Fukushima Nuclear Power Plant Accident and Thereafter

Tadashi Narabayashi

Abstract Many lessons can be learned from the Fukushima Daiichi Nuclear Power Plant (NPP) accident. First, if an isolation condenser (IC) had continued to operate, the accident would have been terminated soon. Reactor core isolation cooling (RCIC) steam turbines also stopped because loss of battery power in Units No. 2 and No. 3 and temperature and pressure in each primary containment vessel (PCV) were so high that the accident management water injection took too long. After the loss of emergency core cooling system (ECCS) and IC core cooling, fuels in the core melted down. Leak of fission product and hydrogen began because of high-temperature damage to the PCV packing. A hydrogen explosion occurred in the upper floor in the reactor building in Units 1, 3, and 4. The Nuclear Regulation Authority (NRA) enforcement of the New Regulatory Requirements was based on the concept of "defense in depth," for commercial nuclear power reactors from July 8, 2013. It is hoped that the lessons learned from this accident will improve the safety of nuclear power plants worldwide.

Keywords Fukushima Daiichi Nuclear Power Plant • Isolation condenser • Emergency core cooling system • Hydrogen explosion • New regulatory requirements • Defense in depth

1 Introduction

On March 11, 2011, Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station (NPS) was struck by a tsunami caused by the Tōhoku-Pacific Ocean Earthquake, resulting in nuclear accidents in Units 1 through 4 [1, 2]. With the aim of improving the safety of nuclear power plants (NPPs) worldwide, we summarize the lessons 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 accident causes and developing countermeasures for other NPPs in Japan as a member of the Committee for the Investigation of Nuclear Safety of the

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Atomic Energy Society of Japan. He is an advisory meeting member of the Nuclear and Industrial Safety Agency (NISA) and Nuclear Regulation Authority (NRA) 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 [3–5].

2 Investigation of Accidents

Figure 1 compares flooded areas at each NPP. Although other NPPs such as Fukushima Daini, Onagawa, and Tokai Daini were also struck by the tsunami, they all were able to safely terminate operation, until the cooldown condition. The Fukushima Daini NPP succeeded in safe shutdown, even though Unit 1 was affected by water flooding through hatches and an emergency diesel generator (EDG) air intake. 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. At the Fukushima Daiichi NPP, Unit 5 was brought under control by using EDG power from Unit 6 [3].

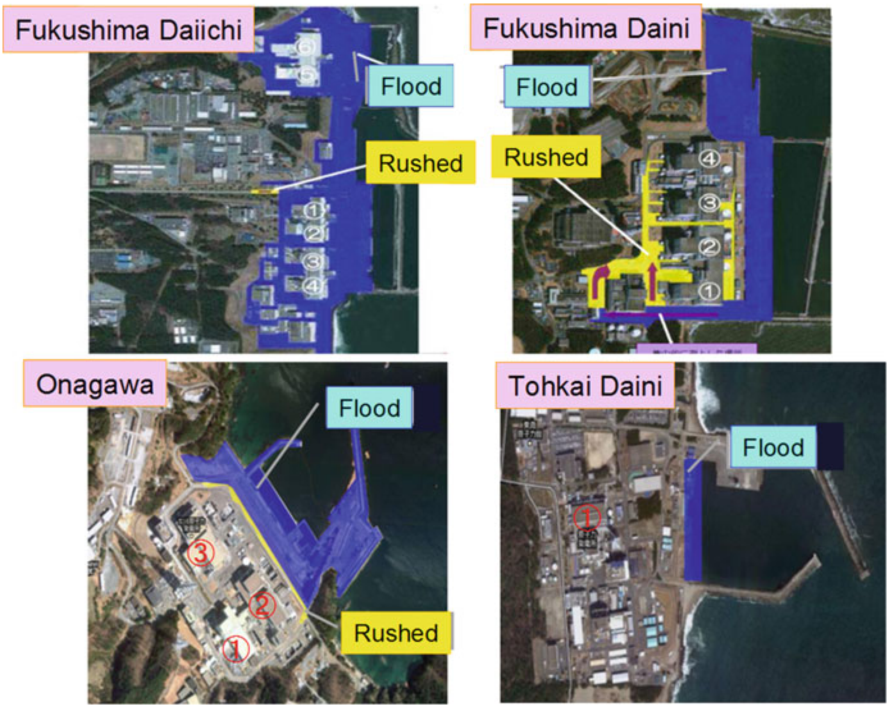


Fig. 1 Comparison of flooded areas at each NPP [3]

Figure 2 shows a comparison of the flood damage to EDGs. At Units 1 through 4, there was a complete loss of both AC power from the EDGs and DC power, and this was the main cause of the ensuring severe accidents [3] (Table 1).

At Unit 1, DC battery power was lost in the main control room. This caused motor-operated (MO) isolation valves to undergo fail-close action, thereby cutting off the isolation condenser (IC), as shown in Fig. 3. This was a fail-dangerous system under such situation. If the IC had continued to operate, the situation would soon have been brought under control [1].

After the loss of both the emergency core cooling system and IC core cooling, primary containment vessel (PCV) pressure increased. Water level measurement drifted because of water evaporation in the reference leg (Fig. 4). Radiation level increased at a turbine building (T/B). There was a hydrogen explosion the after suppression chamber (S/C) wet venting.

As shown in Fig. 5a, both Modular Accident Analysis Program (MAAP) code analysis results and actual data suggest that depressurization of the reactor pressure vessel (RPV) began before its bottom failed. This might have been caused by the melting of traversing in-core probe (TIP) tubes in the core. It was confirmed that the TIP room radiation level is very high even now. Figure 5b shows that the measured water level measurement drifted by more than 4 m owing 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 instrumentation piping.

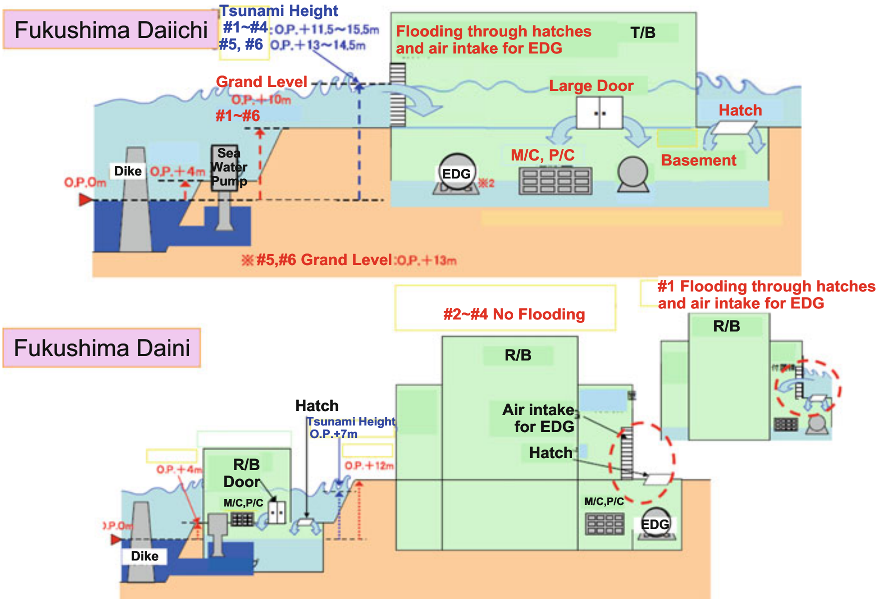
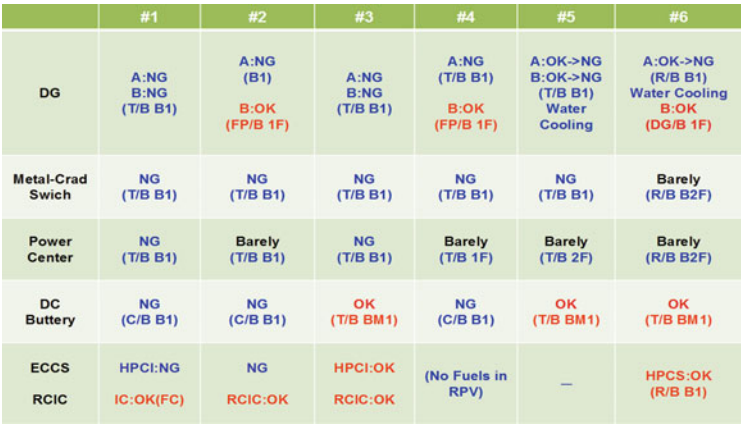


Fig. 2 Comparison of flood damage to emergency diesel generators for Fukushima Daiichi and Daini NPPs [3]

Table 1 Components damaged by tsunami at each unit of Fukushima Daiichi NPP [3]



	#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)

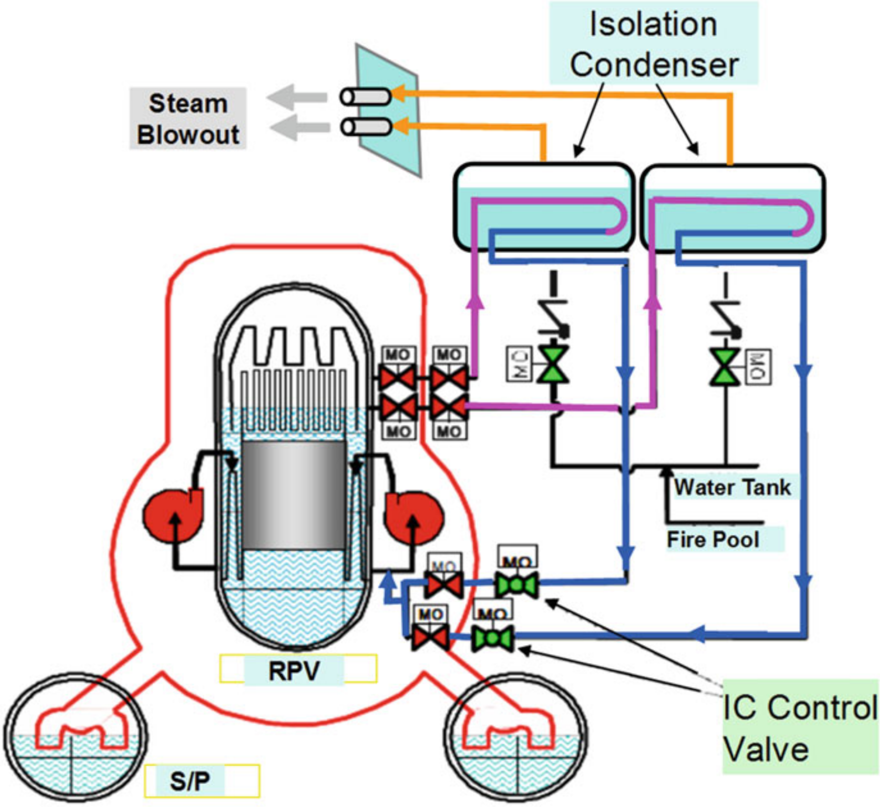


Fig. 3 Isolation condensers in Fukushima Daiichi Unit 1 [1]

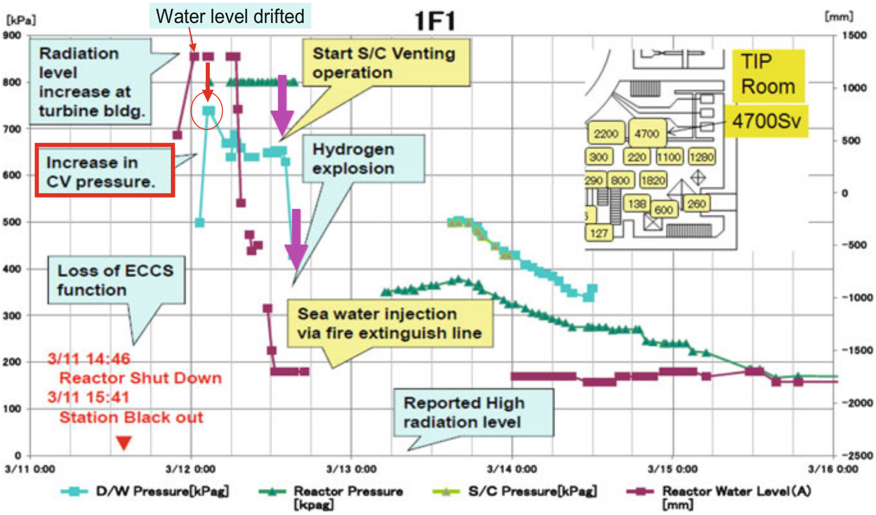


Fig. 4 Measured pressure and water level in RPV and CV of Unit 1 [4, 7]

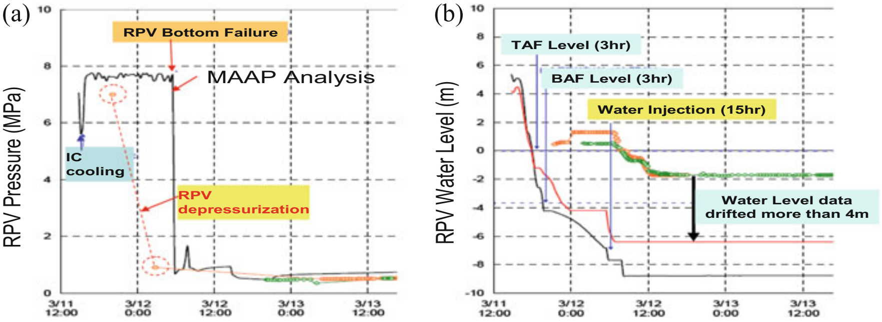


Fig. 5 MAAP analysis results compared with actual plant data for Unit 1 [3]. (**a**) Pressure in RPV. (**b**) Water level in RPV

At Unit 2, reactor core isolation cooling (RCIC) continued to function for about 3 days. Figure 6 shows that soon after the loss of RCIC water injection, the water level in the RPV declined. The safety relief valve (SRV) was opened and seawater injection started. But, RPV pressure shows fluctuation due to water evaporation and metal-water reaction in core. Dry well (DW) pressure increased from 400 to 750 kPa (abs), and PCV top flange leak began through silicon rubber O-ring. It was an initiation of severe contamination around the NPS. In the afternoon on March 15, wind blew toward Iidate village. Melted core relocation into the lower plenum caused the RPV bottom CRD pipe failure and PCV pressure and radiation level increased (Fig. 7). The radiation level was measured by containment atmospheric monitoring system (CAMS) [15].

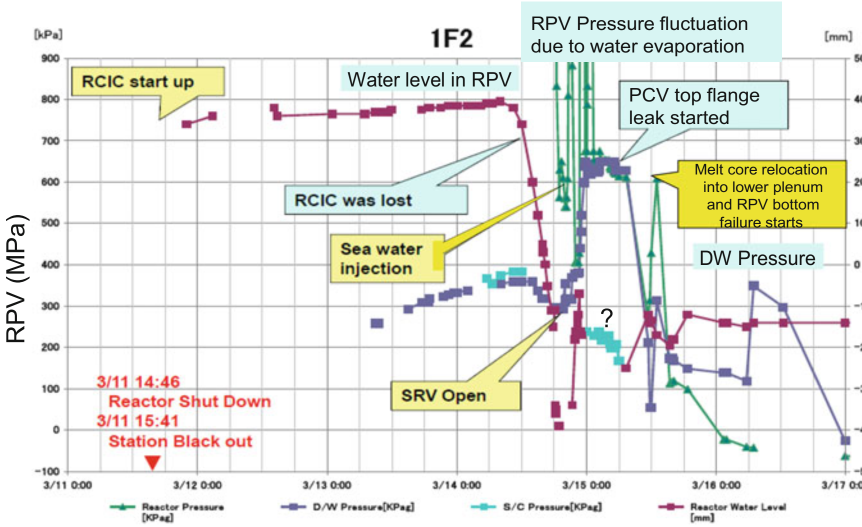


Fig. 6 Measured pressure and water level in RPV and PCV of Unit 2 [4]

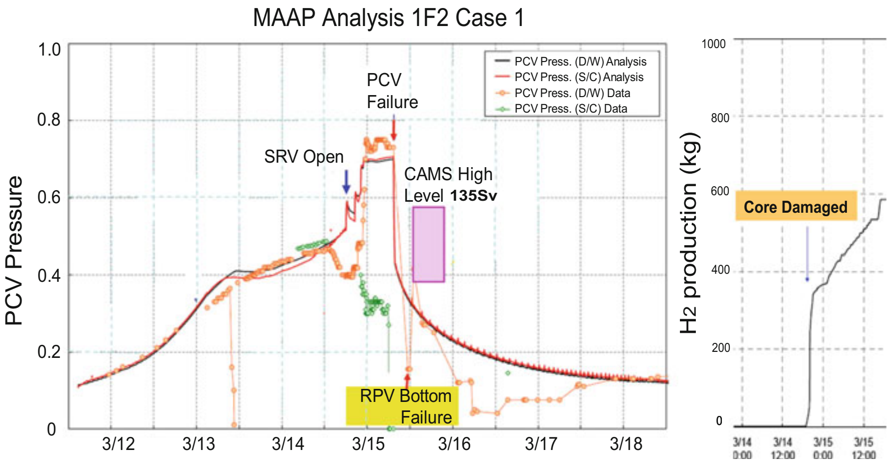


Fig. 7 MAAP analysis results compared with actual plant data for Unit 2 [15]

Figure 8 shows H_2 explosion in Unit Nos. 1, 3, and 4. Upon the occurrence of Unit 3's detonation, the blowout panel of Unit 2 was opened. Hydrogen in Unit 2 was released through the opened blowout panel and there was no explosion/ detonation in that unit. The sound of an explosion was reported near the S/C of Unit 2. However, examination of the data showed that this was due to a hydrogen detonation in the reactor building (R/B) of Unit 4. Soon after this detonation, DW pressure in Unit 2 decreased (Fig. 6). Figure 9 shows trends in monitored radiation

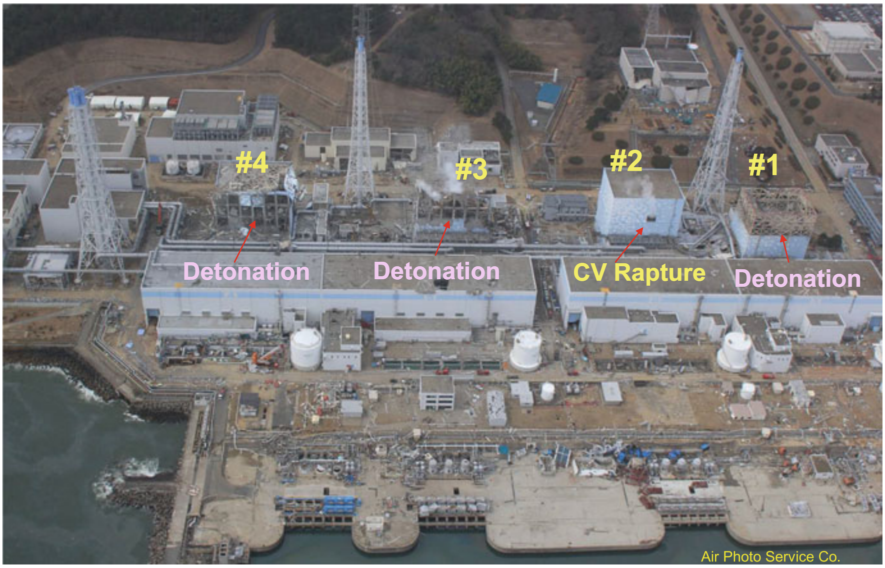


Fig. 8 H_2 detonations occurred after vent operations (Units 1, 3, and 4) [11]

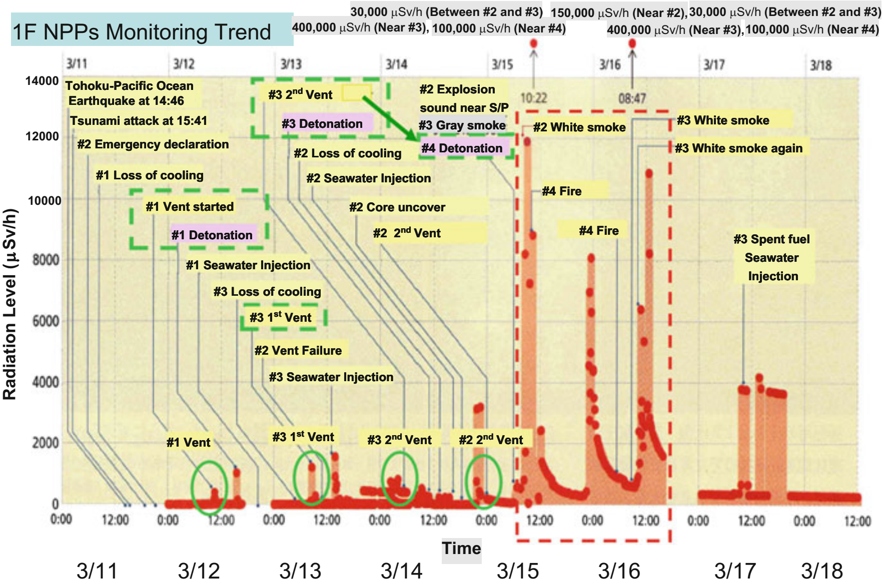


Fig. 9 Monitored radiation levels for Fukushima Daiichi Units 1, 2, 3, and 4 [2]

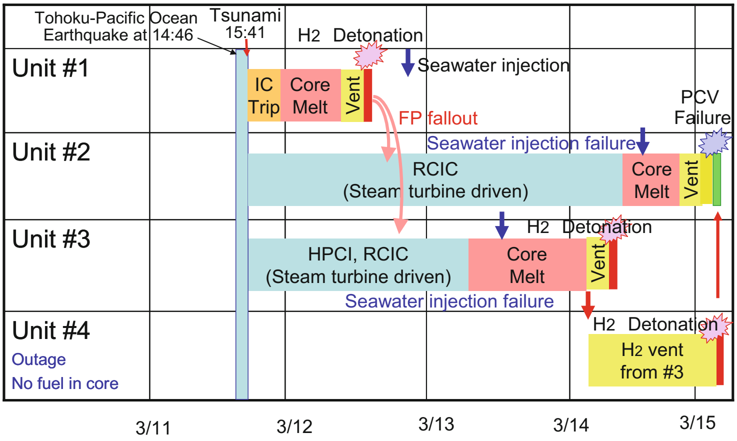


Fig. 10 Chain of major events at Units 1 through 4 causing severe accidents at Fukushima Daiichi NPS [11]

dose levels for Units 1, 2, 3, and 4, which can be compared with events illustrated in Fig. 10.

It appears that the explosion occurred after venting operations. The radiation level increased soon after the Unit 2 PCV rupture on March 15. A loss of core cooling occurred because of the IC trip in Unit 1, and the RCIC steam turbine also tripped owing to loss of battery power in Units 2 and 3. 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 for the chain of severe accidents in the four units of the Fukushima Daiichi NPS, as shown in Fig. 10 [11].

Figure 11 shows that the PCV top flange and hatches can act as leakage pathways. Hydrogen and FP flow upward by way of stairways and hatches. Although there were no nuclear fuels in the reactor 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 (Fig. 12) [3, 6].

There was a strong hydrogen explosion that occurred in the Unit 4 reactor building on March 14. The author pointed out to NISA that the harden vent line might have acted as a means of hydrogen and fission product (FP) leakage through SGTS and HVAC lines (Fig. 13). As shown in Fig. 14, it was confirmed that the SGTS filters were contaminated and all MO valves were open because of the fail-open design in Units 3 and 4. Seats of the butterfly valves were made of neo-plane rubber and damaged by iodine. This might have caused hydrogen detonation in Unit 4, where there were no nuclear fuels in the reactor core, because hydrogen and FP could have flowed back into each room through the exhaust gas ducts. The vent lines of each NPP should have been independent of the SGTS/HVAC line.

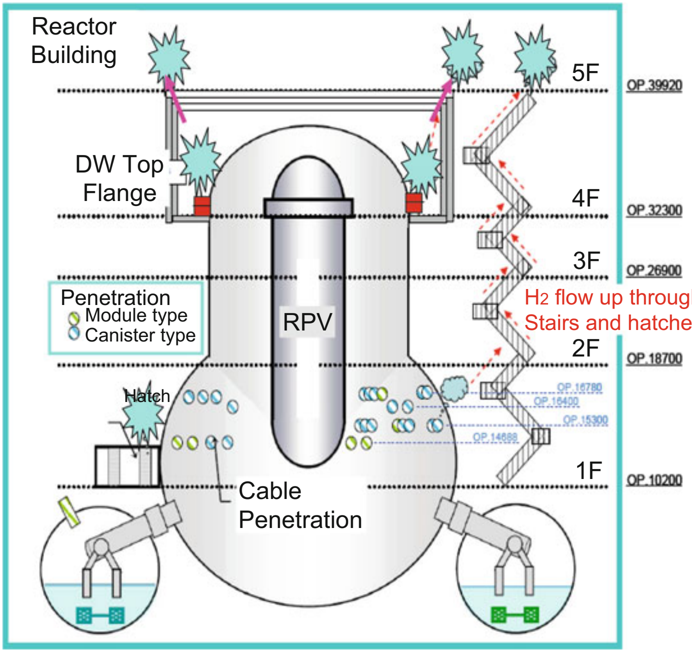


Fig. 11 Estimated leak path from dry well by overpressure and high temperature [3, 6, 11]

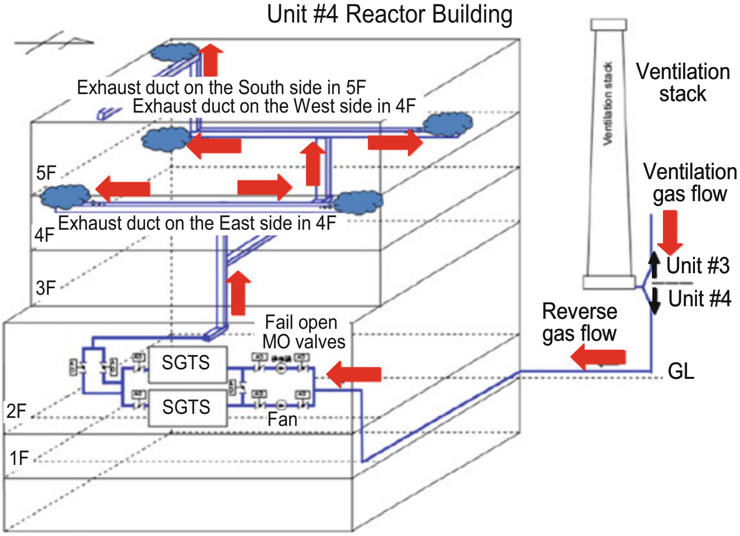


Fig. 12 H_2 gas flow into Unit 4 reactor building from Unit 3 [3, 6, 11]

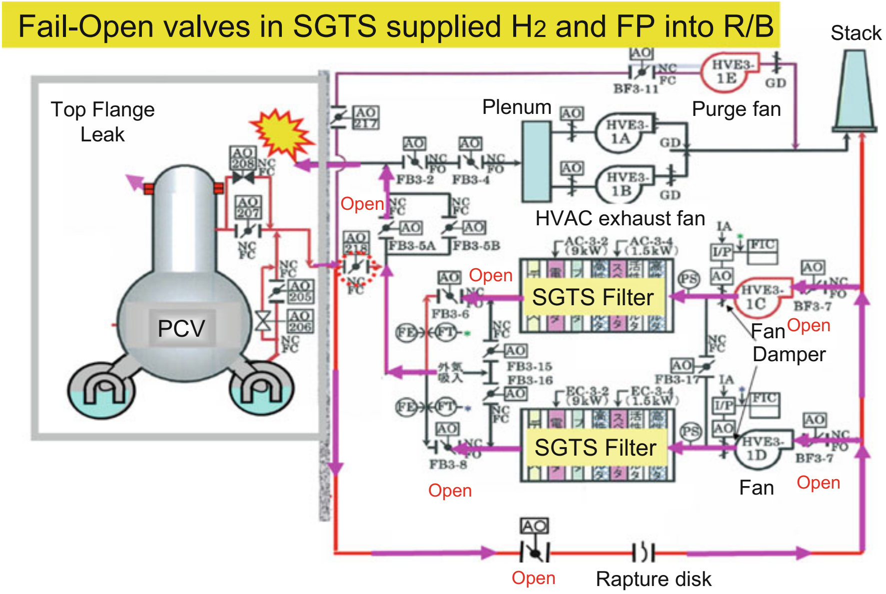


Fig. 13 Flow diagram of SGTS/HVAC and added hard vent system [11]

NISA ordered that the licensees make a new independent vent line for filtered vent system. This is one of the lessons learned. There were no accident reports about Fukushima Daiichi pointing out the vent system fault and potential risks. The causes of severe accidents and countermeasures are shown in Fig. 15, in which (P) means protection and (R) resilience action. Corium cooling was very effective in achieving the cold shutdown cooling, even after the containment failure at the Fukushima Daiichi NPPs.

3 Measures for Severe Accidents Installed in Western NPPs

There are many good practices of countermeasures to prevent FP release in the world. Based on the "defense-in-depth" (DiD) concept (Fig. 16), essential safety features were incorporated in the third layer for design basis accident (DBA) and prevention of simultaneous loss of all safety functions owing to common causes, such as tsunamis. Mobile safety features for the fourth layer such as mobile fire pumps should be deployed for core and containment cooling or corium cooling (Fig. 17) [9].

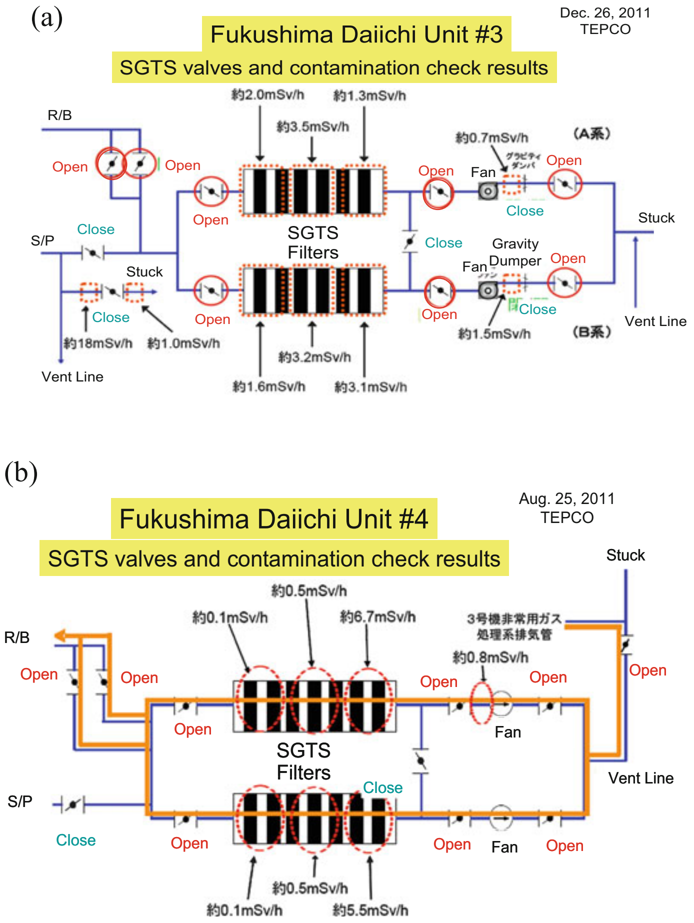


Fig. 14 Results of SGTS valve open/close status and filter contamination [2]. (**a**) Fukushima Daiichi Unit 3. (**b**) Fukushima Daiichi Unit 4

3.1 Filtered Containment Venting System

As shown in Fig. 18, after the Three Mile Island (TMI) Unit 2 and Chernobyl Unit 4 NPP accidents, countries such as France, Germany, Switzerland, Finland, and Sweden decided to install filtered containment venting systems (FCVS) to protect against radioactive material exhaust (Figs. 19 and 20) [8].

Figure 21 shows a schematic diagram of the FCVS installed in the Leibstadt NPP. Venting is automatically initiated when the CV pressure reaches the pressure set for the rupture disk. An operator who wishes to vent early can easily open the vent valve using a hand wheel drive shaft [8].

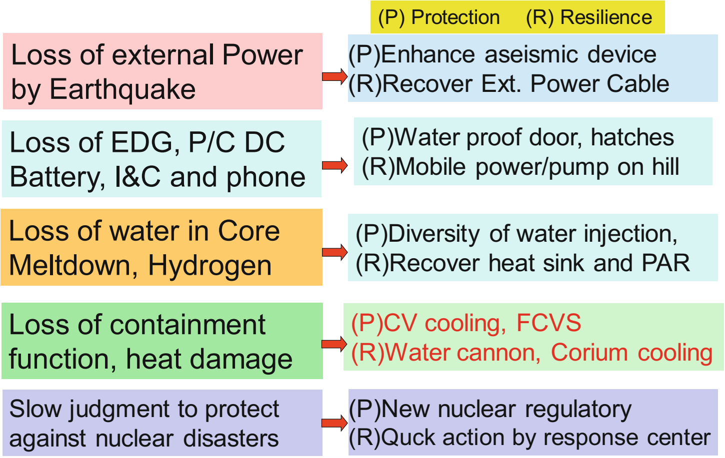


Fig. 15 Causes of severe accidents and countermeasures

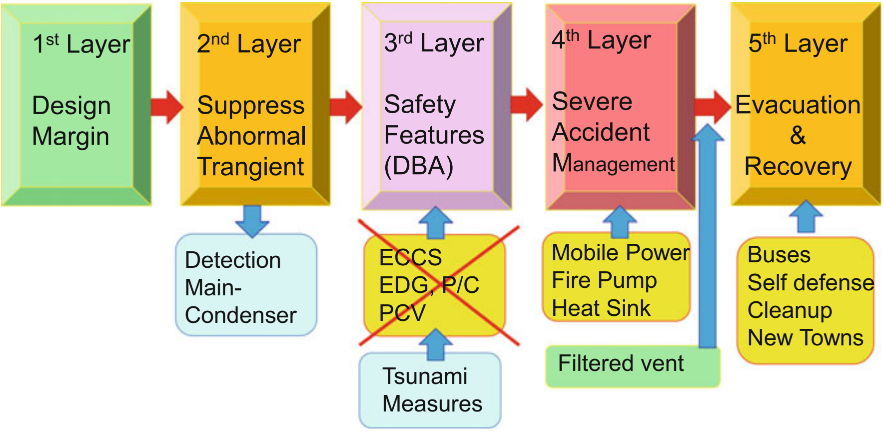


Fig. 16 Concept of "defense in depth" to terminate accidents

In the Fukushima Daiichi NPP accidents, operators should have closed numerous valves in the SGTS system and then opened the vent valve with an air compressor and connecting tubes, because of the station blackout condition. If a FCVS had been installed in the Fukushima Daiichi NPPs, environmental contamination by FP could have been avoided. The decontamination factor is about 1000 for aerosols and 100 for I_2.

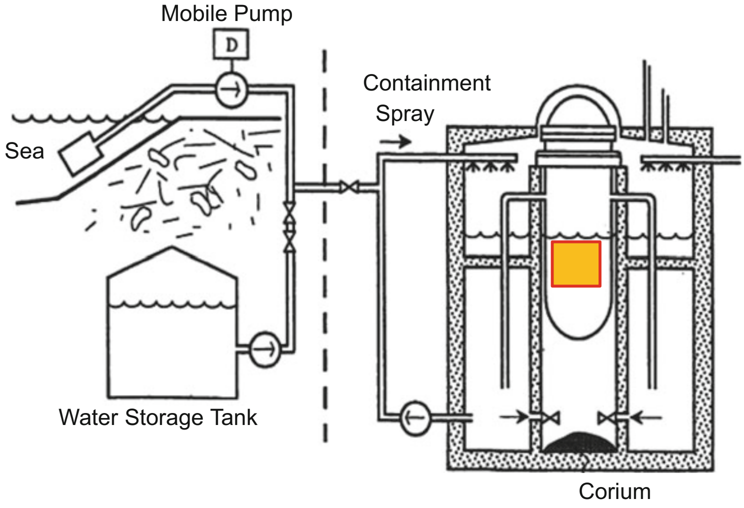


Fig. 17 Mobile safety features for severe accidents in DiD fourth layer [9]

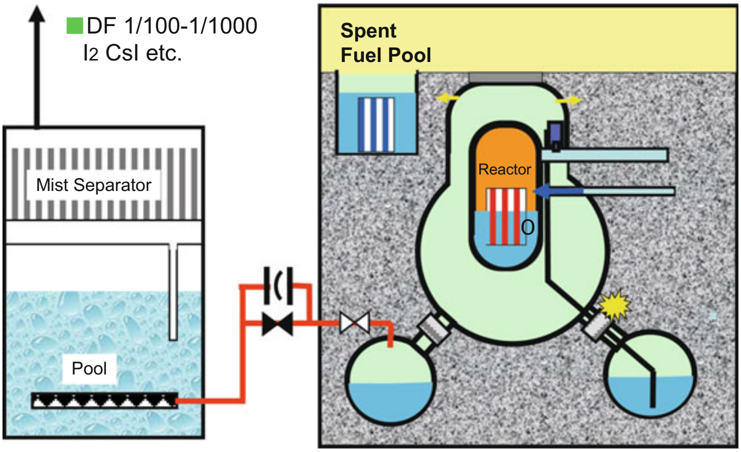


Fig. 18 Filtered containment venting system [8]

After the TMI-2 accident in 1979, Kernkraftwerk Leibstadt (KKL) backfitted the Leibstadt NPP with additional CV cooling (DiD 3) and a mitigation system for severe accidents (DiD 4). The backfitted system was called the Special Emergency Heat Removal (SEHR) system. This system was required by the Swiss regulatory body of Federal Nuclear Safety Inspectorate (ENSI) and Swiss Federal Office of Energy (HSK) in the late 1970s, shortly after the start of project planning, so it was the first backfitting in the present design of KKL.

Fig. 19 FCVS installed in Chooz NPP (PWR), France [8]

Fig. 20 FCVS in Leibstadt NPP (BWR), Switzerland [8]

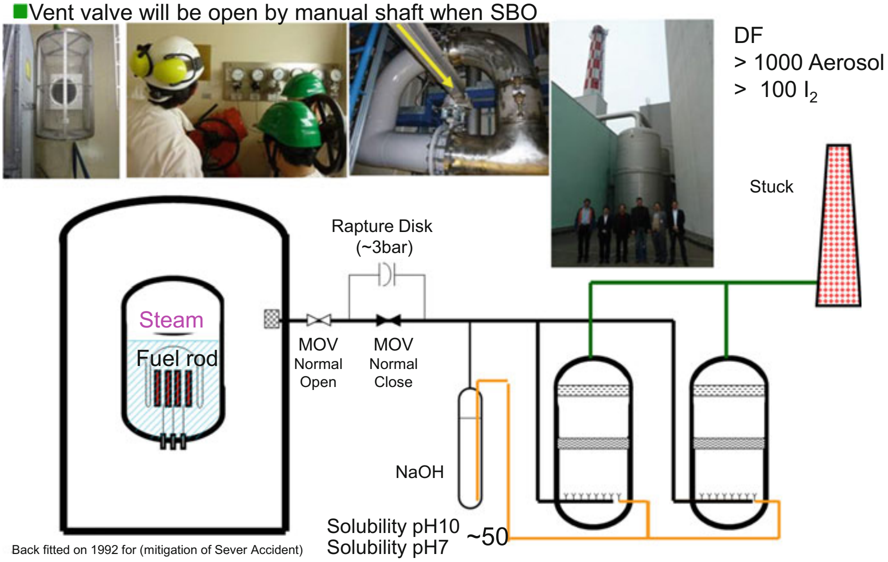


Fig. 21 Schematic diagram of FCVS in Leibstadt NPP [8]

3.2 Special Emergency Heat Removal System

Figure 22 shows SEHR system has two trains of heat removal system. The system was installed to remove a minimum of 36.3 MW (estimated decay heat: 1 % of nominal power). The system has two special EDGs and a huge underground well for water heat sink. The system is able to cool both the core and the CV, using the heat exchanger [8].

3.3 Tsunami Protection

When the Fukushima Daiichi NPP was attacked by the tsunami, all AC and DC power was lost because of damage to the EDGs, power center, metal clad switchgear, and seawater pump motors. At the Fukushima Daini NPP, AC power was able to restore seawater pumps by changing power cable and installing new pump motors. Therefore, it is very important to prevent the seawater flow into important areas. As shown in Fig. 23, at Diablo Canyon NPP in California, USA, the seawater pump motors are equipped with waterproof hatch-type doors and snorkel air ventilation piping for pump motor cooling.

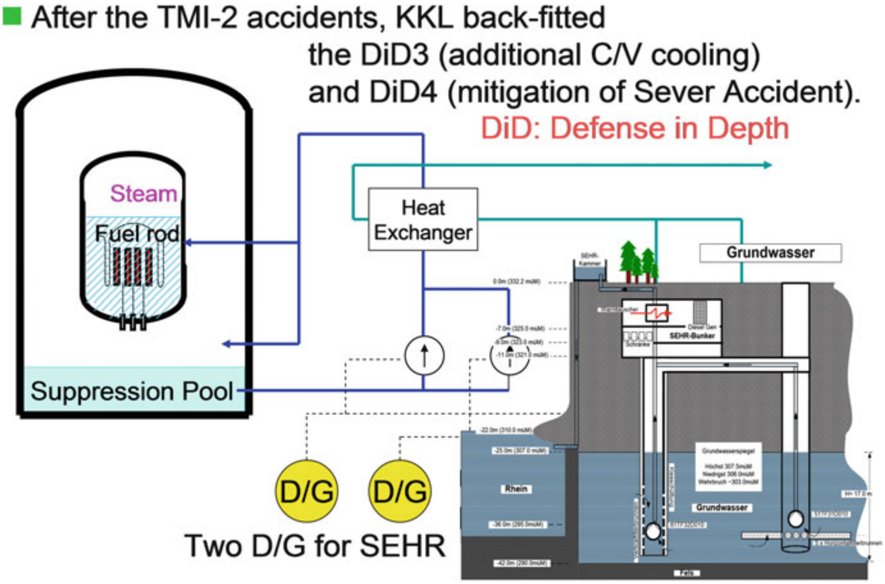


Fig. 22 Special Emergency Heat Removal (SEHR) system [8]

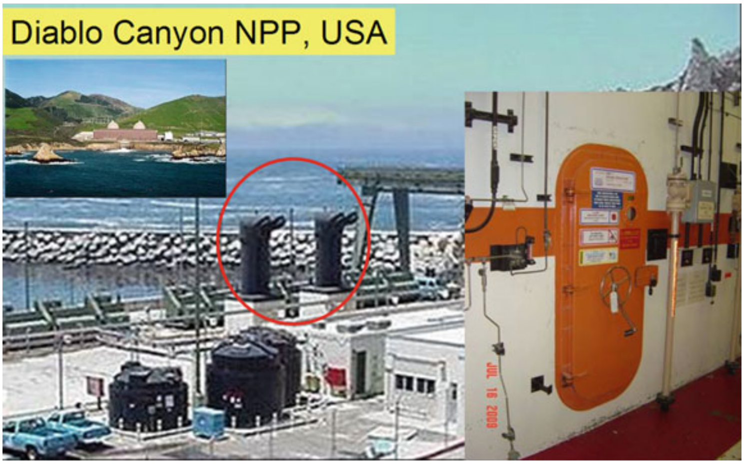


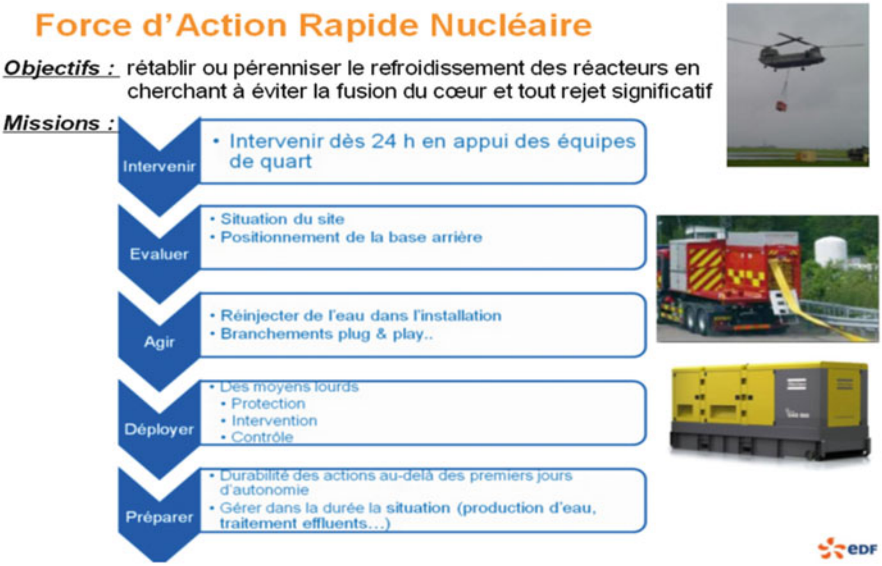
Fig. 23 Tsunami protection at Diablo Canyon NPP, USA [8]

3.4 Force for Action of Nuclear Rapid Response

According to French Nuclear Safety Authority (ASN) requirements, a Nuclear Rapid Response Force (FARN) was established by Électricité de France (EDF) (Figs. 24 and 25) [12]. The FARN should be able to deploy specialized teams and mobile equipment to respond in less than 24 h on station. As shown in Table 2, deployment began in late 2012 and will be completed in late 2015.

"Hardened safety core" equipment and organization are intended to prevent a severe accident or limit its development in case of extreme natural hazards beyond design basis conditions. The ASN requested that EDF define for each plant "a hardened safety core" of equipment and organizational measures needed to control the basic safety functions in emergency situations, before June 30, 2012. Main ASN decision letters for post Fukushima actions already consisted of 36 requirements issued on June 26, 2012.

"Hardened safety core" (HSC) equipment and organization and 16 associated and new requirements were issued in January 2014. The ASN requested in complementary safety assessment (CSA) installation of additional electrical supplies for double-wall containment venting and control room venting systems. Figure 26 shows sodium tetraborate baskets in reactor building sumps to reduce iodine release (to be studied), a passive autocatalytic recombiner (PAR) to limit releases in the event of core meltdown, robustness, and efficiency of filtering existing FCVS seismic reinforcement. EDF showed proposition; SMHV (millennial earthquake) filtration efficiency (iodine filtration) sodium tetraborate baskets will be added to



Force d'Action Rapide Nucléaire

Objectifs : rétablir ou pérenniser le refroidissement des réacteurs en cherchant à éviter la fusion du cœur et tout rejet significatif

Missions :

Intervenir
- Intervenir dès 24 h en appui des équipes de quart

Evaluer
- Situation du site
- Positionnement de la base arrière

Agir
- Réinjecter de l'eau dans l'installation
- Branchements plug & play..

Déployer
- Des moyens lourds
  - Protection
  - Intervention
  - Contrôle

Préparer
- Durabilité des actions au-delà des premiers jours d'autonomie
- Gérer dans la durée la situation (production d'eau, traitement effluents…)

EDF

Fig. 24 Nuclear rapid response force (FARN) established by EDF [12]

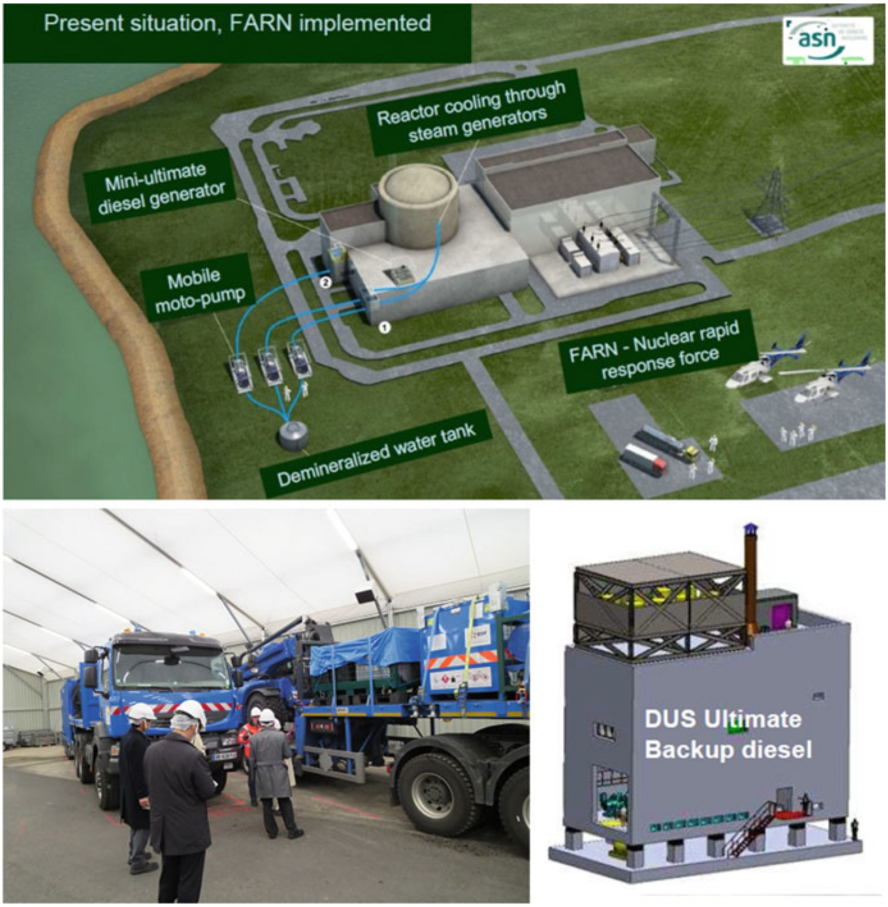
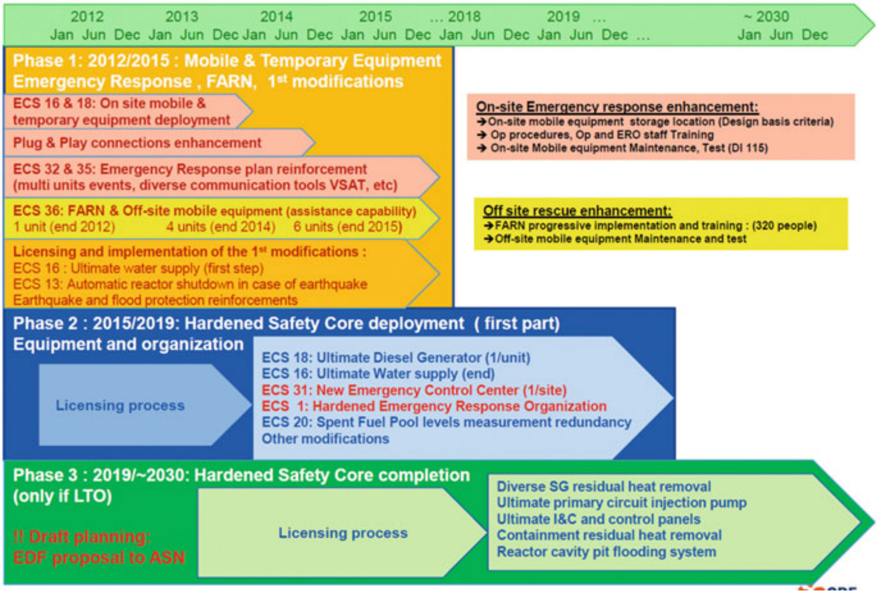


Fig. 25 FARN equipment, mobile trailer trucks, and backup diesel [12]

existing FCVS available for basic design situations. The main control room and site habitability are under study, and new on-site emergency control center will be built. In order to protect/prevent of groundwater pollution in the event of melt through of the reactor vessel by the corium during core melt, core catcher system for current PWR severe accident management (SAM) is under study. This involves core melt spread in the reactor pit to facilitate cooling (dry cavity), basement thickness increase with special concrete, HSC water injection system to cool the core melt, and an HSC containment cooling system (residual heat extraction with recirculation system and external heat exchanger).

Table 2 FARN hardened safety core deployment and completion schedule [12]



2012 2013 2014 2015 … 2018 2019 … ~ 2030
Jan Jun Dec Jan Jun Dec Jan Jun Dec Jan Jun Dec Jan Jun Dec Jan Jun Dec … Jan Jun Dec

Phase 1: 2012/2015 : Mobile & Temporary Equipment Emergency Response , FARN, 1st modifications

ECS 16 & 18: On site mobile & temporary equipment deployment

Plug & Play connections enhancement

ECS 32 & 35: Emergency Response plan reinforcement (multi units events, diverse communication tools VSAT, etc)

ECS 36: FARN & Off-site mobile equipment (assistance capability)
1 unit (end 2012) 4 units (end 2014) 6 units (end 2015)

Licensing and implementation of the 1st modifications :
ECS 16 : Ultimate water supply (first step)
ECS 13: Automatic reactor shutdown in case of earthquake
Earthquake and flood protection reinforcements

On-site Emergency response enhancement:
→On-site mobile equipment storage location (Design basis criteria)
→ Op procedures, Op and ERO staff Training
→ On-site Mobile equipment Maintenance, Test (DI 115)

Off site rescue enhancement:
→FARN progressive implementation and training : (320 people)
→Off-site mobile equipment Maintenance and test

Phase 2 : 2015/2019: Hardened Safety Core deployment (first part)
Equipment and organization

Licensing process

ECS 18: Ultimate Diesel Generator (1/unit)
ECS 16: Ultimate Water supply (end)
ECS 31: New Emergency Control Center (1/site)
ECS 1: Hardened Emergency Response Organization
ECS 20: Spent Fuel Pool levels measurement redundancy
Other modifications

Phase 3 : 2019/~2030: Hardened Safety Core completion (only if LTO)

!! Draft planning:
EDF proposal to ASN

Licensing process

Diverse SG residual heat removal
Ultimate primary circuit injection pump
Ultimate I&C and control panels
Containment residual heat removal
Reactor cavity pit flooding system

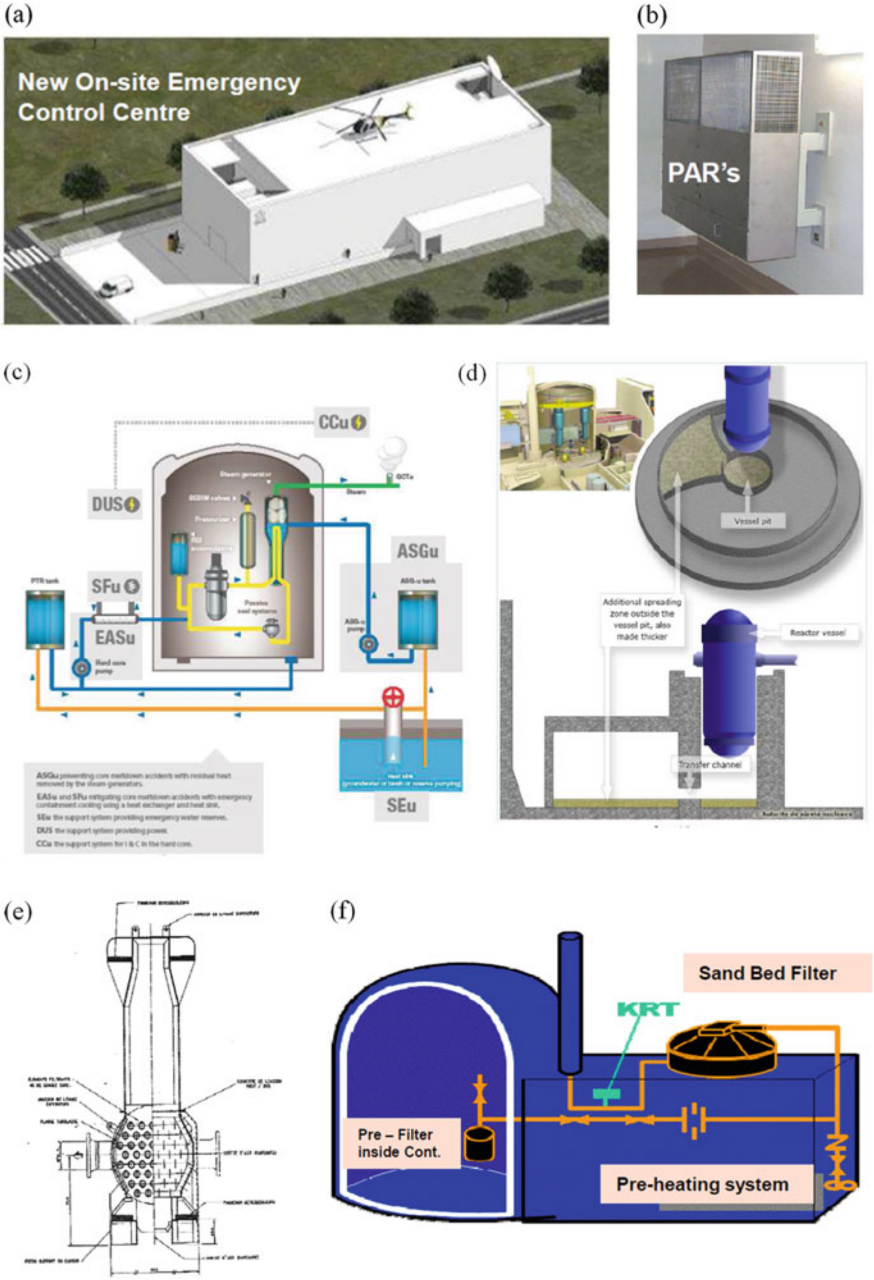
4 Countermeasures Based on New Regulatory Enforcement

4.1 *New Nuclear Regulatory Requirements in Japan*

A new nuclear regulatory body, the Nuclear Regulation Authority (NRA), was established on September 19, 2012. The NRA performed a complete review of safety guidelines and regulatory requirements [10].

On July 8, 2013, new regulatory requirements for commercial power reactors came into force. These requirements stipulate that all Japanese utilities conform to the regulatory requirement before restarting NPP. Design requirements must treat natural phenomena, such as volcanoes, tornados, and forest wildfires (Fig. 27). The new regulatory guidelines (Fig. 28) require direct deployment of mobile power, mobile pumps, fire engine, and installation of tsunami protection. Design requirements should be prepared to protect against cable fire between the reactor building and main control room and against internal inundation by waterproof areas of important safety components and systems.

New design requirements for severe accidents require measures such as mobile powers, mobile pumps, fire engines, and water tanks or reservoirs to protect core



ASGu preventing core meltdown accidents with residual heat removed by the steam generators.

EASu and SFu mitigating core meltdown accidents with emergency containment cooling using a heat exchanger and heat sink.

SEu the support system providing emergency water reserves.

DUS the support system providing power.

CCu the support system for I & C in the hard core.

Fig. 26 Severe accident countermeasures by EDF [12, 13]. (**a**) New on-site emergency control center. (**b**) PAR (Auto passive catalytic recombiner). (**c**) Core and SG water injection cooling system. (**d**) Core catcher for current PWRs. (**e**) Pre-filter with sodium tetra-borate baskets. (**f**) Seismic reinforced FCVS with iodine pre-filter

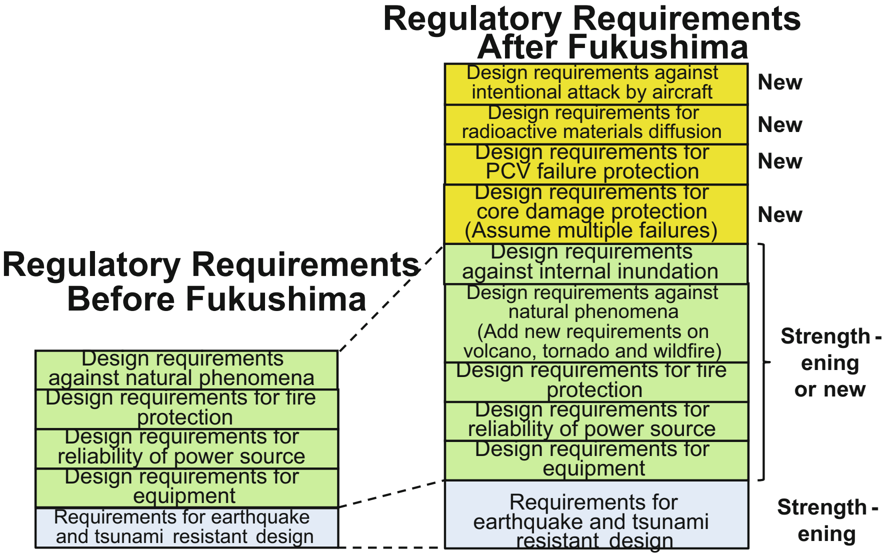


Fig. 27 Regulatory requirement comparison for before and after Fukushima [10]

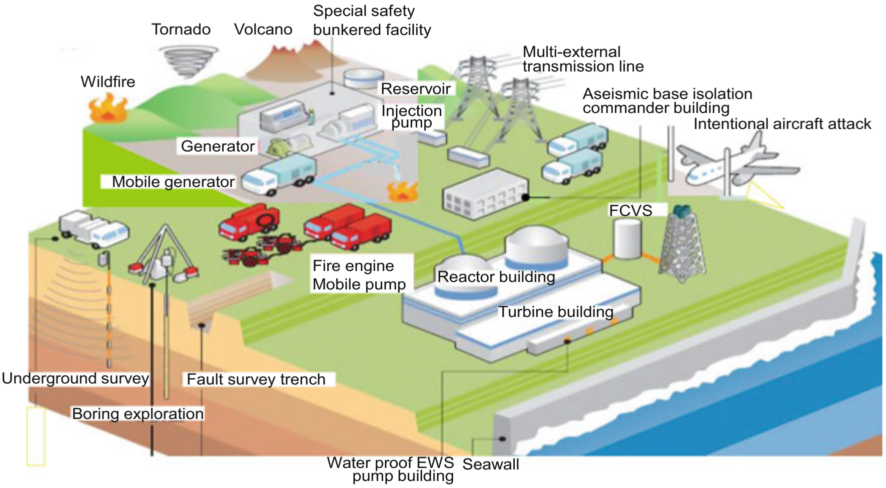


Fig. 28 Enforcement of new regulatory requirements, from July 2013 [19]

damage and to protect containment vessel failure. A bunker-type underground building (Fig. 29) should be constructed to control reactor cold shutdown against intentional attack by aircraft, within a 5-year grace period after approving construction permission.

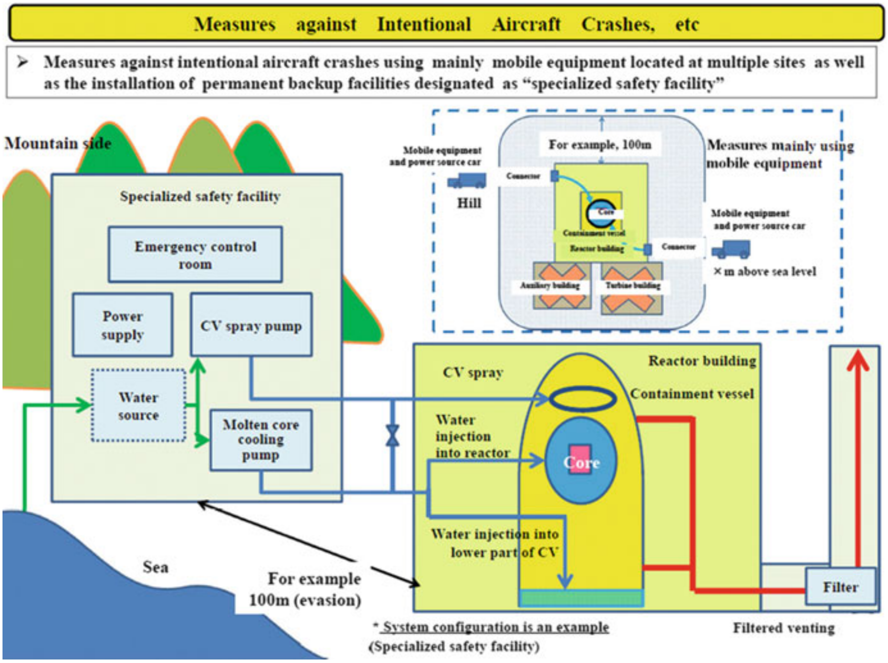


Fig. 29 Measures against intentional aircraft crashes [10]

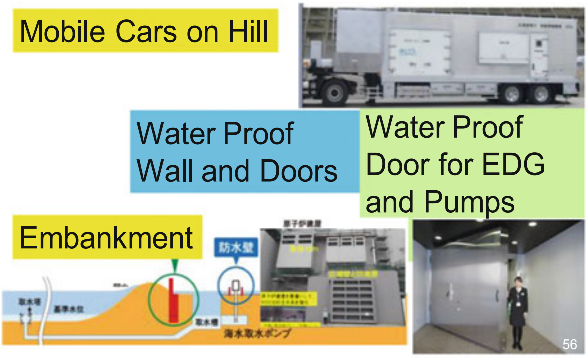


Fig. 30 Tsunami protection concept based on the defense in depth [11]

4.2 *Tsunami Protection Examples*

Tsunami protection is very important in preventing and protecting against severe accident such as what occurred at Fukushima Daiichi. Figure 30 shows tsunami protection concept based on the DiD. Embankments/seawalls are the primary tsunami protection, waterproof walls and doors at entrances to the reactor building

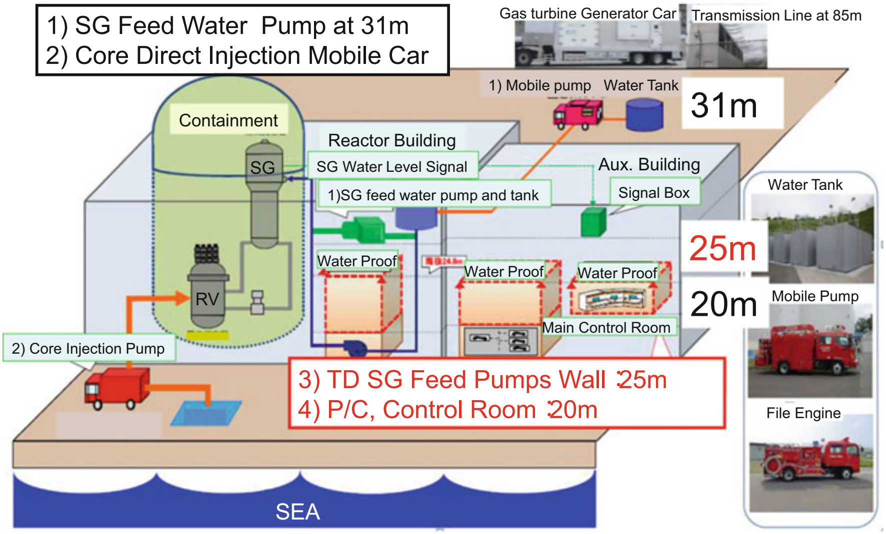


Fig. 31 Tsunami protection measures at Tomari NPS (PWR) [14]

are second, waterproof doors for EDG and pump rooms are third, and mobile gas turbine cars on hill are fourth.

Figure 31 shows tsunami protection measures at Tomari NPS of Hokkaido Electric Power Co. Inc., including a large mobile gas turbine generator and steam generator (SG) feed water pump in a parking area of 31 m height from sea level. Tsunami-proof doors and balconies have been installed in the reactor and auxiliary buildings. Turbine-driven feed pumps for SG are protected against tsunami of 25 m height. The power center (P/C) in the main control room is protected against those of 20 m height.

Figure 32 shows tsunami protection measures at Hamaoka NPS of Chubu Electric Power Co. Inc. A large tsunami wall of 22 m height and 1.6 km length has already been constructed. There is a snorkel building for EWS pumps and 400 kVA (3.2 MW) gas turbine generator at 25 m height. A cross-sectional view of tsunami measures and water reservoir is shown in Fig. 33.

Figure 34 shows examples of tsunami protection measures at NPSs, such as gas turbine generators, an oil tank, and snorkel building at Shimane NPS. At Kashiwazaki-Kariwa NPS, there are a large wall, door and balconies, mobile cooling car, and fire engines. Table 3 shows typical examples of measures that meet requirements at Shimane and Kashiwazaki-Kariwa NPS.

4.3 Tornado Protection Examples

Figure 35 shows a tornado evaluation method and measures for seawater pumps. Tornado wind streamlines were calculated using a model designed by Dr. Fujita.

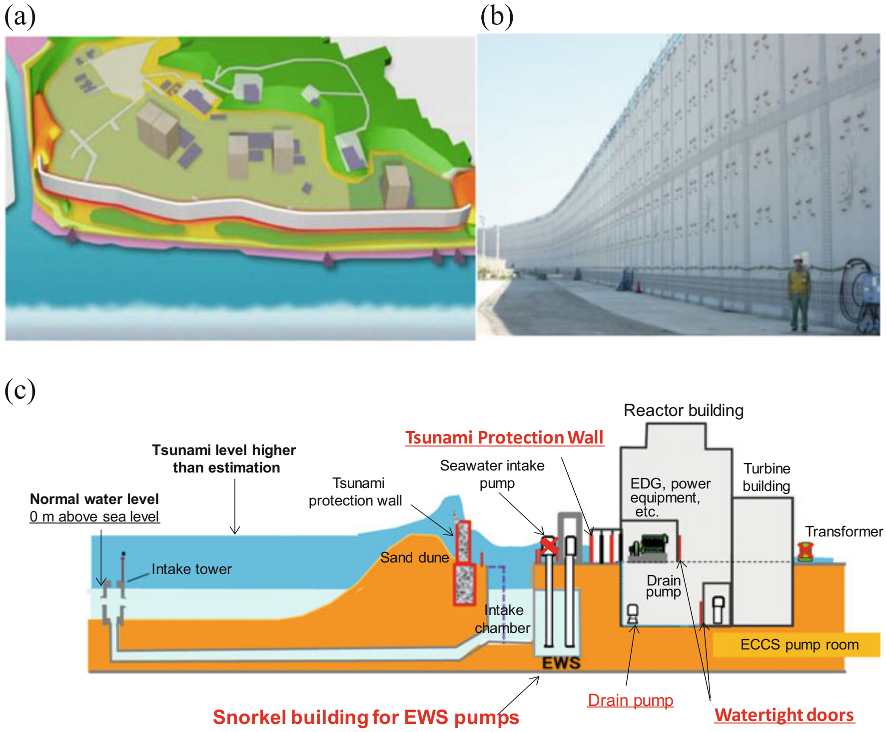


Fig. 32 Tsunami protection measures at Hamaoka NPS (BWR) [14]. (**a**) Tsunami wall (22 m × 1.6 km). (**b**) Complete tsunami wall construction. (c) Cross sectional view of tsunami measures

Based on the wind field, a missile analysis was conducted for both ground level and 40 m height in particular. Final missile speed was used to estimate its kinetic energy for shield strength to protect a seawater pump, reactor building, or other safety-related components.

4.4 PWR NPS to Meet the New Requirements for Restart

In September 2014, Sendai NPS Units 1 and 2 (Kyushu Electric Power, Co.) received NRA permission to upgrade their safety systems as required by the post-Fukushima regulations. This was followed by a construction permit and detailed design review by the NRA. Figure 35 shows the complete cooling strategy for station blackouts (SBOs) to protect against severe accident (SA) for PWR. Fuels in the core are cooled by SGs. A water supply for the secondary side of SG is used to cool the primary side of U tube. The core on the primary loop side is cooled by natural recirculation driven by gravity. In the inverted U tube, the outlet cold-side

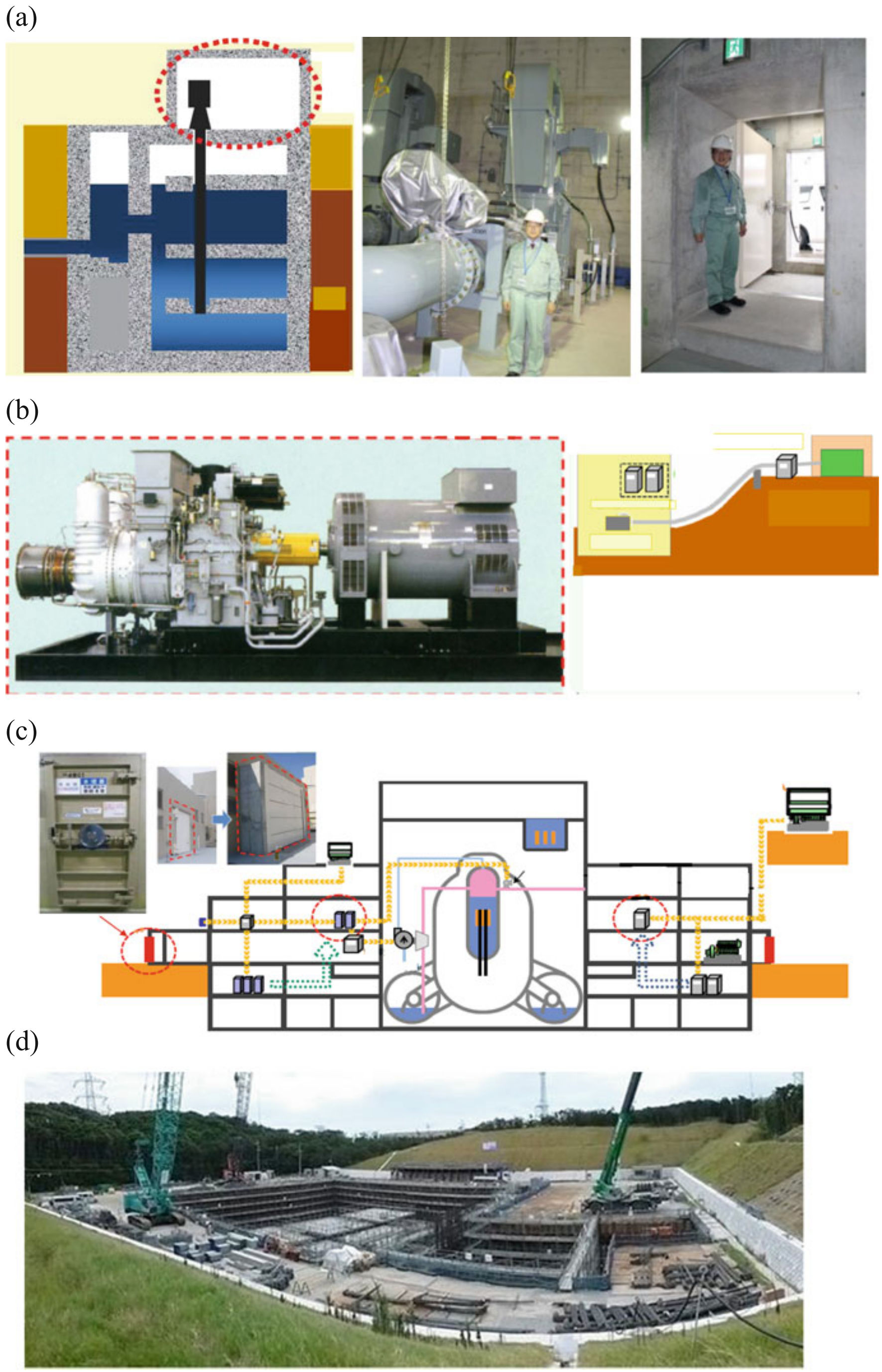


Fig. 33 Tsunami protection measures under construction at Hamaoka NPS [14]. (**a**) Snorkel building for EWS pumps. (**b**) 3.2 MW gas turbine generator installed at 25 m height. (**c**) Cross-sectional view of tsunami measures. (**d**) Water reservoir

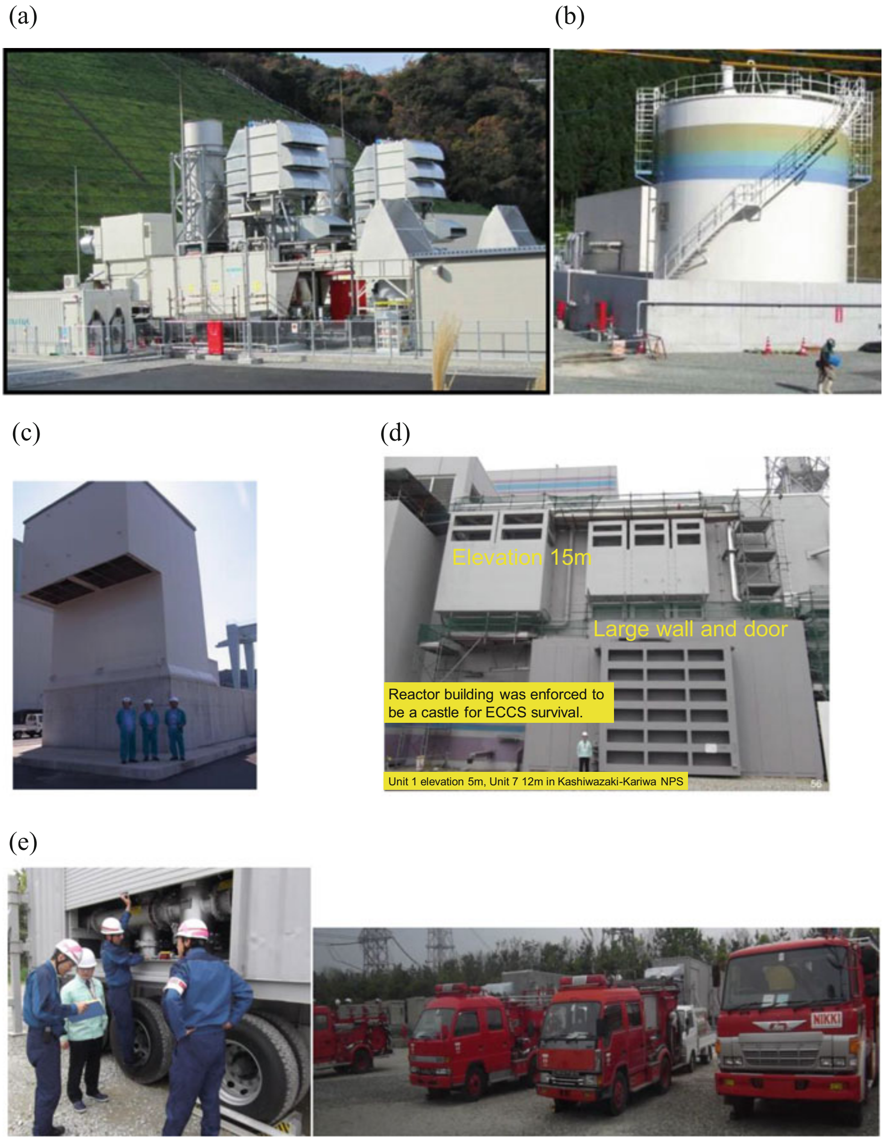
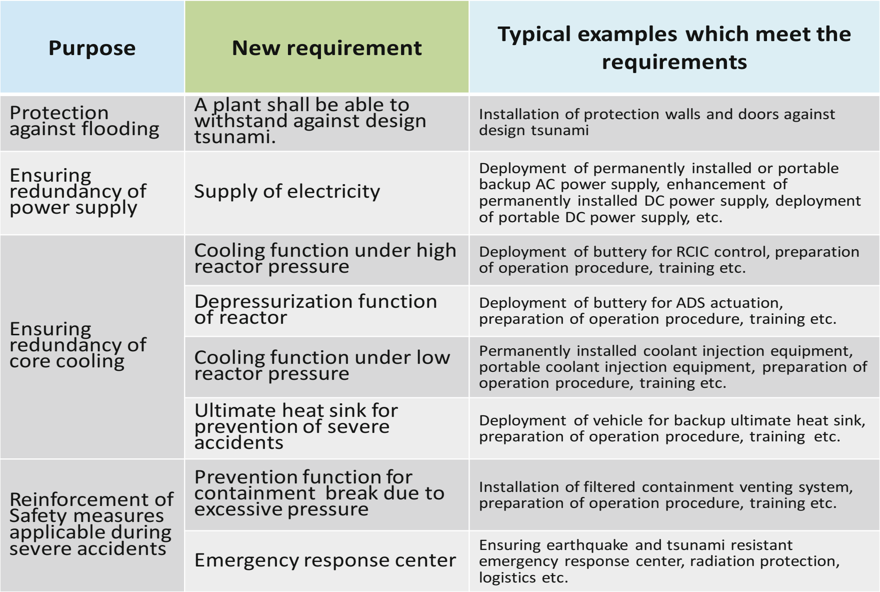


Fig. 34 Examples of tsunami protection measures at NPSs [14]. (**a**) Gas turbine generator at Shimane NPS. (**b**) Oil tank at Shimane NPS. (**c**) Snorkel building at Shimane NPS (**d**) Large wall, door and balconies at Kashiwazaki-Kariwa NPS. (**e**) Mobile cooling car and fire engines at Kashiwazaki-Kariwa NPS

Table 3 Typical examples meeting requirements



Purpose	New requirement	Typical examples which meet the requirements
Protection against flooding	A plant shall be able to withstand against design tsunami.	Installation of protection walls and doors against design tsunami
Ensuring redundancy of power supply	Supply of electricity	Deployment of permanently installed or portable backup AC power supply, enhancement of permanently installed DC power supply, deployment of portable DC power supply, etc.
Ensuring redundancy of core cooling	Cooling function under high reactor pressure	Deployment of buttery for RCIC control, preparation of operation procedure, training etc.
	Depressurization function of reactor	Deployment of buttery for ADS actuation, preparation of operation procedure, training etc.
	Cooling function under low reactor pressure	Permanently installed coolant injection equipment, portable coolant injection equipment, preparation of operation procedure, training etc.
	Ultimate heat sink for prevention of severe accidents	Deployment of vehicle for backup ultimate heat sink, preparation of operation procedure, training etc.
Reinforcement of Safety measures applicable during severe accidents	Prevention function for containment break due to excessive pressure	Installation of filtered containment venting system, preparation of operation procedure, training etc.
	Emergency response center	Ensuring earthquake and tsunami resistant emergency response center, radiation protection, logistics etc.

head is larger than that of the outlet hot side. Core injection using ECCS pumps driven by diesel power supply car and containment vessel (CV) spray is possible, even if under SBO. Spent fuel-water injection is possible because of easy access routes for fire engines (Fig. 36).

Figure 37 shows an additional emergency water injection pump installed on seismic base isolation rubber on the top floor of a turbine building. Discharge piping is via a flexible bellows pipe. The pump can supply water to the core or containment spray as a severe accident resilience action. Personnel in the Genkai NPS are trained to be able to connect the flexible pipe within a very short time.

There are numerous safety reinforcement measures at Genkai Units 3 and 4 (Fig. 38). It is very important to prevent CV failure from overpressure, over temperature, and hydrogen detonation. For this purpose, CV recirculation cooler and CV spray, PAR, and igniter for hydrogen combustion with oxygen in CV are available. A water cannon to suppress radioactive material diffusion has already been deployed to meet requirements of intentional aircraft impact or tornado-driven missiles on the reactor building and CV. These measures are based on the DiD concept and use diverse strategies.

As shown in Fig. 39, many mobile pumps driven by diesel/gasoline engines are deployed at Ikata NPS. Such devices have already been deployed at all NPSs in Japan.

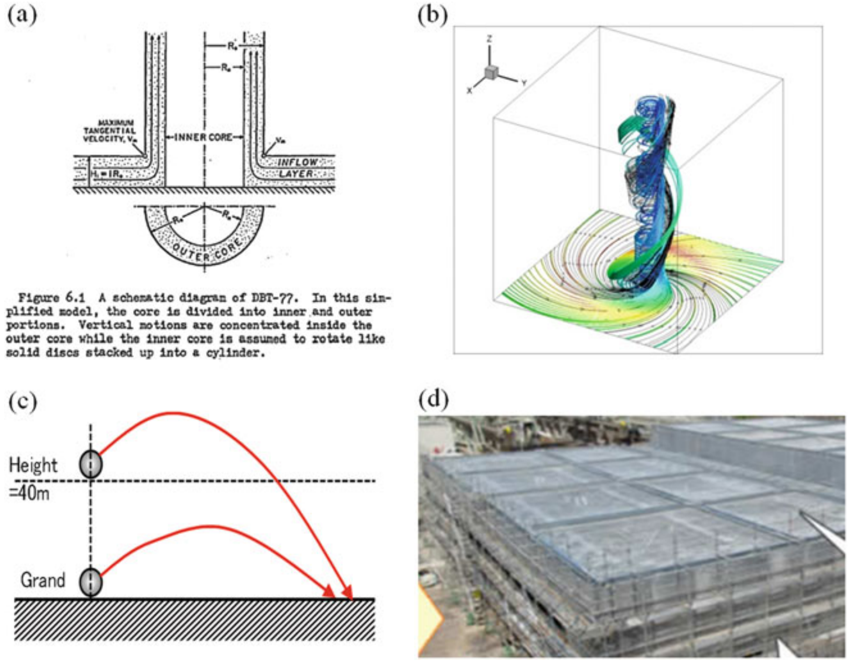


Figure 6.1 A schematic diagram of DBT-77. In this simplified model, the core is divided into inner and outer portions. Vertical motions are concentrated inside the outer core while the inner core is assumed to rotate like solid discs stacked up into a cylinder.

Fig. 35 Tornado evaluation method and measures for seawater pumps. (**a**) Tornado wind field (Dr. Fujita). (**b**) Tornado streamlines from Dr. Fujita model. (**c**) Tornado trajectories for missile analysis. (**d**) Missile shield for sea water pump

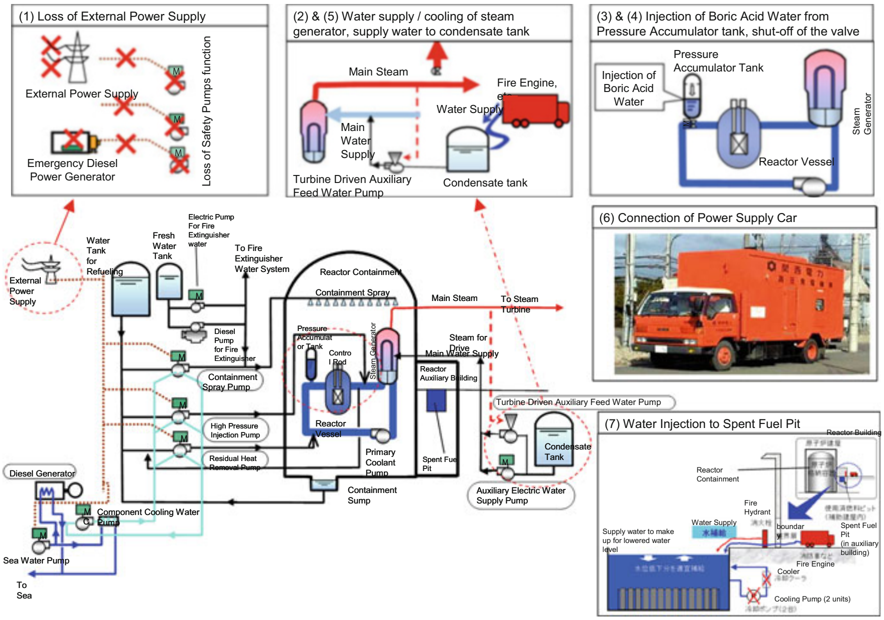


Fig. 36 Full cooling strategy for SBO to protect against SAs for PWR [14]

Fig. 37 Water injection pump

4.5 BWR NPS to Be Reviewed for the New Requirements or Restarting

Following the design reviews of 12 PWRs, nine BWRs with enhanced safety measures were in ongoing design review for restarting.

As shown in Fig. 40, by using seawater cooling system, suppression pool water in suppression chamber will be cooled, and core injection system can remove decay heat from the core to the pool via a main steam safety relief valve (SRV). The system can be operated using mobile generators and heat exchanger car, even for a natural disaster such as a major earthquake or tsunami or sudden flooding. It is very important to cool the suppression pool water by a connected mobile cooling car using plate-fin heat exchanger cooled by seawater pump to maintain an ultimate heat sink.

Upon occurrence of a SA, vent gas with radioactive fission products is blown out to a scrubbing pool through numerous venturi nozzles (Fig. 41). Mist in steam moves upward to a metal fiber filter through a multi-hole baffle plate. After the mist is removed by that filter, radioactive methyl iodide (CH_3I) is captured on the surface of a molecular sieve or AgX, made from zeolite particles with silver coating [16, 17].

Figure 42 shows the FCVS pit at Hamaoka NPS of Chubu Electric and the installing of FCVS at Kashiwazaki-Kariwa NPS of TEPCO, respectively.

Figure 43 shows the FCVS visualization test facility at Hokkaido University. An AgX filter is used downstream of the scrubbing pool and metal fiber filter. This study was conducted by Kakenhi (B) funded No. 2436038802. The thickness of AgX filter is a very important parameter to obtain enough decontamination factor (DF). As shown in Table 4 of TUV test result in Germany, the DF for the radioactive iodine exceeds 10,000 at bed depth (AgX filter thickness) greater than 75 mm [16].

Fig. 38 Safety reinforcement measures at Genkai Units 3 and 4 for SBO. (**a**) CV recirculation cooler and CV spray. (**b**) PAR and ignaiter for hydrogen. (**c**) Mobile motor-driven pump. (**d**) Mobile diesel engine-driven pump. (**e**) Water cannon to suppress radioactive material diffusion

Fig. 39 Mobile pumps deployed in Ikata NPS [14]

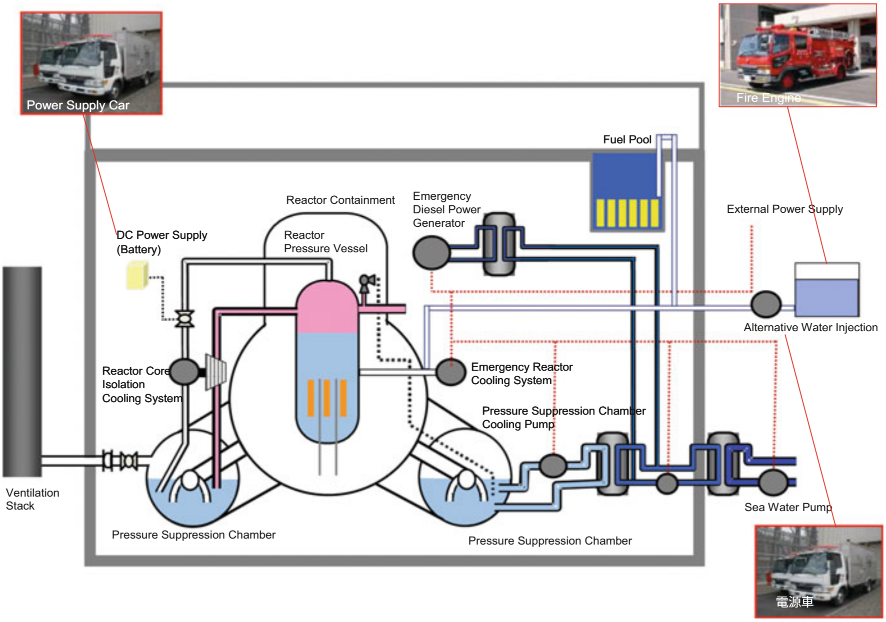


Fig. 40 Core injection heat removal by suppression pool cooling system [14]

Figure 44 shows the full cooling strategy for SBO to protect against SA for BWR [16]. Fuels in the core are cooled by direct water injection via ECCS line of feed water line. Core injection, PCV spray, PCV head flange cooling, suppression pool cooling, and pedestal water injection using MUCW pumps are driven by gas turbine generator, mobile power supply car, and mobile ultimate heat sink car.

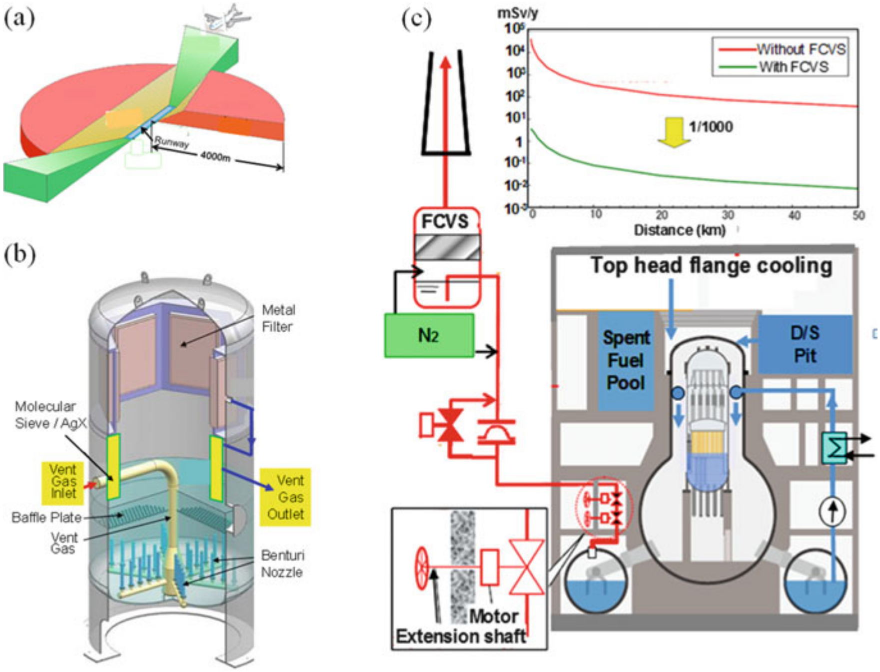


Fig. 41 Filtered containment venting system (FCVS) with silver zeolite [16]. (**a**) Aircraft landing zone. (**b**) Internal structure of vent filter. (**c**) Outline and effect of FCVS

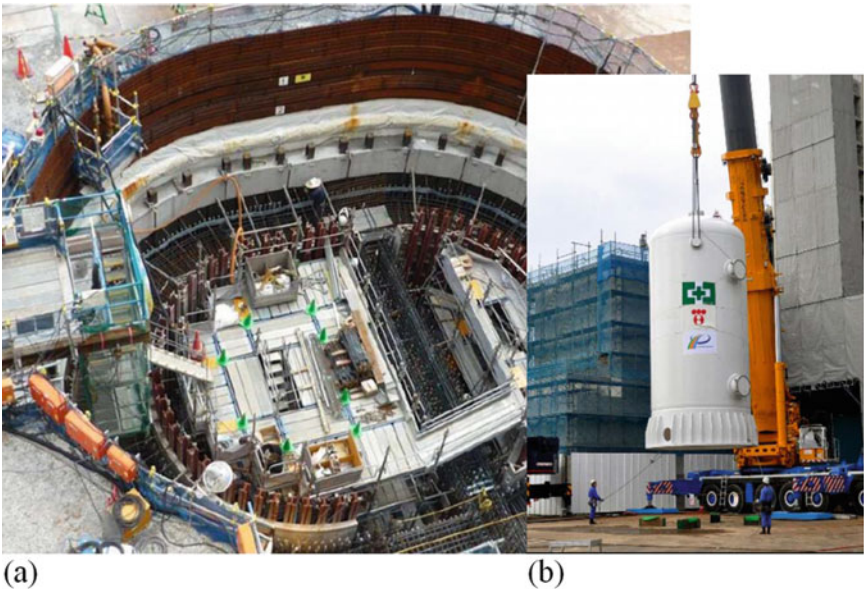


Fig. 42 Installation of filtered containment venting systems (FCVS) [16]. (**a**) FCVS pit at Hamaoka NPS. (**b**) Installation of FCVS at Kashiwazaki-Kariwa NPS

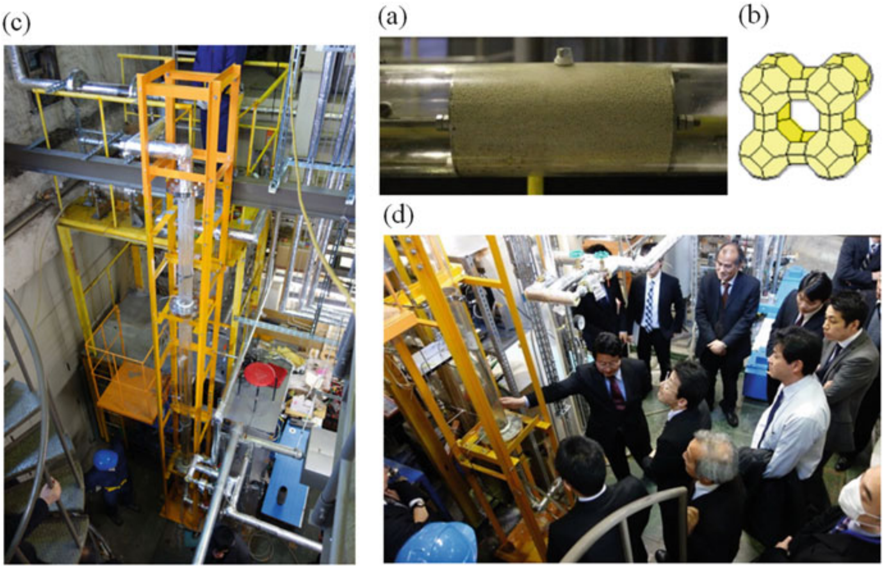


Fig. 43 Development of high-DF FCVS using silver zeolite at Hokkaido University [16]. (**a**) AgX filter test section. (**b**) Zeolite model. (**c**) FCVS test facility at Hokkaido Univ. (**d**) Review meeting of FCVS-WG/JSME

Table 4 Test result of adsorption efficiency of CH_3I under various bed depths [17]

Bed depth (mm)	Residence time (sec.)	Adsorption efficiency of CH_3I (%)
50	0.246	99.967
75	0.369	> 99.999
100	0.492	> 99.999

Testing conditions
Temperature: 130 °C, Pressure: 399 kPa, LV: 20 cm/sec.;
Relative humidity (RH): 95 %, CH_3I concentration: 1.75 mg/m^3 (I-131).

Figure 45 shows a new TWL-RCIC by using a steam turbine-driven, water-lubricated pump. The pump is compact and has a head of 900 m under 183 m^3/h and does not need an oil lubricant pump. The required DC power supply is about half that of current RCIC pumps. These new types of high-pressure water injection devices will provide substantial diversity under SBO conditions. Some BWR utilities will install the TWL-RCIC pump. R&D items in progress to improve safety and resolve problems are shown in Table 5.

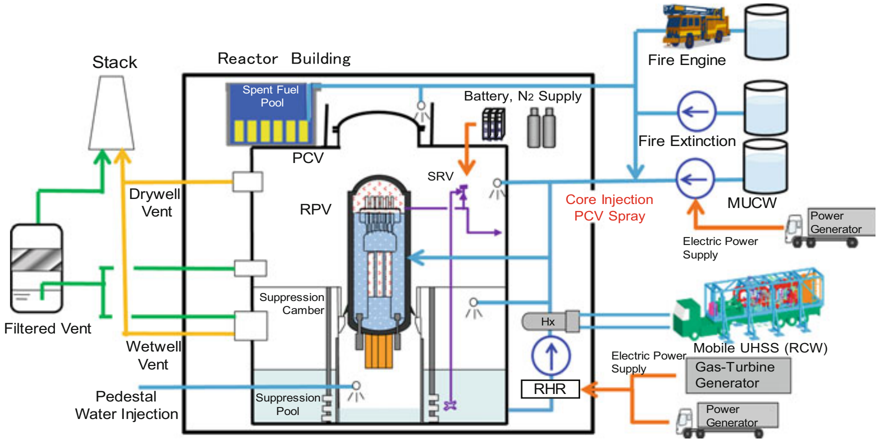
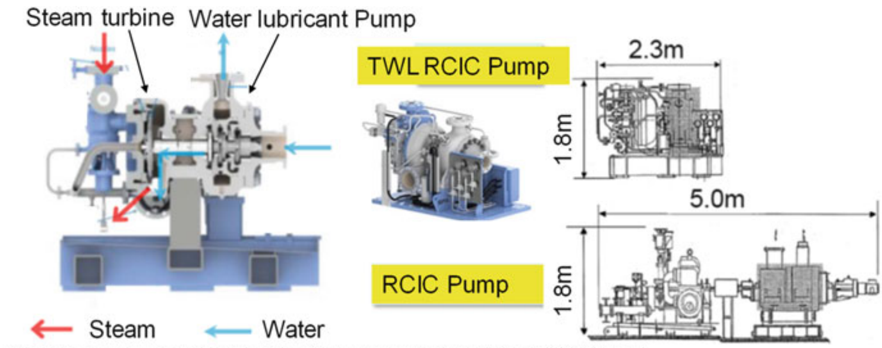


Fig. 44 Full cooling strategy for SBO to protect against SA for BWR [14]



http://www.spx.com/en/clydeunion-pumps/pd-TWL%E2%84%A2/

Fig. 45 TWL-RCIC using a steam turbine-driven water-lubricated pump [19]

5 Activities Toward Decommissioning Fukushima Daiichi

5.1 Current Status of the Reactors at Units 1 Through 4

Figure 46 shows the current status of the reactors in Units 1 through 4. It is assumed that the reactor cores of Units 1 through 3 are melted and that some portion dropped onto the pedestal floor of the CV. It is very important to survey the melted core debris distribution from the core to pedestal floor. Some of debris may be attached on the surface of the control rod drive outer casing. Table 6 shows the temperature and water injection flow rate. Units 1 through 4 are in a stable and safe condition because of controlled water cooling. About 4 ton/h of water are injected into the

Table 5 R&D items in progress to improve safety and resolve problems [19]

Measurement value	Problems	Review items (BWR)	Review items (PWR)
Reactor water level	• The water level could not be obtained due to vaporization of water in reference legs. • Multiplexing was ineffective because the same problem happened in all the places.	• Procedures to prevent vaporization of water and refill water in reference legs • Multiplexing with different types of measuring methods	• Reference legs are sealed in existing differential pressure type water level gauges. • Water level can be estimated from the temperature on the outlet of the reactor core.
Dry well water level	• The water level could not be obtained because the measurement points were limited.	• A measuring method to obtain the water level at every height down to the bottom of a dry well	• The water level of the recirculation sump can be monitored. The environmental effect should be investigated.
Dry well hydrogen concentration	• The measuring method was the sampling method that did not work due to loss of power and coolant.	• A measuring method without sampling	• Installation of hydrogen concentration meters in containment vessels. • A measuring method without sampling
Reactor building hydrogen concentration	• There was no hydrogen concentration meter in reactor buildings.	• A measuring method for hydrogen concentration in reactor buildings	• Installation of hydrogen concentration meters in annulus.

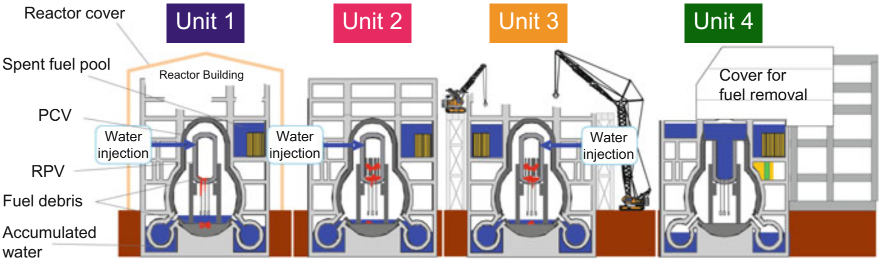
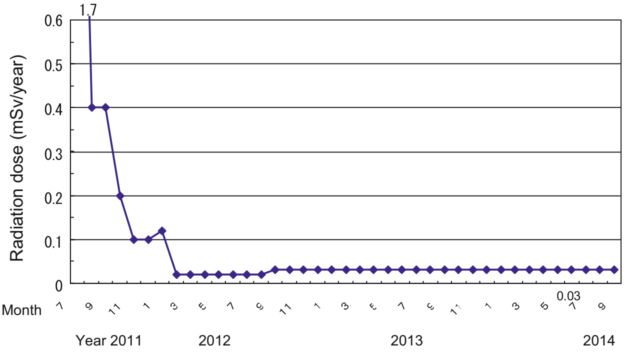


Fig. 46 Current status of reactors in Units 1 through 4 [18, 19]

Table 6 Temperature and water injection flow rate of reactors in Unit 1 through 4

	Unit 1	Unit 2	Unit 3	Unit 4
RPV bottom temp.	About 29℃	About 36℃	About 34℃	-
PCV internal temp.	About 29℃	About 37℃	About 34℃	-
Fuel pool temp.	About 26℃	About 22℃	About 21℃	About 22℃
Reactor cooling water injection volume	About 4.6m^3/h	About 4.5 m^3/h	About 4.3 m^3/h	-

cores of units 1 through 3, and temperature in the pressure vessel is maintained around 30–40 °C. Temperature in the spent fuel pool (SFP) is maintained around 30 °C [18, 19].



（Reference）
* Concentration limit in the air of environment surveillance area：
[Cs-134]：2× 10^{-5}Bq/cm^3
[Cs-137]：3× 10^{-5}Bq/cm^3

* Dust concentration in the area surrounding 1F site boundary：
[Cs-134]：ND（Detection limit: approx. 1× 10^{-7}Bq/cm^3），
[Cs-137]：ND（ Detection limit: approx. 2× 10^{-7}Bq/cm^3）

Fig. 47 Annual radiation dose at site boundary of Fukushima Daiichi NPS [18, 19]

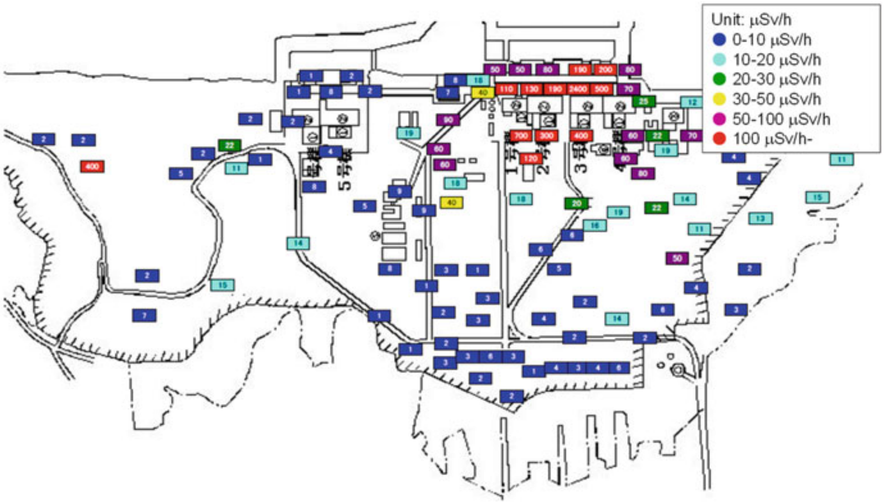


Fig. 48 Exposed dose distribution at Fukushima Daiichi NPS [18, 19]

Figure 47 shows the annual radiation dose from radioactive materials at the site boundary of Fukushima Daiichi NPS, released from Units 1 through 4. At the time of the accident, a vast amount of these materials were released, but the maximum annual dose is now 0.03 mSv/y equivalent to 1/70 that from background radiation.

Figure 48 shows that an approximate half area dose is <10 μSv/h (87.7 mSv/y), but the dose in the reactor building is >100 μSv/h (877 mSv/y).

Just after the accident, contaminated water accumulated in the reactor and turbine buildings leaked into the plant harbor through an underground tunnel. The leak was stanched at the end of October 2014. The current concentration of

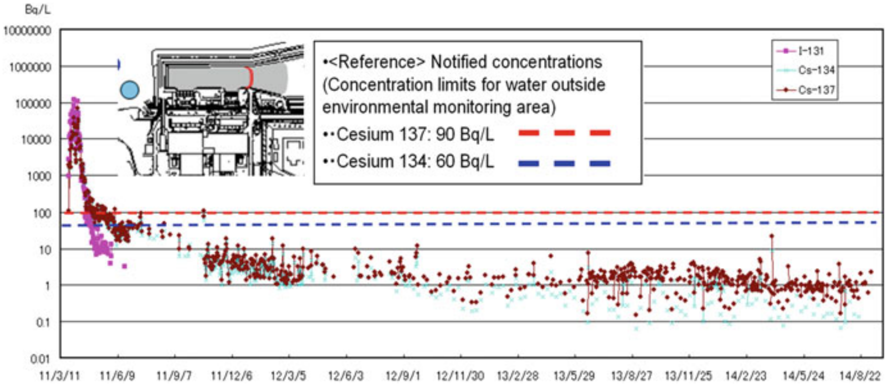


Fig. 49 Concentration of radioactive materials in seawater at the north side of water outlets in Units 5 and 6 [18, 19]

Table 7 Mid- and long-term road map [18]

Dec 2011 (development of roadmap)
Nov 2013
First half of 2025 at the earliest
After 30 - 40 years

Approach toward stabilization	Phase 1	Phase 2	Phase 3
<Accomplishment of cold shutdown> •Cold shutdown condition •Suppression of radiation emission	Period to the start of fuel removal from the spent fuel pool (within 2 years)	Period to the start of fuel debris removal (within 10 years)	Period to the end of decommissioning (after 30-40 years)

radioactive materials in the seawater is below WHO's (World Health Organization) standard for drinking water (Fig. 49).

Table 7 shows the mid- and long-term road map, developed by the government and TEPCO. The decommissioning work will be undertaken in three phases. Phase 1 is fuel removal from spent fuel pool (SFP), Phase 2 is fuel debris removal, and Phase 3 is plant dismantling.

Figure 50a shows the reactor building of Unit 1 after the hydrogen explosion on March 12, 2011. The cover structure was constructed with a controlled ventilation system, to minimize the dispersion of radioactive material. To remove the spent fuel from the SFP, rubble should be removed, and cover should be removed after ensuring countermeasures for local communities during the removal operation.

Figure 50b shows the current status of Unit 2. Its reactor building is undamaged, because the blowout panel was opened owing to the hydrogen explosion in Unit 3. Therefore, the dose rate in the Unit 2 reactor building is very high. Considering this fact, the process for removing SFP fuels is under study.

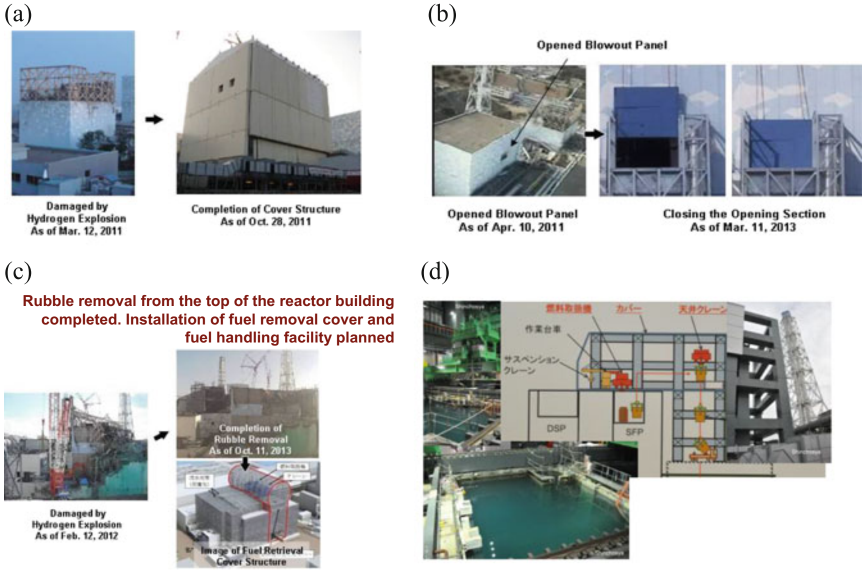


Fig. 50 Current status of reactors; Units 1 through 4 [18, 19]. (**a**) Unit 1, (**b**) Unit 2, (**c**) Unit 3, (**d**) Unit 4

Figure 50c shows the current status of Unit 3. Rubble removal at Unit 3 was completed in October 2013. Preparations are continuing for installation of a temporary cover, to be used while fuels are removed from the SFP by remote-controlled handling equipment. The current level of radiation on the operating floor remains high for workers to safely install the necessary equipment. Therefore, the next step is to reduce the radiation to an acceptable dose.

Figure 50d shows the current status of Unit 4. A cover structure was constructed and fuel-handling machine and heavy-duty ceiling crane were installed, and spent fuel removal from Unit 4 was completely ended by the end of December 2014. The cover structure is supported by a huge cantilever structure, which enables to support the handling of the fuel into transport cask with the ceiling crane.

5.2 *Finding Contaminated Water Leak Path for Leak Shutdown of PCV*

Figure 51 shows the estimated leak path of fission products from the PCV. After recirculating water injection to the core, melted core debris was cooled and reached cold shutdown. However, contaminated water still leaked from the damaged PCV and flowed out of the reactor building.

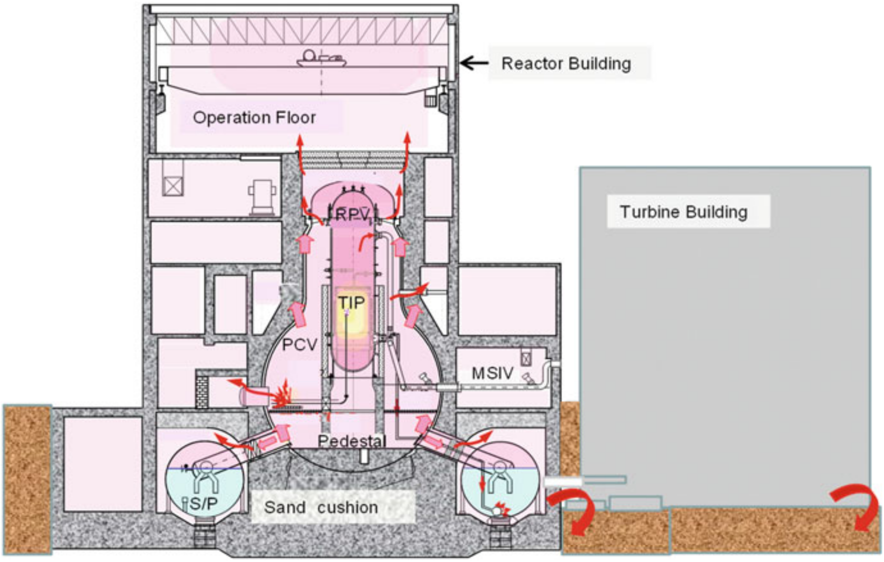


Fig. 51 Estimated leak path of fission products from primary containment vessel

Therefore, the leak location was found by using robots. Figure 52a shows boat-type robots with a camera checking water flow out of the bottom of the PCV area in a torus room on the basement floor of Unit 1. Video from the boat robot discovered water flow from a sand cushion drain pipe [18, 19]. This indicates some failure at the bottom of the PCV wall and that water leaked through the sand cushion drain. Sand cushions are used to mitigate the stress on the bottom flange of the PCV.

Figure 52b shows another type of robot, which can walk on the external catwalk on the torus of the suppression chamber and survey water leakage on the upper side of that chamber and piping. Such robot found leakage from the protection cover of a vacuum breaker expansion joint in Unit 1. This is consonant with the discovery of the water flow on the surface of the suppression chamber torus by the boat-type robot.

Figure 53 shows the effort in Unit 2 to find the water level in PCV. A water level probe with thermocouple was inserted through X-53 penetration. This found a water depth of 300 mm, which is near the overflow height into vent pipe. This indicates a leakage path at the vent pipe or suppression chamber torus. This leak can be stopped using balloon plugs, which are used for main steam line plugging during the annual maintenance of main steam isolation valve (MSIV) [15].

As shown in Fig. 54, a video camera was used to find PCV water leak in the reactor building at Unit 3. The camera was inserted from the second floor and discovered leakage from the expansion joint of main steam line pipe D from the PCV in the MSIV room on the rector building first floor.

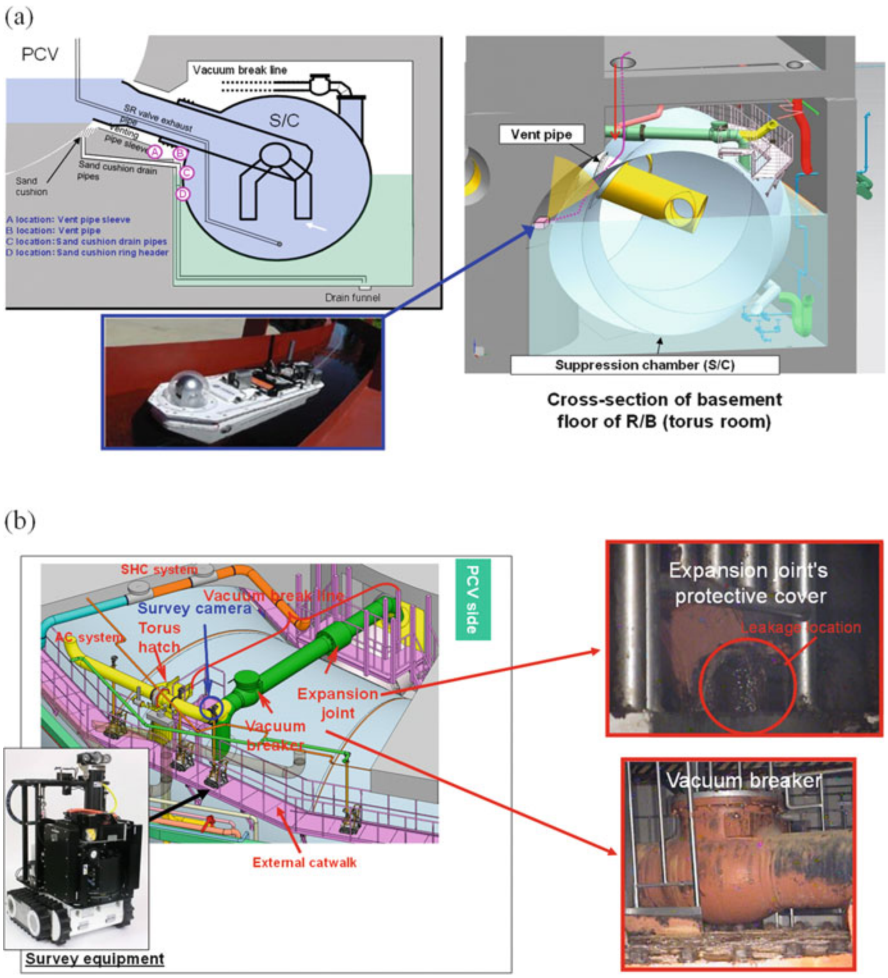
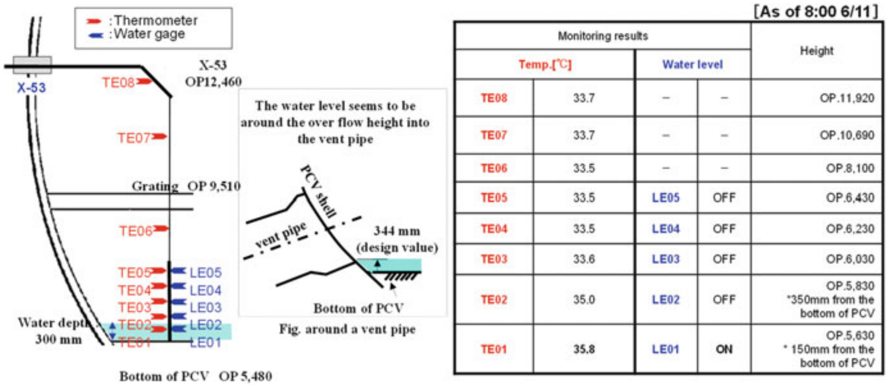


Fig. 52 Survey robot to discover contaminated water leakage in Unit 1 [18, 19]. (**a**) A boat-type robots with a camera checking water flow. (**b**) Survey robot walking on catwalk outside of SC

5.3 Isolation of Groundwater Flow from Contaminated Water

There are several trenches for pipelines and power lines between buildings and pumps in the seaside area, in which extremely contaminated water was discovered. To isolate groundwater mixed with contaminated water flow from the buildings to the trenches, a groundwater bypass system was installed and began operation in May 2014 (Fig. 55). With this system, the volume of water flow into the buildings



[As of 8:00 6/11]

Monitoring results				Height
Temp.[℃]		Water level		
TE08	33.7	–	–	OP.11,920
TE07	33.7	–	–	OP.10,690
TE06	33.5	–	–	OP.8,100
TE05	33.5	LE05	OFF	OP.6,430
TE04	33.5	LE04	OFF	OP.6,230
TE03	33.6	LE03	OFF	OP.6,030
TE02	35.0	LE02	OFF	OP.5,830 *350mm from the bottom of PCV
TE01	35.8	LE01	ON	OP.5,630 * 150mm from the bottom of PCV

Fig. 53 Water-level checking at bottom of PCV of Unit 2 [15]

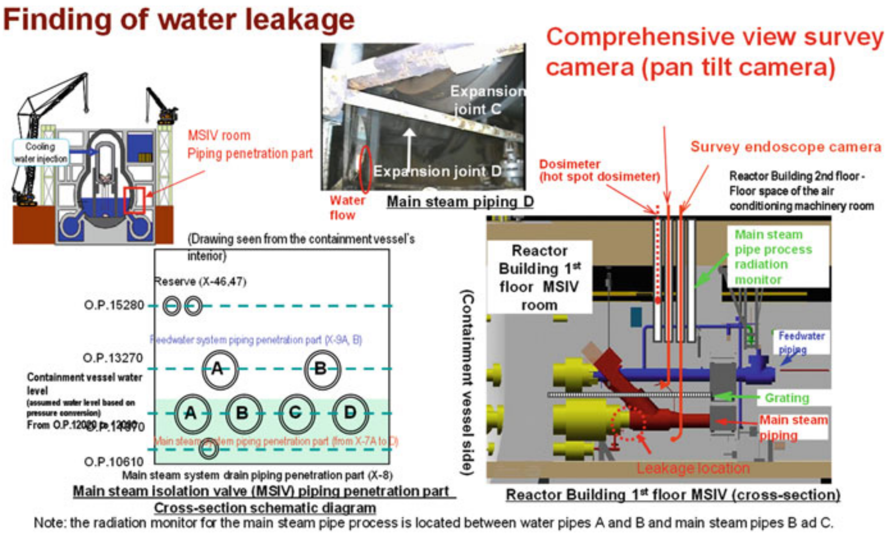


Fig. 54 Investigation to find leakage location in Unit 3 [15]

was reduced from 350 to 80 t/day. As a result, the volume of contaminated water was also reduced. The next fundamental countermeasure is to build an impermeable wall to prevent contaminated water flowing into the sea (Fig. 56). Further, TEPCO has been preparing equipment of landside water shielding wall and subdrain pump-up system to greatly diminish groundwater flow into the contaminated buildings.

The landside impermeable wall composed of frozen soil (ice wall) surrounds the buildings of Units 1 through 4 to block the groundwater from getting contaminated (Fig. 57). After a small-scale demonstration test succeeded, the large ice wall

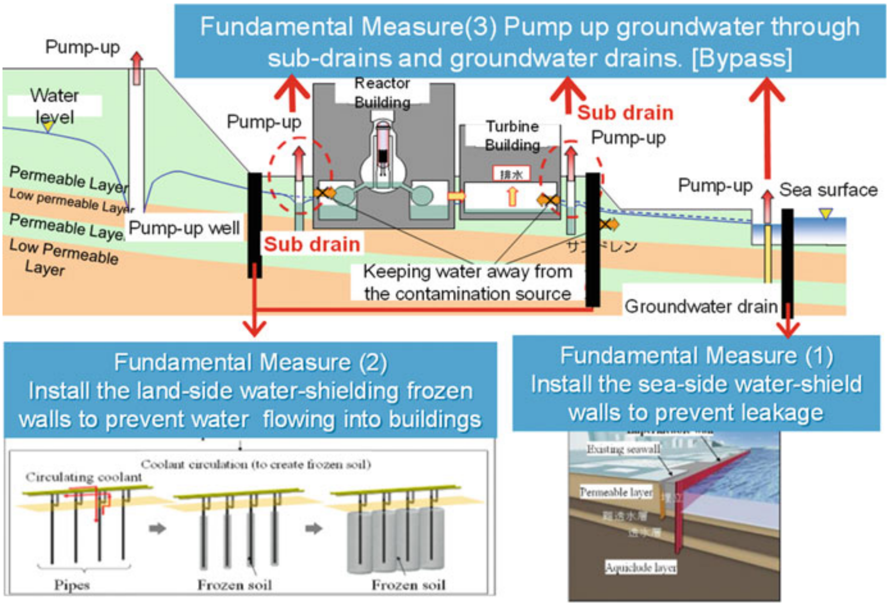


Fig. 55 Measures to prevent contaminated water flowing into the sea by isolation of groundwater [18, 19]

Fig. 56 Impermeable wall to prevent contaminated water flowing into the sea [18, 19]

construction began. There are 1500 bores of 30 m depth at 1 m intervals, for installation of coolant-circulating pipes. Construction should be complete by June before the hot summer in 2015. After ice wall establishment, daily groundwater flows into the buildings of the four units will be reduced to near zero, as will contaminated water flowing out from the ice wall.

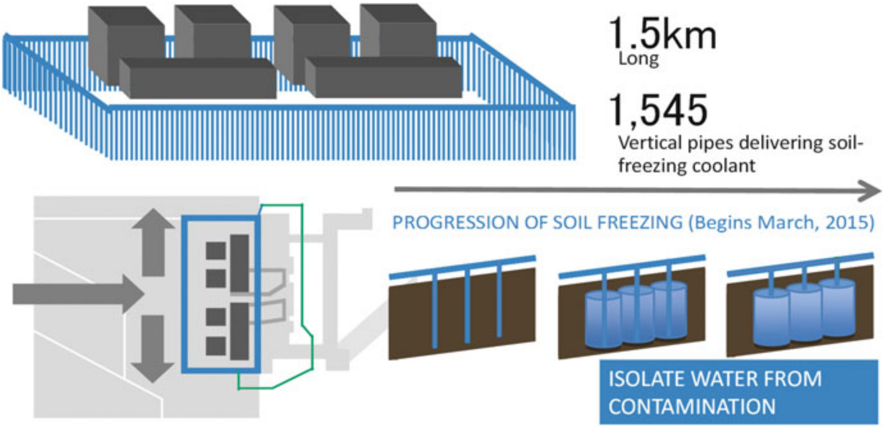


Fig. 57 Landside impermeable “ice wall” [18, 19]

5.4 *Contaminated Water Management*

Contaminated water management is presently the most important and urgent issue at Fukushima Daiichi NPS. Contaminated water is transferred to cesium removal systems and then to desalination systems of reverse osmosis or evaporation type. Then the desalinated water is injected into the reactors as coolant. The concentrated water after desalination is still radioactive. Therefore, it was transferred to storage tanks at a rate of 400 t/day before the establishment of the groundwater isolation system. There are a huge number of tanks at Fukushima Daiichi. Therefore, an advanced liquid processing system (ALPS) was developed to remove various radioactive materials including strontium, which were then safely stored in the storage tanks. Currently, a total of more than 500,000 t of contaminated water is stored in the tanks. Current tank capacity is ~600,000 t, and this will be increased to 800,000 t by the end of March 2015.

Figure 58 shows the contaminated water processing system with the cesium removal system (SARRY), desalination system (KURION), and ALPS. The ALPS was designed to remove all radionuclides except tritium. The first system consists of three independent lines. Total treatment capacity is 750 t/day. To increase total processing capacity, a second system was constructed. A high-performance ALPS was designed to reduce the volume of secondary waste and will increase the rate of radionuclide removal to 2000 t/day with the first installed system plus additional and high-performance systems. About 120,000 t of contaminated water was processed by the end of October 2014. The ALPS has the important role of water decontamination.

Figure 59 shows the capabilities of the three water processing systems for removing radioactive materials. The cesium and strontium concentration level at the ALPS outlet is reduced by 10^{-8} relative to the original concentration. However, tritium concentration is unchanged. Tritium processing remains to be solved.

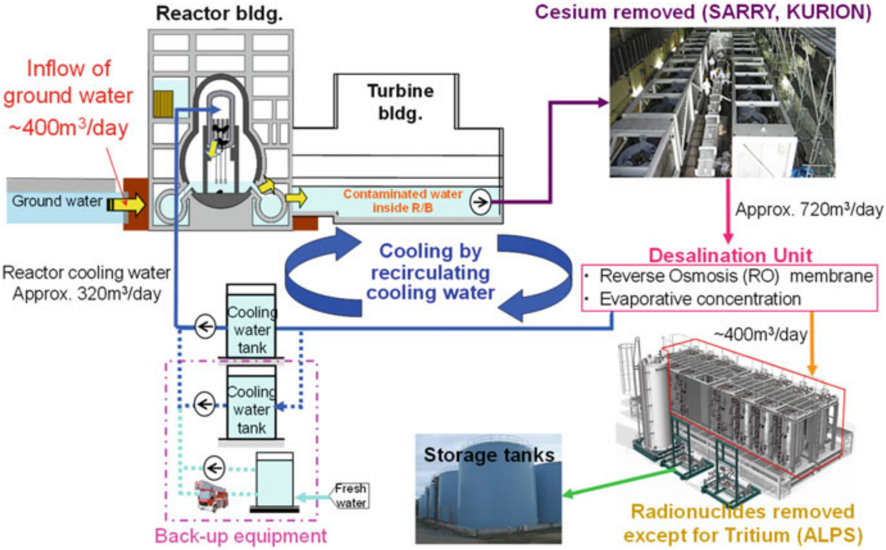


Fig. 58 Contaminated water processing system with SARRY, KURION, and ALPS

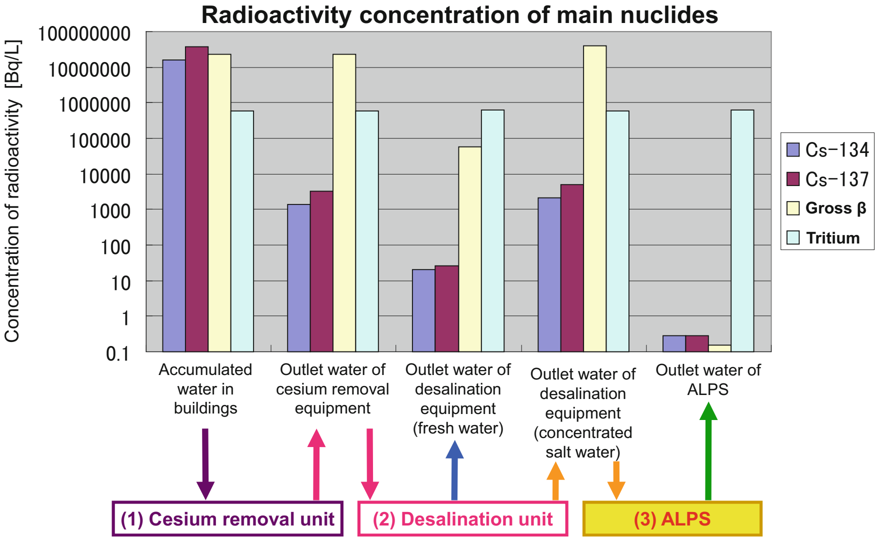


Fig. 59 Capabilities of various water processing systems to remove radioactive materials [18, 19]

5.5 *Preparation for Fuel Debris Removal*

To find melted debris under the RPV, a transformer-type robot was developed by Hitachi GE Nuclear [17, 18]. As shown in Fig. 60, the robot will investigate debris inside the pedestal and estimate the location of fuel debris dropped from the core in

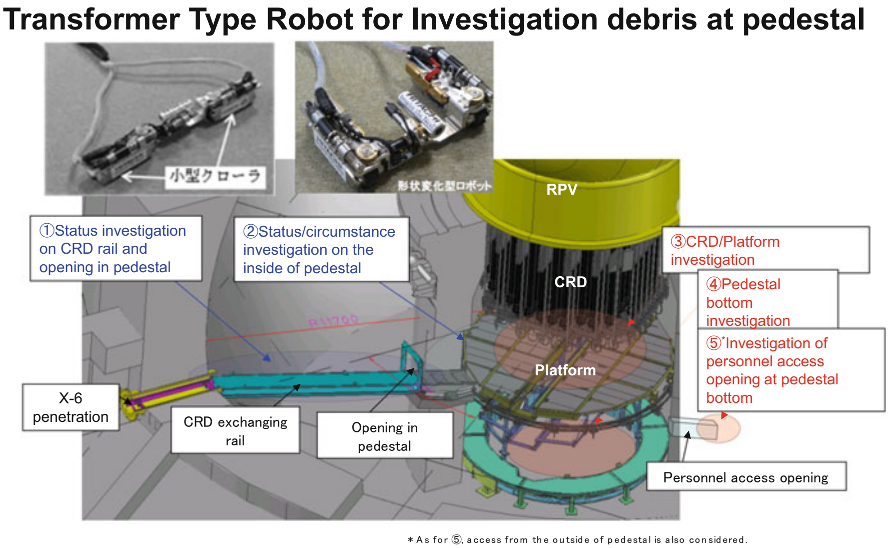


Fig. 60 Transformer-type robot for investigating debris at the pedestal in Unit 2

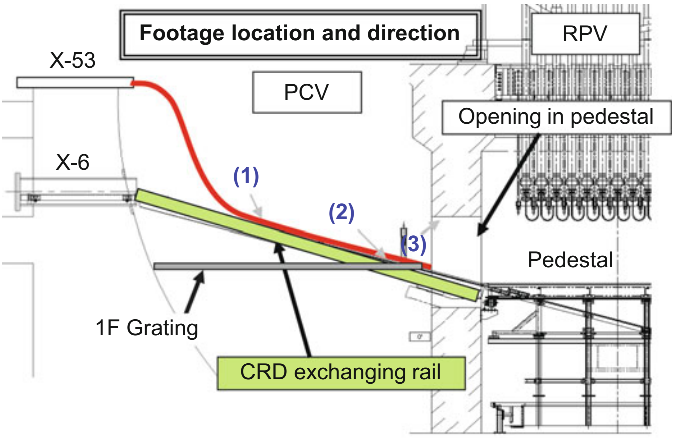


Fig. 61 Robot investigation route into the pedestal using X-6 large penetration

Unit 2. Figure 61 shows that the robot will move into the pedestal using X-6 large penetration, which was used like a snake for CRD exchanges through the penetration pipe. After passing the penetration pipe, the robot transforms its shape from a snake to an “E”-shape vehicle, which has a radiation-proof CCD camera at the center of front flame “E.” TEPCO has a plan to investigate in several steps. The preliminary investigation will identify an access route into the pedestal via CRD rail and survey the status of PCV inside the pedestal. A full-scale investigation for

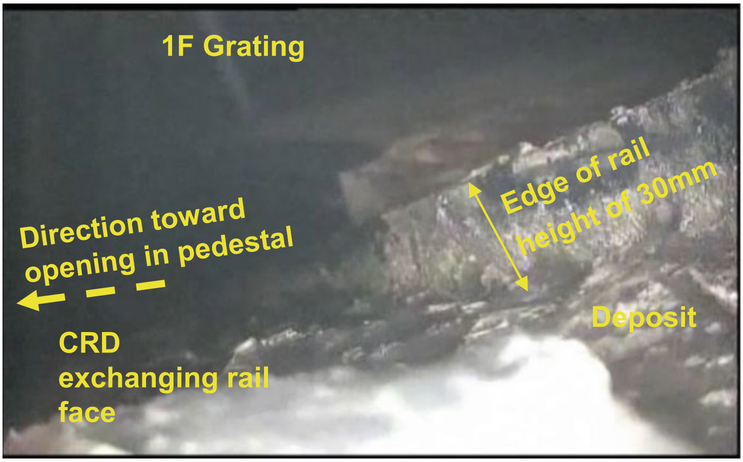


Fig. 62 Video capture at position (2) on CRD exchange rail [18, 19]

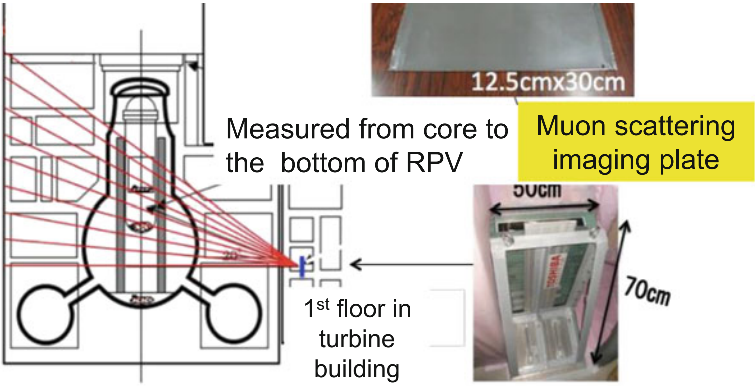


Fig. 63 Muon radiography to find fuel debris [20]

identifying the location of fuel debris will then follow. This is the result of the first preliminary investigation, using X-53 penetration. Figure 55 is video capture at position (2) on the CRD exchange rail, in Fig. 62. It is possible to identify an edge of rail and some deposit on the rail. However, the robot could not enter the pedestal because of some blockage by an unknown deposit on the CRD rail.

In March 20, Nagoya University and Toshiba released to the press results of muon radiography to find fuel debris. Figure 63 shows a layout of the muon detector imaging plate and measurement area from the core in the RPV to the RPV bottom.

Figure 64 compares muon radiography results between Units 2 and 5. No fuels were found in the core or lower plenum at the RPV bottom. All fuels melted downward through the melted piping of the control rod drive (CRD) mechanism and fell to the pedestal concrete floor.

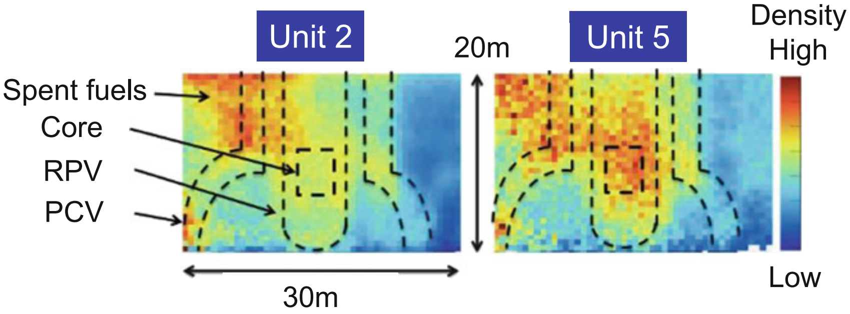


Fig. 64 Comparison of muon radiography results between Unit 2 and Unit 5 [20]

6 Concluding Remarks

There are numerous effective countermeasures to prevent the FP release and tsunami in the world. TEPCO and NISA should consider such systems.

The Fukushima Daiichi NPP accident could have been quickly brought under control if adequate countermeasures had been installed, such as waterproof doors and mobile power sources.

In Europe, as a result of lessons learned from the TMI and Chernobyl accidents, heat removal systems and FCVS have already been installed.

Using the lessons learned from this analysis of the Fukushima Daiichi accident, the author wishes to contribute to achieving first-class nuclear safety worldwide.

In response to the Fukushima Daiichi nuclear disaster, measures for the safety of Japanese NPPs have been strengthened or are being greatly bolstered. It has been pointed out that DiD in Japan before Fukushima was “Level 3” and now it is enhanced to “Level 4.”

Therefore, the author submits proposals as shown below to provide scientific and technological support. The lessons can be incorporated in measures taken by institutions and government agencies, thereby enhancing the safety of the many nuclear power plants in operation worldwide.

1. Enhance seismic 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. For station blackout (SBO) caused by wetting of EDG, P/C, DC battery, I&C and cell phones, waterproof door or hatches, and mobile power should be installed on hills.
3. To prevent core meltdown by loss of water injection, diversification of water injection and heat sinks is very important.
4. To prevent loss of containment function by overheating damage, CV cooling and FCVS should be installed independently from hard vent systems.

5. Pedestal water injection during severe accident is very important to avoid PCV bottom failure that causes water pollution around the reactor building.

Design reviews of 12 PWRs and 9 BWRs with enhanced safety measures are ongoing for restarting. Sendai Nuclear Power Station Units 1 and 2 of Kyushu EPCO received the NRA permission in September 2014 and Unit 1 has restarted since August 2015.

The plant licensing period of 40 years should be determined based on technical aging assessment.

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List of Nomenclature

AC	Alternating current
ALPS	Advanced liquid processing system
AM	Accident management
AO	Air-operated valve
BWR	Boiling water reactor
CRD	Control rod drive
CV	Containment vessel
DBA	Design base accident
DC	Direct current
DF	Decontamination factor
DiD	Defense in depth
DW	Dry well
EDF	Électricité de France
EDG	Emergency diesel generator
ENSI	National regulatory body with responsibility for the nuclear safety and security of Swiss nuclear facilities
FARN	Nuclear rapid response force established by EDF
FCVS	Filtered containment venting system
FP	Fission product
GIS	Gas-insulated switchgear
HSK	Swiss Federal Office of Energy
HVAC	Heating, ventilation, and air conditioning
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 and Technology

MO	Motor-operated valve
NISA	Nuclear and Industrial Safety Agency
NRA	Nuclear Regulation Authority
P/C	Power center
PAR	Passive autocatalytic recombiner
PWR	Pressurized water reactor
R/B	Reactor building
RCIC	Reactor core isolation cooling system
RPV	Reactor pressure vessel
RV	Reactor vessel
S/C	Suppression chamber
S/P	Suppression pool
SA	Severe accident
SAM	Severe accident management
SBO	Station blackout
SEHR	Special Emergency Heat Removal
SGTS	Standby gas treatment system
SRV	Safety relief valve
T/B	Turbine building
TEPCO	Tokyo Electric Power Company Inc.
TIP	Traversing in-core neutron probe
WW	Wet well

References

1. Narabayashi T, Sugiyama K (2011) Fukushima Daiichi NPPs accidents caused by the Tohoku – Pacific Ocean earthquake and tsunami. AESJ Atoms 53(6):387–400
2. Nakajima H, Narabayashi T (2011) Start from level 7. Nikkei Science, July. (in Japanese). http://www.nikkei-science.net/modules/journal/index.php?vol=201107
3. NISA (2012) Technical knowledge of Fukushima-Daiichi NPP's accidents and countermeasure (Interim report). (in Japanese). http://www.meti.go.jp/press/2011/03/20120328009/20120328009.html
4. NISA, JNES (2011) The 2011 Pacific coast of Tohoku Pacific Earthquake and the seismic damage to the NPPs
5. JNES (2011) IC performance and transient analysis for Fukushima Daiichi NPP unit 1 accidents
6. TEPCO (2011) Fukushima-Daiich NPPs accidents investigation meeting's report (Interim report of Fukushima Nuclear Accidents Investigation Committee). http://www.tepco.co.jp/en/press/corp-com/release/11120205-e.html
7. Report of Japanese Government (2011) The accident at TEPCO's Fukushima Nuclear Power Stations, IAEA Ministerial conference on nuclear safety
8. Narabayashi T (2012) 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

9. Gavrilas M et al (2000) Safety features of operating light water reactors of western design, CNES
10. Nuclear Regulation Authority (2013) Nuclear regulation authority enforcement of the new regulatory requirements for commercial nuclear power reactors. http://www.nsr.go.jp/data/000067212.pdf
11. Narabayashi T (2012) Lessons learned from the Fukushima Daiichi Nuclear Power Plant accident, turbulence, heat and mass transfer 7, Begell House, Inc. www.gepr.org/en/contents/20121231-01/KeynoteDrNarabayashi-THMT-12r2.pdf
12. EDF'S Commitment to Enhance Safety (2014) The post-Fukushima modification programme is part of the continuous improvement initiative for EDF nuclear fleet
13. EDF PWR fleet overview and developments experience and challenges, Japan Society of Mechanical Engineers (JSME) & EDF meeting Paris (November 12, 2014)
14. FVCS working group report, Power and Energy System Division, JSME. (Dec 2013). http://www.jsme.or.jp/pes/Research/A-TS08-08/index03.html
15. TEPCO (2014) Second progress report for Fukushima Daiichi. http://www.tepco.co.jp/cc/press/2014/1240099_5851.html
16. Narabayashi T et al (2014) Development of high efficiency filtered containment venting system by using AgX, Short paper of ICMST-Kobe
17. Wang J, Kobayashi T, Endo K (2014) Properties and applications of silver zeolite (AgX), short paper of ICMST-Kobe
18. Yamashita N (2014) Activities towards the decommissioning of Fukushima-Daiichi (TEPCO), ICMST Kobe
19. Narabayashi T (2015) Lessons learned from the Fukushima Daiichi accident to establish resilience technology for nuclear plants based on the defense in depth philosophy (invited plenary), North American ISOE ALARA symposium, Ft. Lauderdale
20. Nagoya Univ. (2015) Press release of muon radiography results at Fukushima Daiichi. https://www.youtube.com/watch?v=qw_445aOefs, http://www.nagoya-u.ac.jp/about-nu/public-relations/researchinfo/upload_images/20150320_esi.pdf