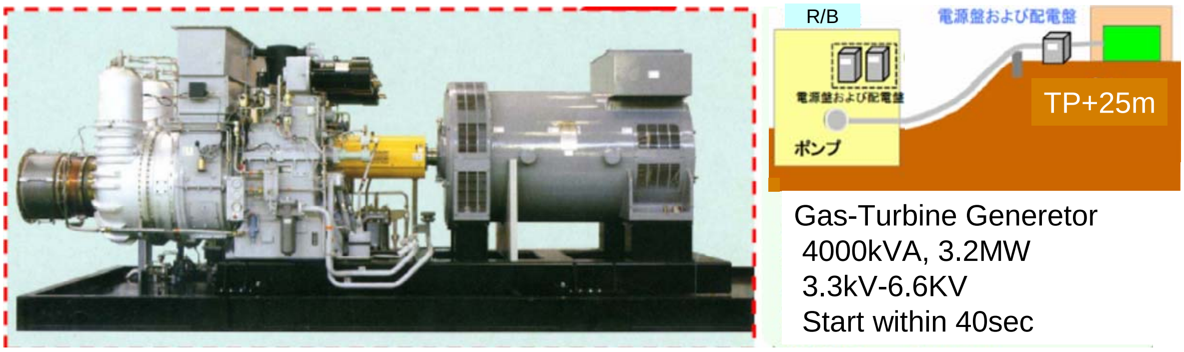
Fig.20 Tsunami protection at Diablo Canyon NPP, USA

3.3 Tsunami Protection

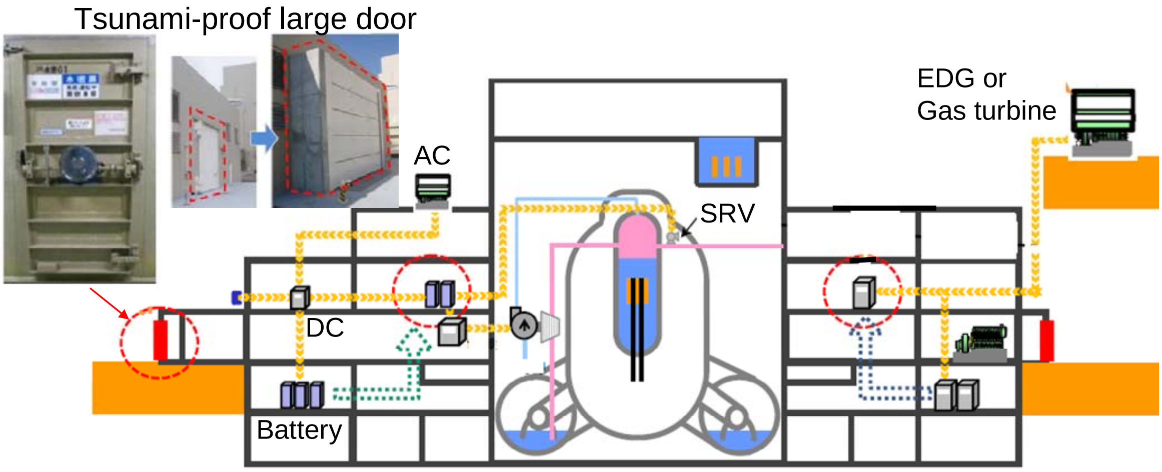
When the Fukushima Daiichi NPP was hit by the tsunami, all AC and DC power was lost due to damage to the EDGs, power center, metal switchgear, and seawater pump motors. In the case of the Fukushima Daini NPP, the AC power could be restored by changing the power cable and new seawater pump motors were installed. Therefore, it is very important to prevent the flow of water into important areas. As shown in Fig. 20, at the Diablo Canyon NPP in Florida, the seawater pump motors are equipped with waterproof hatch-type doors and snorkel piping. Figure 21 shows several tsunami protection examples, such as a large mobile gas-turbine generator and an electricity receiver/transmitter device on top of a hill (85 m high). Tsunami-proof doors and hatches have been installed in PWR/BWR NPPs in Japan, as shown in Fig. 21(c).

As shown in Fig. 22, decay heat removal and CV spray cooling with FCVS can be carried out using mobile generators and heat exchangers to maintain a permanent heat sink even in a natural disaster such as a large earthquake or tsunami, or sudden flooding.

(a) 4000 kVA mobile gas-turbine generator at 31 m parking and GIS at 85 m height (Hepco).

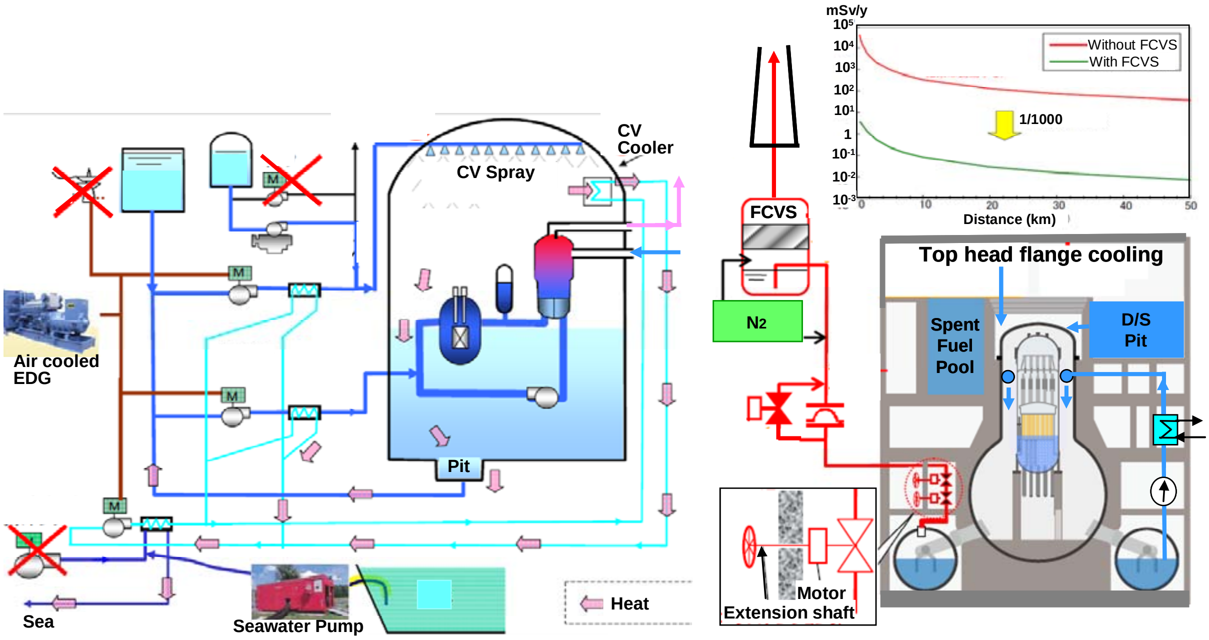


(b) 3.2 MW Gas-turbine generator to be installed at 25 m height (Chubu Electric).



(c) Tsunami-proof doors and hatches (BWR Utilities in Japan)

Fig. 21 Tsunami protection example at Tomari NPP (Hepco) and Hamaoka NPP (Chubu Electric) [7]



(a) Decay heat removal system in PWR (b) CV cooling system and FCVS in BWR

Fig. 22 Decay heat removal system and CV spray cooling system with FCVS [7]

4. Conclusion

The Fukushima Daiichi NPP accident could have been quickly brought under control if sufficient countermeasures had been installed, such as waterproof doors and mobile power sources. In Europe, as a result of the lessons learned from the TMI and Chernobyl accidents, heat removal systems and filtered containment venting systems had already been installed.

Using the lessons learned from this analysis of the Fukushima Daiichi NPP accident, we hope to contribute to achieving 1st class nuclear safety throughout the world. We intend to make earnest proposals and provide scientific and technological support so that these lessons can be reflected in measures taken by institutions and government agencies, thereby enhancing the safety of the large number of nuclear power stations in operation throughout the world.

References

1. T. Narabayashi and K. Sugiyama, "Fukushima Daiichi NPPs accidents caused by the Tohoku- Pacific Ocean Earthquake and Tsunami", AESJ Atoms, vol.53, No.6, P.387-400 (2011).
2. NISA, "Technical knowledge of Fukushima-Daiichi NPP's Accidents and countermeasure (Interim report)", (2012), (in Japanese), (http://www.nisa.meti.go.jp/shingikai/800/28/008/8-2-1.pdf).
3. NISA, JNES, "The 2011 Pacific coast of Tohoku Pacific Earthquake and the seismic damage to the NPPs", (2011).
4. JNES, "IC Performance and Transient Analysis for Fukushima Daiichi NPP unit 1 accidents", (2011).
5. Tepco's Fukushima Daiich NPPs Accidents Investigation meeting's report (Interim report), (2011), (http://icanps.go.jp/post-1.html), (in Japanese).

6. T. Narabayashi, "Lessons of Fukushima-Daiichi NPP's Accidents for Achievement of the 1st Class Safety in the World", Fukushima Severe Accident Dose Management & Global Lessons Learned in Occupational Dose Reduction, 2012 International ISOE ALARA Symposium, (Fort Lauderdale, Florida, Jan 9, 2012).
7. "Making efforts of licensees to ensure the NPPs safety in Japan", Federation of Electric Power Companies' report, (March 7, 2012). (http://www.nisa.meti.go.jp/shingikai/800/28/240307/240307-1.pdf)

Abbreviation List

AC: alternating current, DC: direct current, SBO: station blackout, SA: severe accident,
AM: accident management, RPV: reactor pressure vessel, RV: reactor vessel,
CV: containment vessel, DW: drywell, S/C: suppression chamber, S/P: suppression pool,
SRV: safety relief valve, AO: air operated valve , MO: motor operated valve,
IC: isolation condenser, RCIC: reactor core isolation cooling system,
R/B: reactor building, T/B: turbine building, FP: fission product
TIP: trabersing incore neutron probe, CRD: control rod drive

M/C: metal clad switchgear, P/C: power center,
GIS: gas insulated switchgear, EDG: emergency Diesel generator,
SGTS: Standby gas treatment system, HVAC: house ventilation and air conditioner,
FCVS: filtered containment venting system, SEHR: special emergency heat removal,

NISA: Nuclear and Industrial Safety Agency,
JNES: Japan Nuclear Energy Safety Organization
METI: Ministry of Economy, Trade and Industry, NSC: Nuclear Safety Commission
MEXT: Ministry of Education, Culture, Sports, Science & Technology