Lessons learned from the Fukushima Daiichi Nuclear Power Plant Accident

NARABAYASHI Tadashi[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 turbines also stopped due to loss of battery power in Units No.2 and No.3. suppression pool (S/P) temperature and pressure were so high that the accident management water injection 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.

Keyword: nuclear safety; Fukushima Daiichi; severe accident; tsunami, station blackout

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 No.1 to No.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 Nuclear and Industrial Safety Agency (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 No.1 to No.4. As shown in Fig. 1, although the other NPPs such as Fukushima Daini, Onagawa and Tokai Daini were also hit by the tsunami, they all were able to terminate operation and safely, until cool down condition. The Fukushima Daini NPP succeeded in shutdown safely even though Unit No.1 was affected by water flooding 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 No.5 was brought under control by using EDG power from Unit No.6.

Figure 2 shows a comparison of the flood damage to emergency diesel generators (EDGs). However, for Units No.1 to No.4, there was a complete loss of both AC power by the EDGs and DC power, and this was the main cause of the severe accidents that followed.

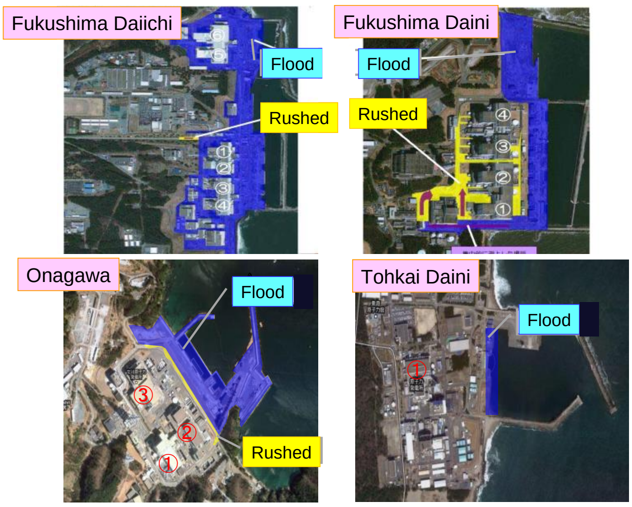


Fig. 1 Comparison of flooded area for each NPP [2].

Received date: November 15,2013
(Revised date: November 24,2013)

Table 1 Cause of station blackout for Units No.1 to No.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)

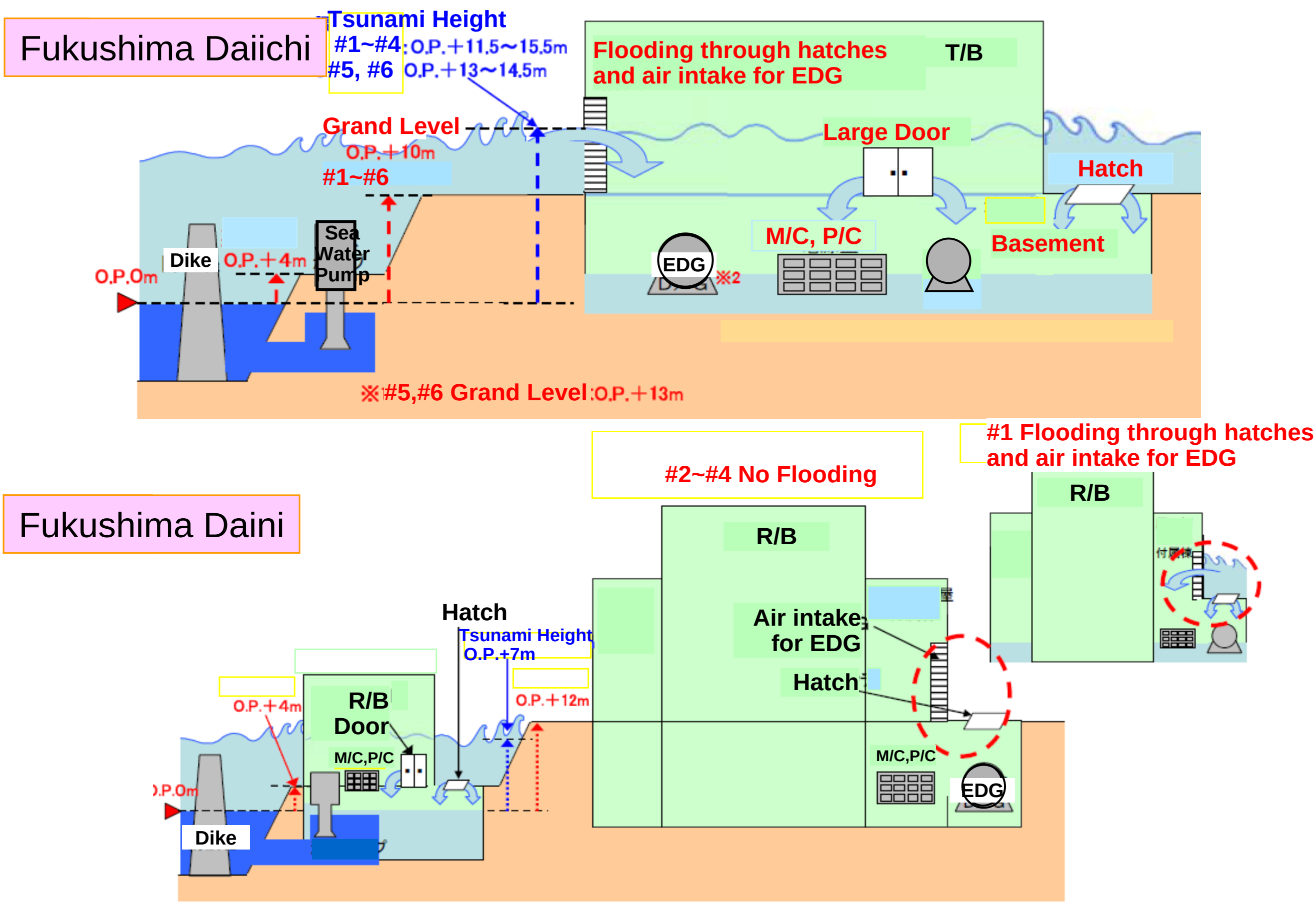


Fig. 2 Comparison of flood damage to emergency diesel generators for Fukushima Daiichi and Daini NPPs [2].

In the case of Unit No.1, DC battery power was lost in the main control room. This caused the motor operated (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.

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 of water in the reference leg, as shown in Fig. 4. The radiation level increased at a turbine building (T/B). A hydrogen explosion occurred after suppression chamber (S/C) wet venting.

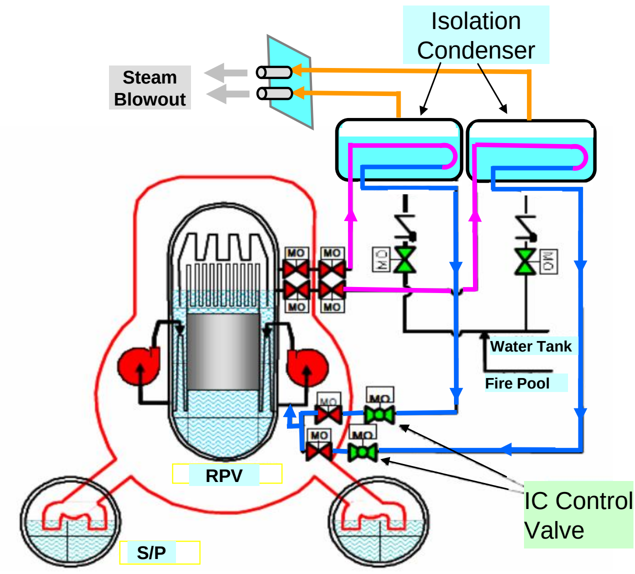


Fig. 3 Isolation condensers in Fukushima Daiichi Unit No.1.

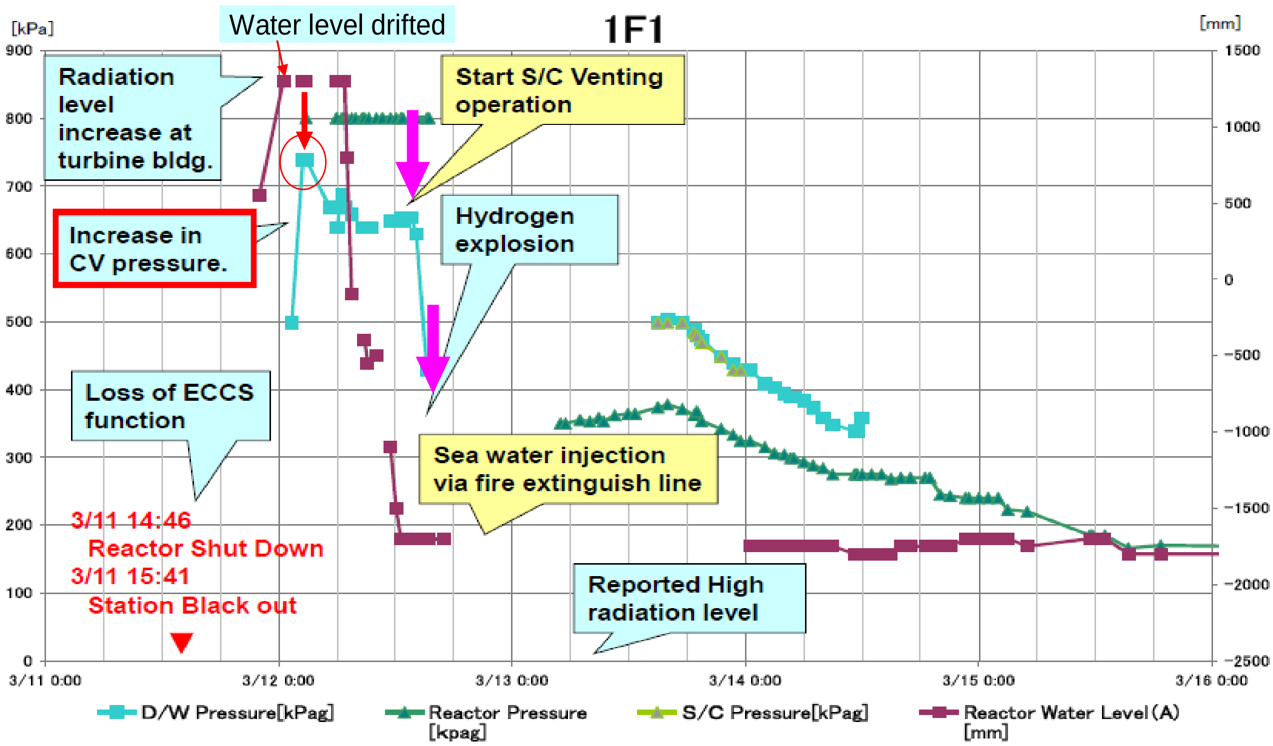
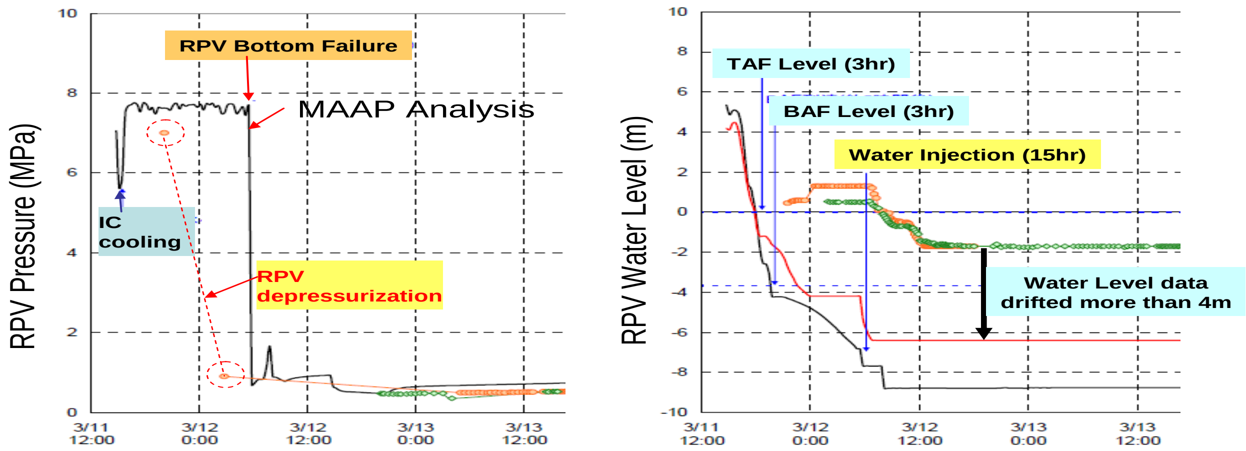


Fig. 4 Measured pressure in RPV and CV of Unit No.1, and water level in RPV [3].

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 the melting of 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.
Water should have been supplied to the water level reference leg through the instrumentation piping.
In the case of Unit No.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.



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

Fig. 5 MAAP analysis results compared with actual plant data for Unit No.1 [2].

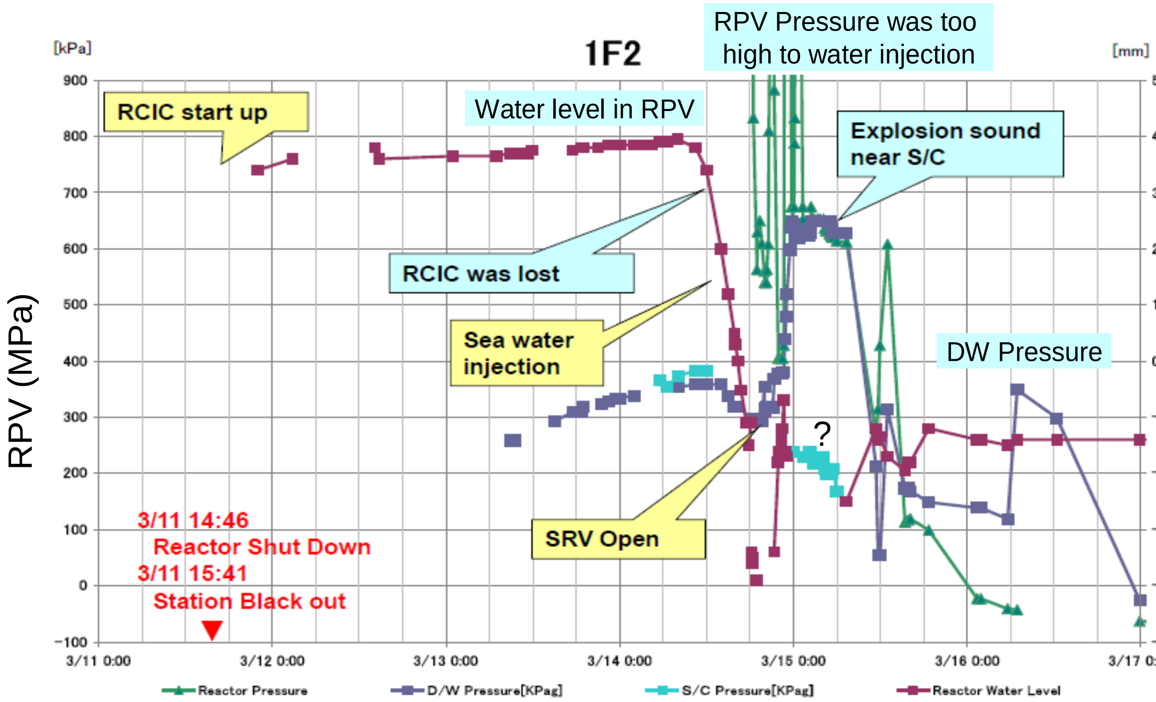


Fig. 6 Measured pressure in RPV and CV of Unit No.2, and water level in RPV [3].

The RPV pressure was too high to allow water injection by using a fire engine pump. This failure to inject water soon after the stop of RCIC in Unit No.2 promptly lead to core damage and the generation of H_2, gas as shown in Fig. 7. A high-pressure discharge pump driven by a diesel engine or motor should have been used for the backup of RCIC trip.

As shown in Fig. 8, H_2 detonations occurred in Unit No.1, No.3 and No.4. When the Unit 1's detonation occurred the blowout panel of Unit No. 2 was opened. The hydrogen in Unit No.2 was released through the opened blowout panel and detonation didn't occurred in Unit 2.

It was reported that an explosion sound was also heard near the S/C of Unit 2. However, examination of the data showed that it was due to a hydrogen detonation in the reactor building (R/B) of Unit No.4. Soon after the detonation, the Unit No.2 DW pressure decreased, as seen in Fig. 6. Figure 9 shows the trend in monitored radiation levels for Fukushima Daiichi Units No.1, No.2, No.3 and No.4, which can be compared with the events as illustrated in Fig. 10.

It seemed that the detonation occurred after venting operations. The radiation level increased soon after the Unit No.2 CV rupture on March 15.

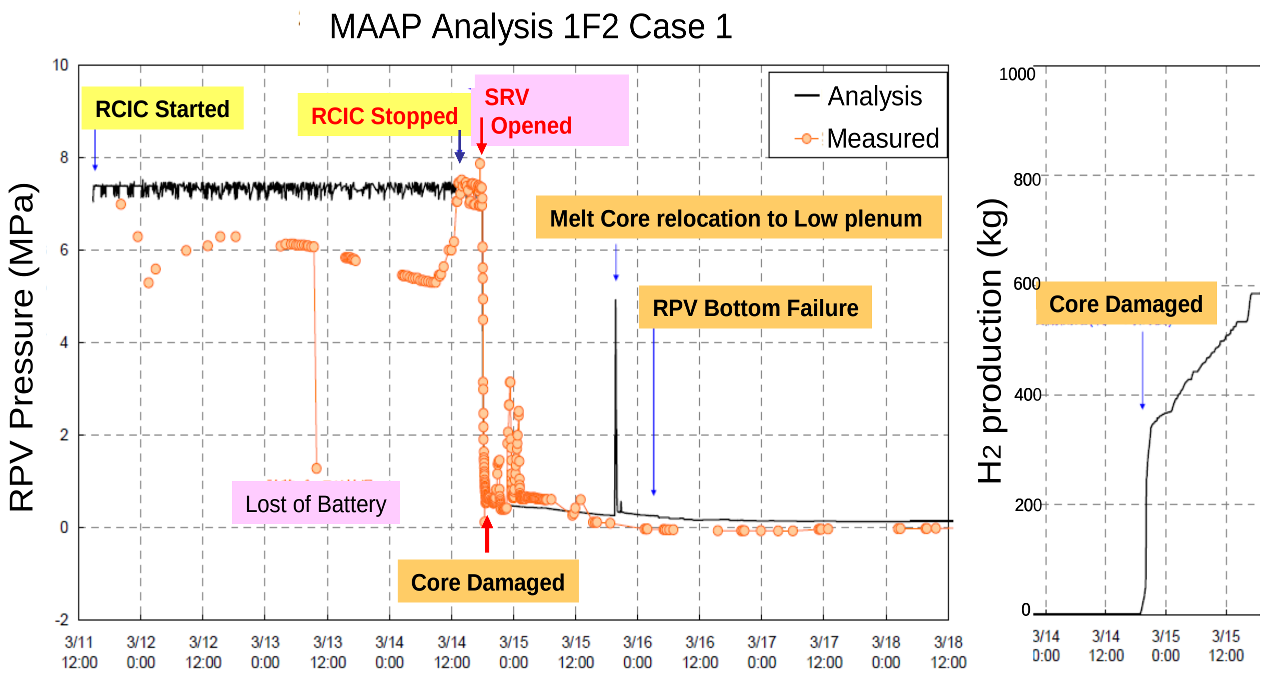


Fig.7 MAAP analysis results compared with actual plant data for Unit No.2 [2].

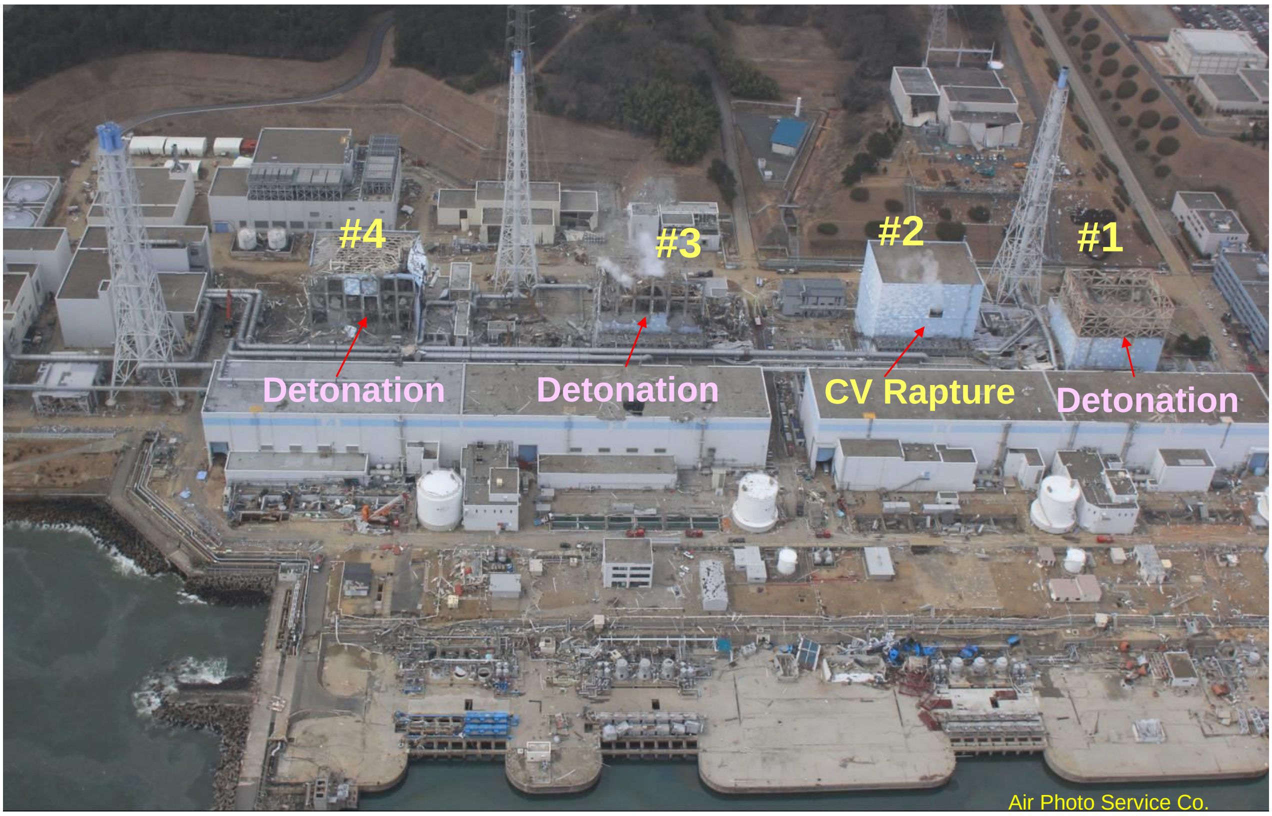


Fig. 8 H_2 detonations occurred after vent operations (Units No.1, No.3 and No.4).

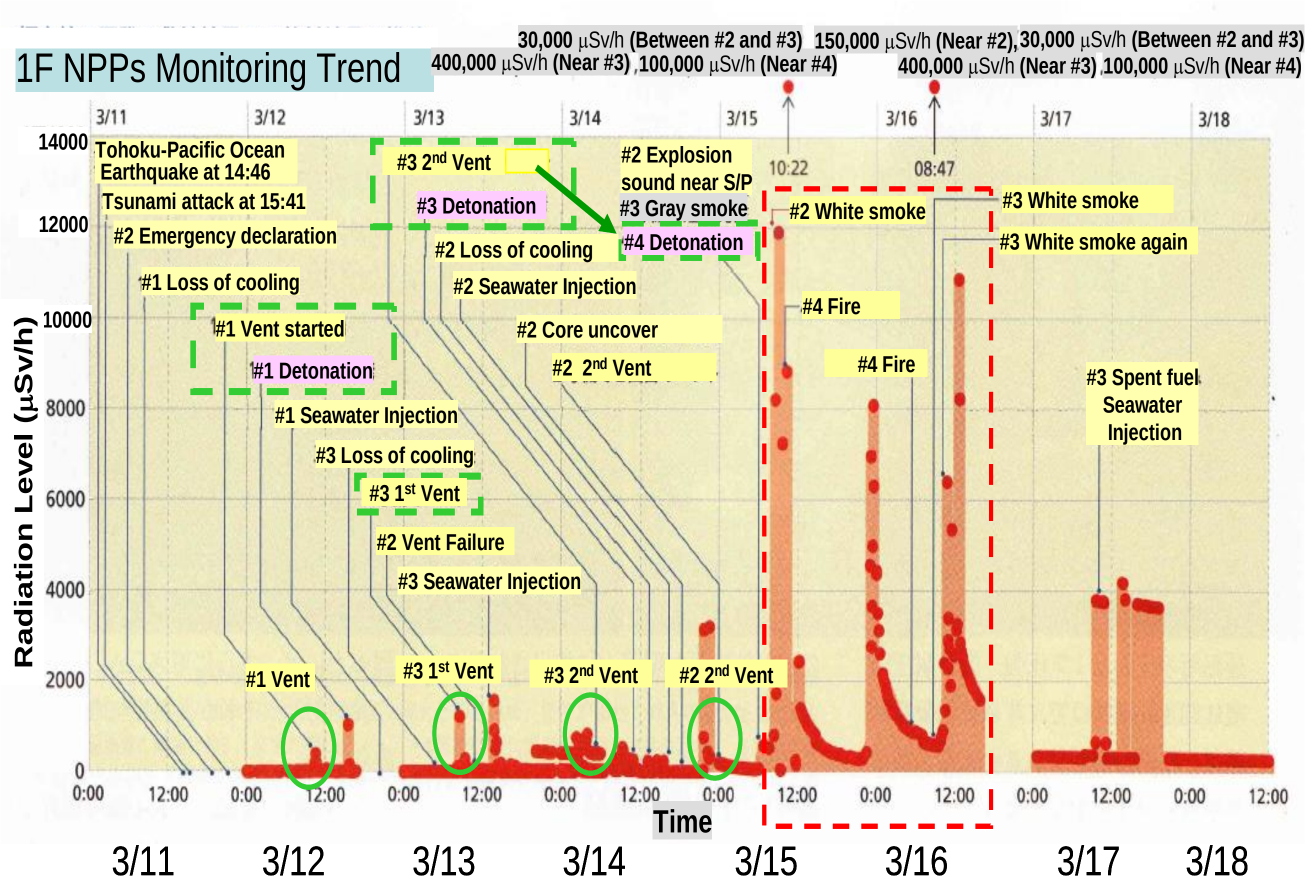


Fig. 9 Monitored radiation levels for Fukushima Daiichi Units No.1, No.2, No.3 and No.4 (Nikkei Science, 2011).

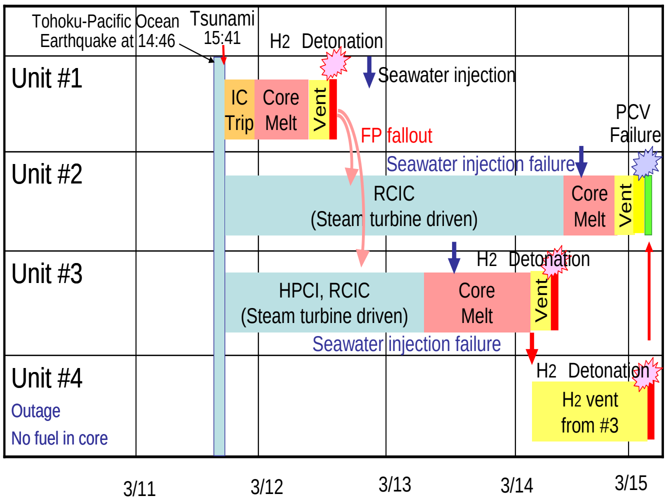


Fig. 10 Chain of major events in Units No.1 to No.4 to bring about severe accidents in the Fukushima Daiichi NPP.

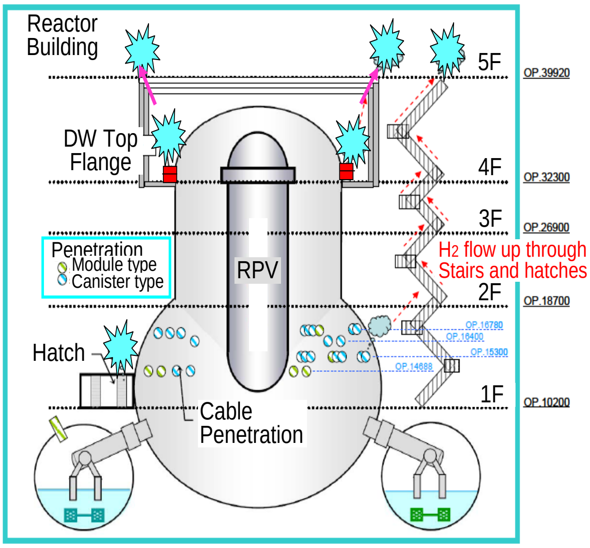


Fig.11 H_2 leak path from drywell in Unit No.1 toNo.3.

A loss of core cooling occurred due to the IC trip in Unit No.1, and the RCIC steam turbine also tripped due to loss of battery power in Units No.2 and No.3. The suppression pool (S/P) temperature and pressure became so high that water injection actions for accident management took a long time.

This was the reason why the chain of severe accidents occurred in the four units of 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 flow upwards by way of stairways and hatches.

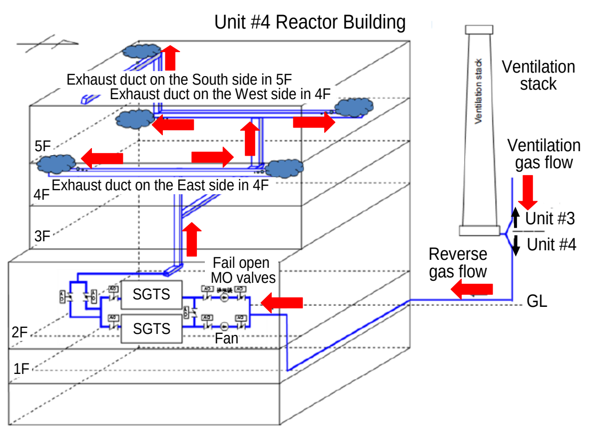
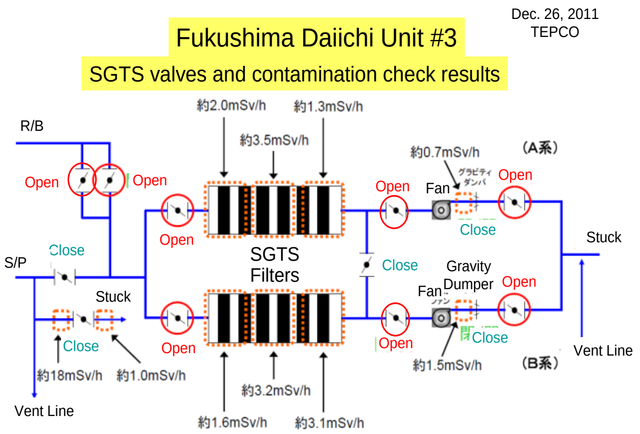
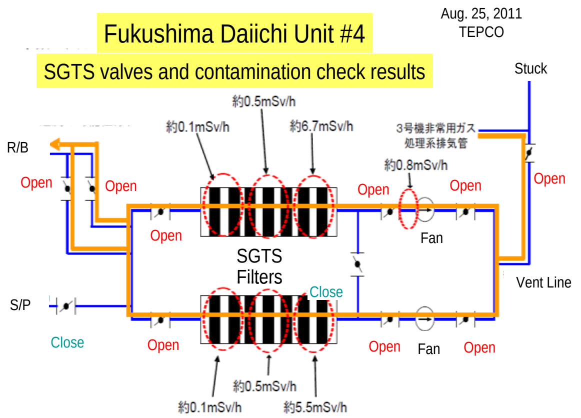


Fig.12 H^2 gas flow into unit No.4 reactor building from unit No.3.



(a) Fukushima Daiichi Unit No.3



(b) Fukushima Daiichi Unit No.4
Fig. 13 Results of SGTS valves open/close check and SGTS filter contamination survey [2]

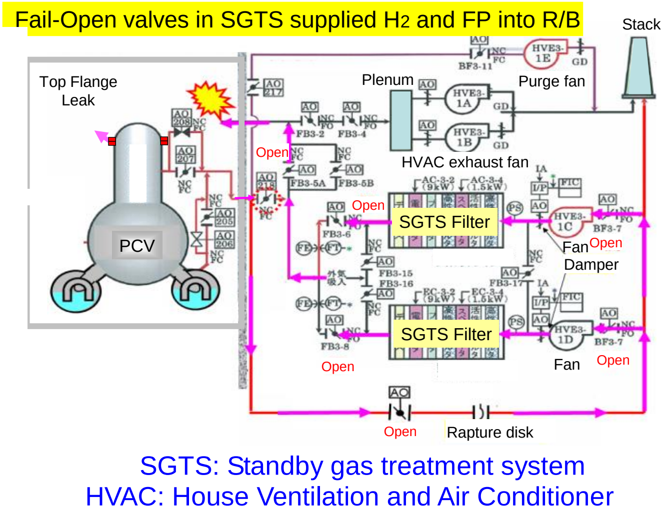


Fig. 14 Flow diagram of SGTS/HVAC and added hard vent system. [2]

Although there was no nuclear fuels in the reactor core of Unit No.4, hydrogen flowed from Unit No.3 through the stack line into Unit No.4 and underwent reverse flow through the standby gas treatment system (SGTS) filters, as shown in Fig. 12.

A strong hydrogen detonation occurred in the Unit No.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 No.3 and No.4. This might be reason why hydrogen detonation in Unit 4, where these were no nuclear fuels in reactor core.

The author pointed out to NISA that the added vent line might have acted as a means of hydrogen and fission products (FP) leaked through the SGTS and HVAC lines, as shown in Fig. 14. Because hydrogen and FP might flow back into each room through the exhaust gas ducts. The vent lines of each NPP should have been independent from the SGTS/ HVAC line.

The NISA ordered to the licensees to make a new independent vent line for filtered vent system. This is the one of the point of lessons and learn. There were no accident reports about Fukushima-Daiichi which point out the vent system's fault and potential risk.

3 Countermeasures

There are a lot of good practices of countermeasures to prevent the FP release and tsunami in the world. TEPCO and NISA should be considered such systems.

3.1 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. 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.

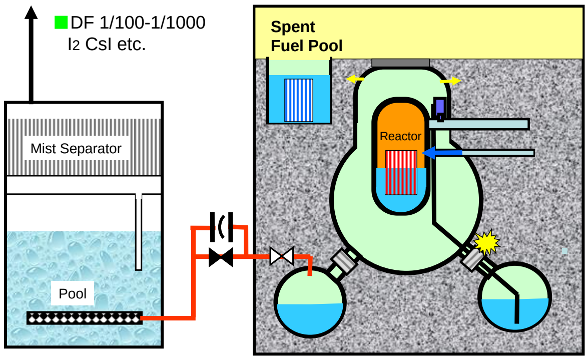


Fig.15 Filtered containment venting system

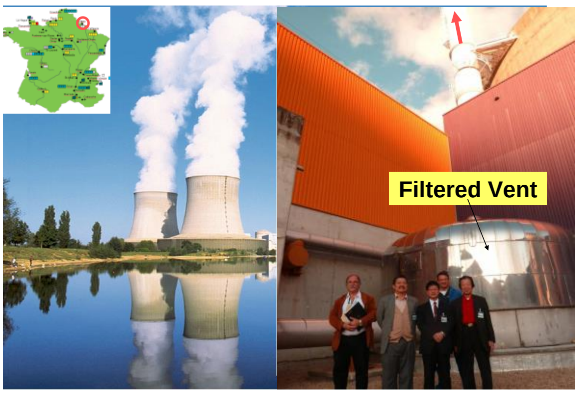


Fig. 16 Installed FCVS in Chooz NPP (PWR), France [6].

Fig. 17 FCVS in Leibstadt NPP (BWR), Switzerland[6].

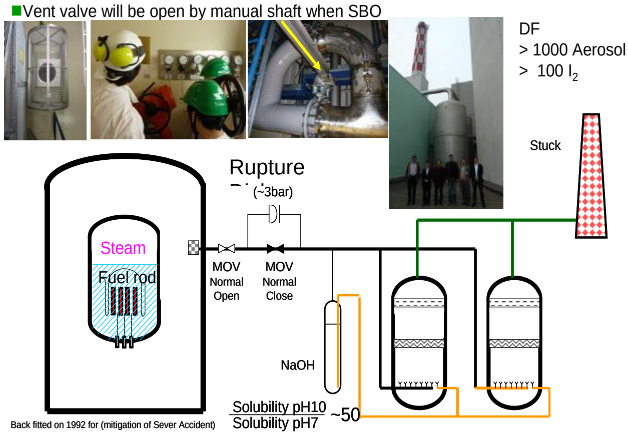


Fig. 18 Schematic diagram of FCVS in Leibstadt NPP[6].

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 having 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.

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

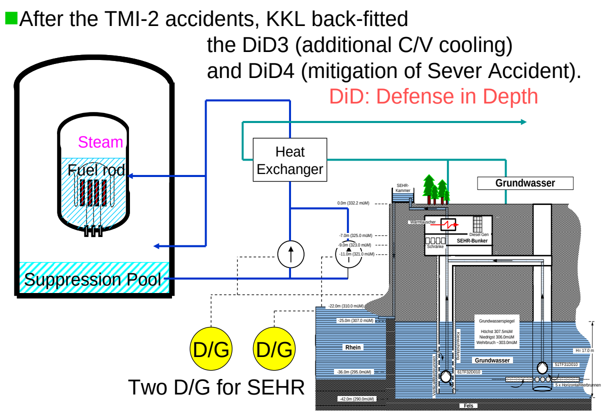


Fig.19 SEHR (Special Emergency Heat Removal) System[6].

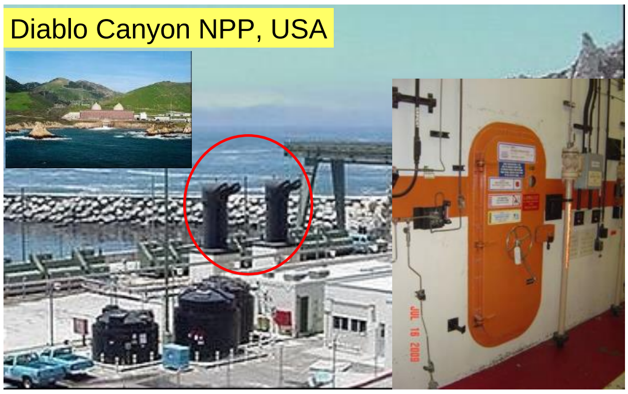
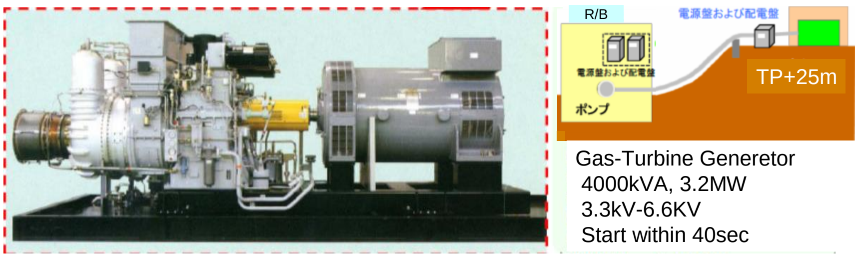


Fig.20 Tsunami protection at Diablo Canyon NPP,USA [6].

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

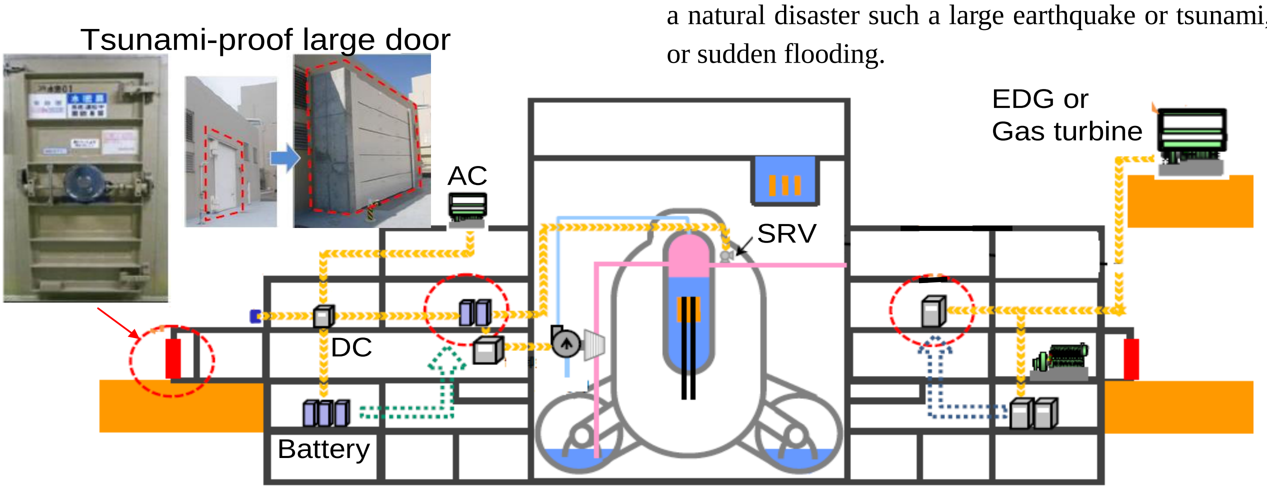


(b) 3.2 MW Gas-turbine generator to be installed at 25 m height(Chubu Electric).

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 both PWR and BWR plants 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 a large earthquake or tsunami, or sudden flooding.



(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].

4 Concluding remarks

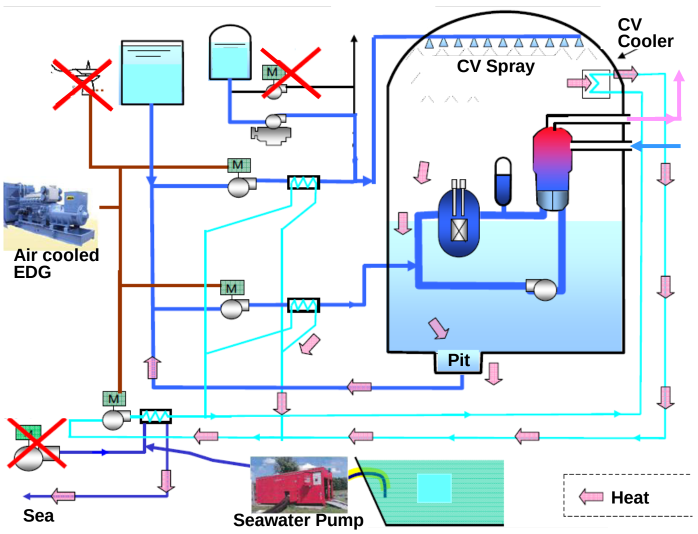
There are a lot of good practices of countermeasures to prevent the FP release and tsunami in the world. TEPCO and NISA should be considered such systems. The Fukushima Daiichi NPP accident could have been quickly brought under control if sufficient counter-measures had been installed, such as waterproof doors and mobile power sources.

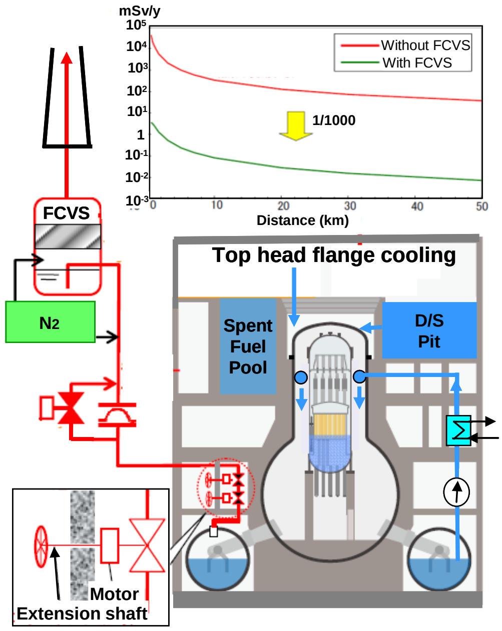
In Europe, as a result of the lessons learned from the TMI and Chernobyl accidents, heat removal systems and filtered containment venting systems had already been installed.

Using the lessons learned from this analysis of the Fukushima Daiichi NPP accident, the author hope to contribute to achieving 1st class nuclear safety throughout the world.

Therefore, the author recommend such proposals as shown below to provide scientific and technological support. These lessons can be reflected in measures taken by institutions and government agencies, thereby enhancing the safety of the large number of nuclear power plants in operation throughout the world:

1) Enhance aseismic electric device to prevent loss of external power by earthquake, SF_6 gas insulated switchgear (GIS) and flexible insulators should be installed for transmission line.
2) Station blackout (SBO) occurred by wetting emergency diesel generator (EDG), power center (P/C), DC Battery, I&C and cell phone. Therefore, water proof door or hatches and mobile power should be installed on hill.
3) To prevent the core meltdown by loss of water injection, diversity of water injection and heat sink is very important.
4) To prevent the loss of containment function by over heat damage, containment vessel cooling and filtered containment vent system (FCVS) should be installed independently from hard vent system.





(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].

List of Nomenclature

AC: alternating current, DC: direct current,
AM: accident management,
AO: air operated valve, MO: motor operated valve
CRD: control rod drive
CV: containment vessel,
DW: drywell, WW: wet well
EDG: emergency Diesel generator,
FCVS: filtered containment venting system,
FP: fission product
GIS: gas insulated switchgear,
HVAC: house ventilation and air conditioner,
IC: isolation condenser,
JNES: Japan Nuclear Energy Safety Organization
M/C: metal clad switchgear,
METI: Ministry of Economy, Trade and Industry,
MEXT: Ministry of Education, Culture, Sports, Science & Technology
NISA: Nuclear and Industrial Safety Agency,
NRA: Nuclear Regulation Authority
P/C: power center,
R/B: reactor building, T/B: turbine building,
RCIC: reactor core isolation cooling system,
RPV: reactor pressure vessel, RV: reactor vessel,
SA: severe accident, SBO: station blackout,
S/C: suppression chamber,
SEHR: special emergency heat removal,
SGTS: standby gas treatment system,
S/P: suppression pool,
SRV: safety relief valve,
TIP: traversing incore neutron probe.

References

[1] NARABAYASHI, T., and SUGIYAMA, K.: "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 and 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: Fukushima Daiich NPPs Accidents Investigation meeting's report (Interim report), (2011), (http://icanps.go.jp/post-1.html), (in Japanese).

[6] NARABAYASHI, T.: 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] Federation of Electric Power Companies: Report on making efforts of licensees to ensure the NPPs safety in Japan, (March 7, 2012). (http://www.nisa.meti.go.jp/shingikai/800/28/240307/240307-1.pdf).