What should we learn from the severe accidents at the Fukushima Dai-ichi Nuclear Power Plant?

Final Report

- Team H2O Project -

December, 21st, 2011

Background

— Regarding this project —

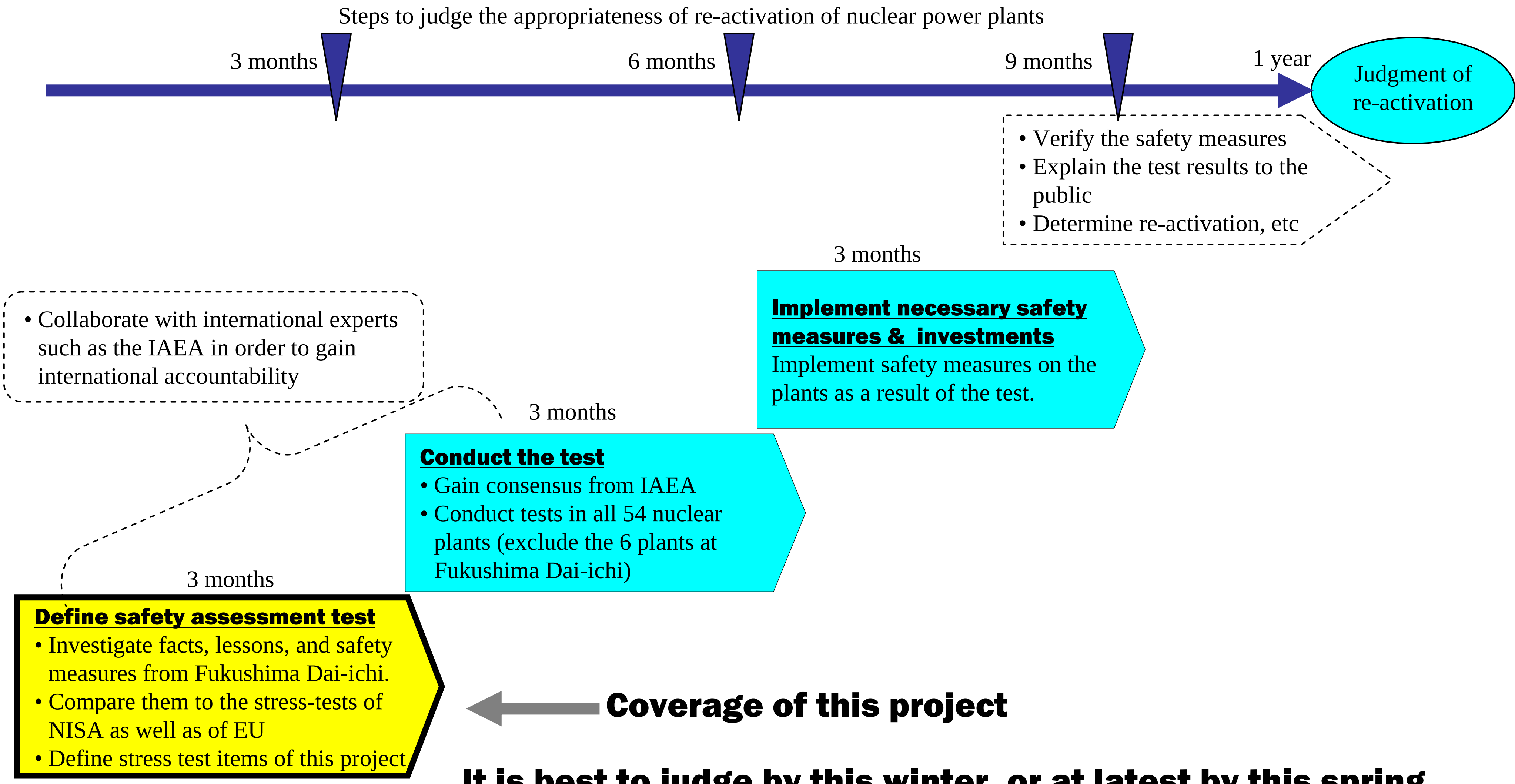
The Purpose of This Project

1 To investigate the facts regarding what had happened in the Great East Japan Earthquake and Tsunami, and the severe accidents at Fukushima Dai-ichi, Dai-ni, Onagawa, and Tokai Dai-ni Nuclear Power Plants, and identify the truth, issues, and lessons to share.

2 Based on the above, to provide a scientific, technical, and logical framework for the discussion and examination of the pros/cons of re-activation of the nuclear power plants.

3 Research methodology, findings, and conclusions of the project should be internationally neutral and receive a consensus from internationally trusted agencies such as the IAEA.

In order to logically discuss the re-activation of the nuclear power plants, safety assessment tests which live up to international accountability are essential. => As the first step towards that, this project covers the first phase.



Steps to judge the appropriateness of re-activation of nuclear power plants

- Verify the safety measures
- Explain the test results to the public
- Determine re-activation, etc

- Collaborate with international experts such as the IAEA in order to gain international accountability

3 months

Define safety assessment test

- Investigate facts, lessons, and safety measures from Fukushima Dai-ichi.
- Compare them to the stress-tests of NISA as well as of EU
- Define stress test items of this project

3 months

Conduct the test

- Gain consensus from IAEA
- Conduct tests in all 54 nuclear plants (exclude the 6 plants at Fukushima Dai-ichi)

3 months

Implement necessary safety measures & investments

Implement safety measures on the plants as a result of the test.

Coverage of this project

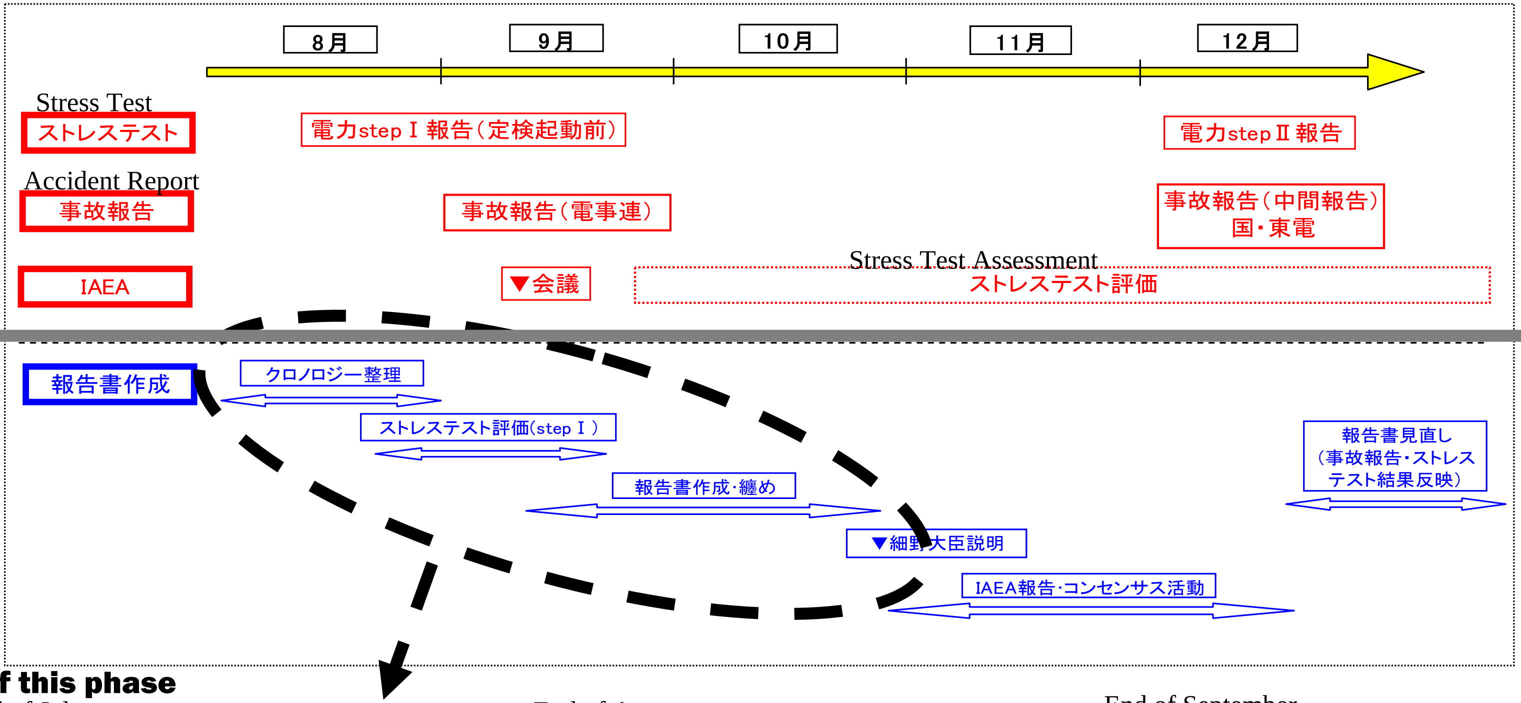
It is best to judge by this winter, or at latest by this spring.

Source: How to Manage the Risk of Complete Shutdown of All Nuclear Reactors in Japan. (by Kenichi Ohmae)

The project was kicked off on July 24th of 2011. The interim report was submitted on October 28th with regards to the lessons learned from the severe accidents at Fukushima Dai-ichi Nuclear Power Plant and the safety measures for BWR .

Events that are anticipated/planned in the future

Orientation of this project



８月

９月

１０月

１１月

１２月

Stress Test

ストレステスト

電力step Ⅰ 報告（定検起動前）

電力stepⅡ報告

Accident Report

事故報告

事故報告（電事連）

事故報告（中間報告）
国・東電

IAEA

▼会議

Stress Test Assessment
ストレステスト評価

報告書作成

クロノロジー整理

ストレステスト評価(step Ⅰ)

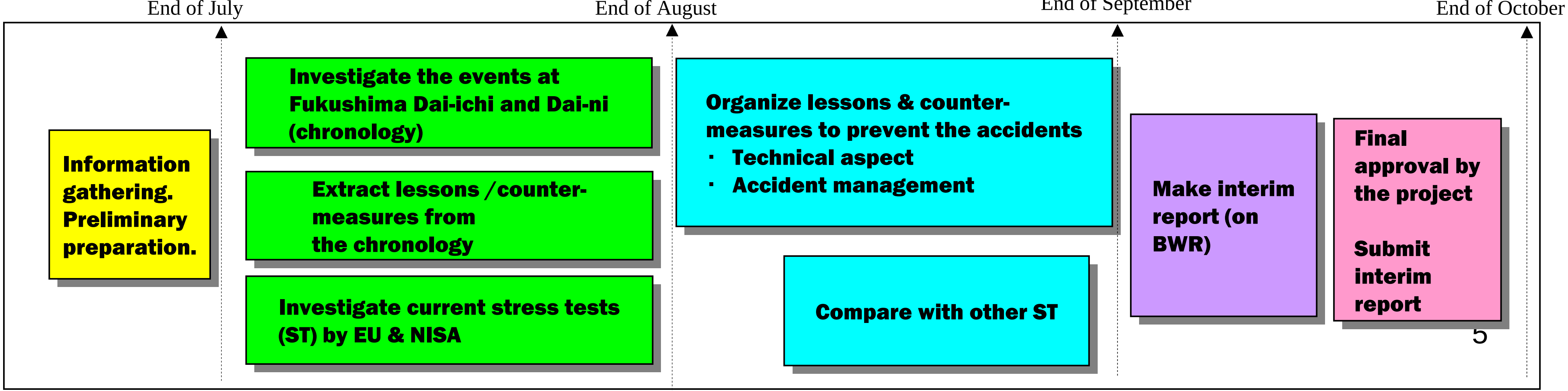
報告書作成･纏め

▼細野大臣説明

IAEA報告･コンセンサス活動

報告書見直し
（事故報告･ストレステスト結果反映）

Investigation of this phase



End of July

End of August

End of September

End of October

Information gathering. Preliminary preparation.

Investigate the events at Fukushima Dai-ichi and Dai-ni (chronology)

Extract lessons /counter-measures from the chronology

Investigate current stress tests (ST) by EU & NISA

Organize lessons & counter-measures to prevent the accidents
- **Technical aspect**
- **Accident management**

Compare with other ST

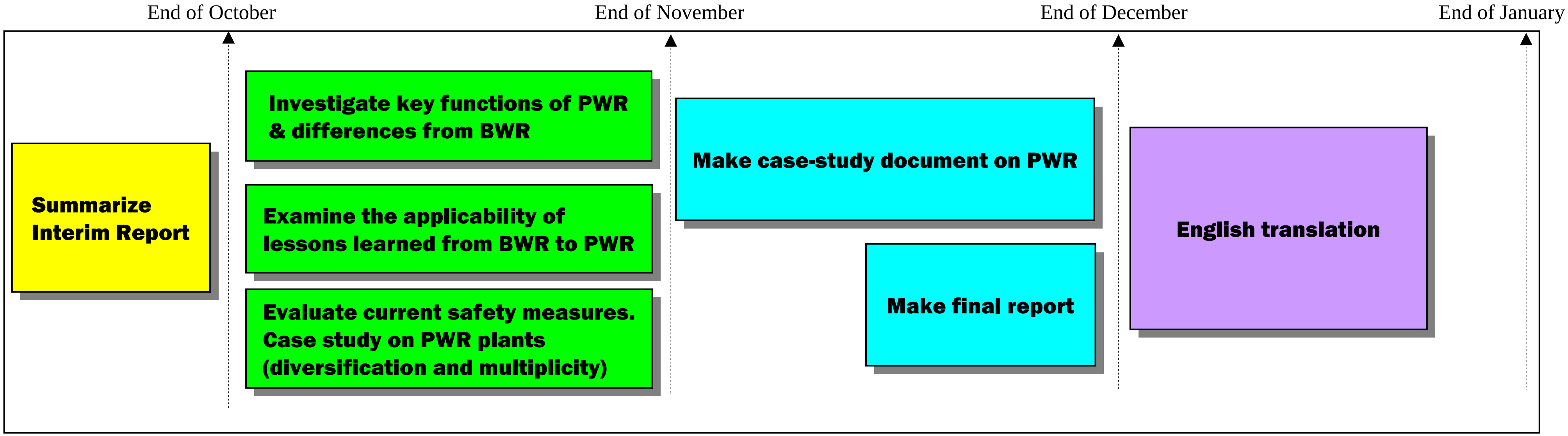
Make interim report (on BWR)

Final approval by the project

Submit interim report

Based on the findings of the interim report, the project conducted a case-study on PWR during November and December 2011, then the final report was submitted.

Nov-Dec 2011 master schedule for this project



The project formation on the BWR and interim-report was as follows:

Kenichi Ohmae

Head Office

- Ohmae and Associates, Inc. Partner, Mr. Iwao Shibata
- Japan Nuclear Fuel Ltd. General Manager, Reprocessing Planning Dept., Reprocessing Business Div., Mr. Manabu Yusa

Those who cooperated with interviews, hearings and data-gathering:

Electric Group

- Japan Nuclear Fuel Ltd. Managing Director and Executive General Manager, Corporate Planning Office, Mr. Harukuni Tanaka
- Tokyo Electric Power Co., Inc. General Manager, Nuclear Power Plant Management Dept., Mr. Takeshi Takahashi

Toshiba

- TOSHIBA CORPORATION Power Systems Company Senior Manager, Fukushima Restoration Project Engineering Dept., Nuclear Energy Systems & Service Div., Mr. Mamoru Hatazawa
- TOSHIBA CORPORATION Power System Company Chief Specialist, Fukushima Restoration Project Engineering Dept., Nuclear Energy Systems & Service Div., Mr. Shigeru Yukinori and 2 others

Hitachi

- Hitachi-GE Nuclear Energy, Ltd. Corporate Chief Engineer, Mr. Kumiaki Moriya
- Hitachi-GE Nuclear Energy, Ltd. Professional Engineer and Chief Project Manager, Nuclear Plant Engineering Dept., Next Generation Reactor Center, Mr. Masayoshi Matsuura

The project formation on the PWR are the following:

Kenichi Ohmae

Head Office

- Ohmae and Associates, Inc. Partner, Mr. Iwao Shibata
- Japan Nuclear Fuel Ltd. General Manager, Reprocessing Planning Dept., Reprocessing Business Div., Mr. Manabu Yusa

Those who cooperated with interviews, hearings and data-gathering:

Kansai Electric Power Company

- Kansai Electric Power Co., Inc. Manager, Nuclear Accident Management and Nuclear Power Div., Mr. Kensuke Yoshihara
- Kansai Electric Power Co., Inc. Project Manager, Plant & Maintenance Engineering Group, Nuclear Power Div., Mr. Toshihiko Tanaka
- Kansai Electric Power Co., Inc. Tokyo Office
  Manager, Mr. Toshikazu Sendo
  Assistant Manger, Mr. Takahiro Ohgami

Mitsubishi Heavy Industries

- Mitsubishi Heavy Industries, Ltd. Acting Manager, Advanced Plant Safety Dept., Nuclear Energy Systems Div., Mr. Daisaku Okuno

The research focused on the technical aspect of the events and accidents, including the hydrogen explosion and dispersion of radioactive materials, in order to identify safety measures for the plant safety as well as the local safety.

Main scope of the research

- Damage of the earthquake and tsunami disaster.
- Chronology of the events at the Fukushima Dai-ichi Nuclear Power Plant
- Chronology of the events at the other plants (Fukushima Dai-ni, Higashidori, Onagawa, Tokai Dai-ni).
- Differences in the chronologies between Fukushima Dai-ichi and the other plants, and their causes.
- Loss of power supply.
- High-pressure cooling function.
- Ventilation function.
- Low-pressure cooling function.
- Hydrogen explosion (mechanism of hydrogen generation, leakage, and explosion).
- Effect, limits, and issues of existing accident management (AM).
- Issues, causes, and safety measures implied from the chronologies and analysis.
- Safety measures to prevent recurrence.
- Comparison to stress tests of NISA and EU.
- Cooperation with IAEA, etc.

Out of scope

- Important/related events and issues outside of the nuclear plants.
  - Actions and decision-making of the central government and relevant ministries
  - Actions and decision-making of the local governments
- Policies and decision making of evacuation, its zoning, and compensations for damage.

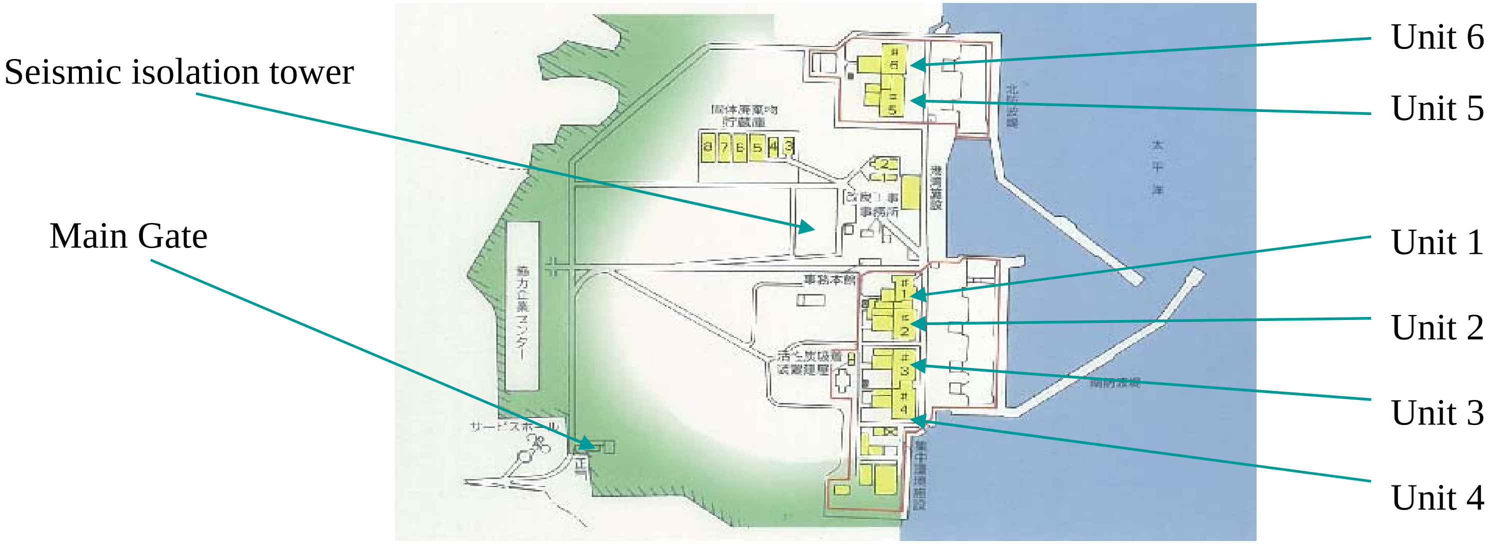
Fukushima Dai-ichi Nuclear Power Plant

- What happened?
- What are the implications?

Details of the Earthquake and Tsunami on March 11th (at Fukushima Dai-ichi)

- Scale and damage caused by earthquake and tsunami
- Its implications of the damage on the plant

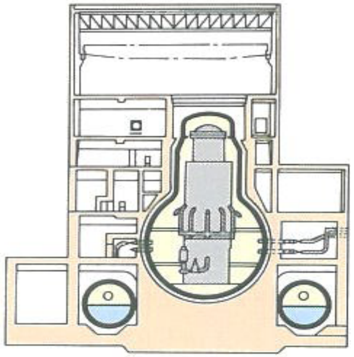
Overview of Fukushima Dai-ichi: With 6 reactors, it is one of the oldest plants in Japan, and its operation started about 40 years ago. Of 6 reactors, No. 1 - 3 were the oldest, located at the lower altitude, and only under regular operation on March 11th.



Location	Unit	Operation started in	PCV Type	Output (10,000 kW)	Main contractor	Operation status at the time of earthquake	
Okuma Town	**Unit 1**	1971.3	BWR-3	46.0	GE	**Under regular operation**	
	Unit 2	1974.7	BWR-4	78.4	GE/Toshiba	**Under regular operation**	
	Unit 3	1976.3	BWR-4	78.4	Toshiba	**Under regular operation**	
	Unit 4	1978.10	BWR-4	78.4	Hitachi	Regular Inspection	All fuel removed. Pool gate closed (Under shroud exchange)
Futaba Town	Unit 5	1978.4	BWR-4	78.4	Toshiba	Regular Inspection	Reactor pressure vessel was sealed
	Unit 6	1979.10	BWR-5	110	GE/Toshiba	Regular Inspection	Reactor pressure vessel was sealed

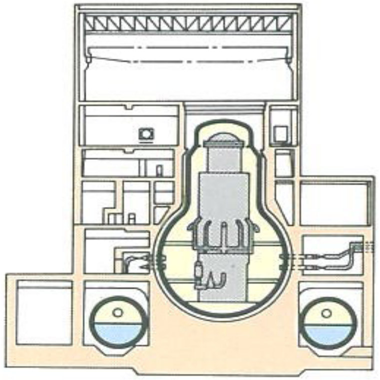
Type of Primary Containment Vessel: The Mark-I and Mark-II were used at Fukushima Dai-ichi Plant.

Fukushima Dai-ichi Unit 1
（Output 460,000kW）
"1971”



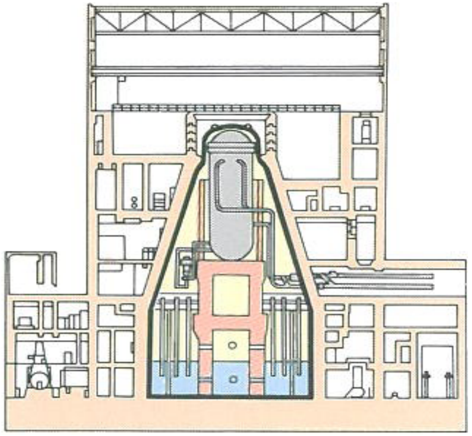
BWR-3
Mark-I
（Flask form）

Dai-ichi Units 2-5
（Output 784,000kW）
"1974～1978”



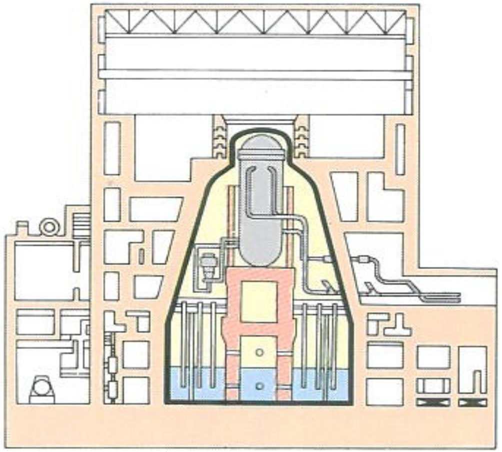
BWR-4
Mark-I
（ Flask form ）

Dai-ichi Unit 6
Fukushima Dai-ni Unit 1
（Output 1,100,000kW）
"1979-1985”

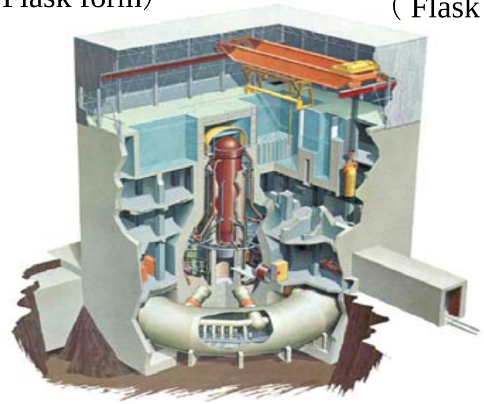


BWR-5
Mark-II
（Circular）

Fukushima Dai-ni Units 2-4
（Output 1,100,000kW）
"1984-1994”



BWR-5
Mark-II Improved
（Hangar shape）



Source：NRC Homepage

Fukushima Dai-ni Unit 1

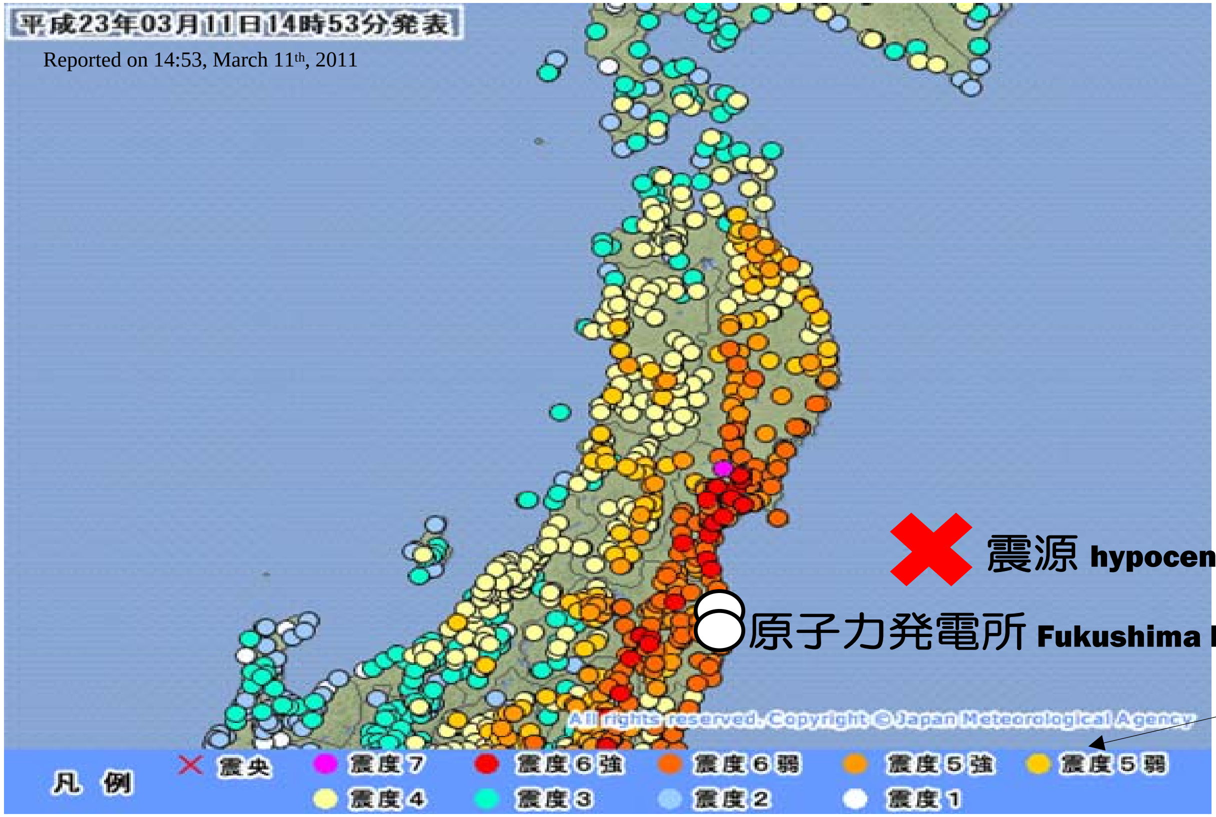
Fukushima Dai-ni Unit 3

Tohoku Region Pacific Coast Earthquake: A gigantic earthquake, magnitude 9.0, occurred at 14:46 on March 11th (Fri), 2011. Intensity around the Fukushima Dai-ichi exceeded 6.5.

- Date of earthquake: 2:46 PM, March 11th (Fri), 2011
- Location of hypocenter: Off the Sanriku Coast （North latitude 38、East longitude 142.9） **Depth 24km、Magnitude 9.0**

- Scale in each location:

Intensity 7:	Miyagi-ken Kurihara-shi
Intensity upper 6:	**Fukushima-ken, Naraha-cho, Tomioka-cho, Okuma-cho, Futaba-cho**
Intensity lower 6:	Miyagi-ken, Ishinomaki-cho, Onagawa-cho, Ibaragi-cho; Ibaragi-ken, Tokai-mura
Intensity lower 5:	Niigata-ken, Kariha-mura
Intensity lower 4:	Rokkasho village, Higashidori village, Mutsu city (Aomori pref.), Ohma town, Kashiwazaki city (Niigata pref.)



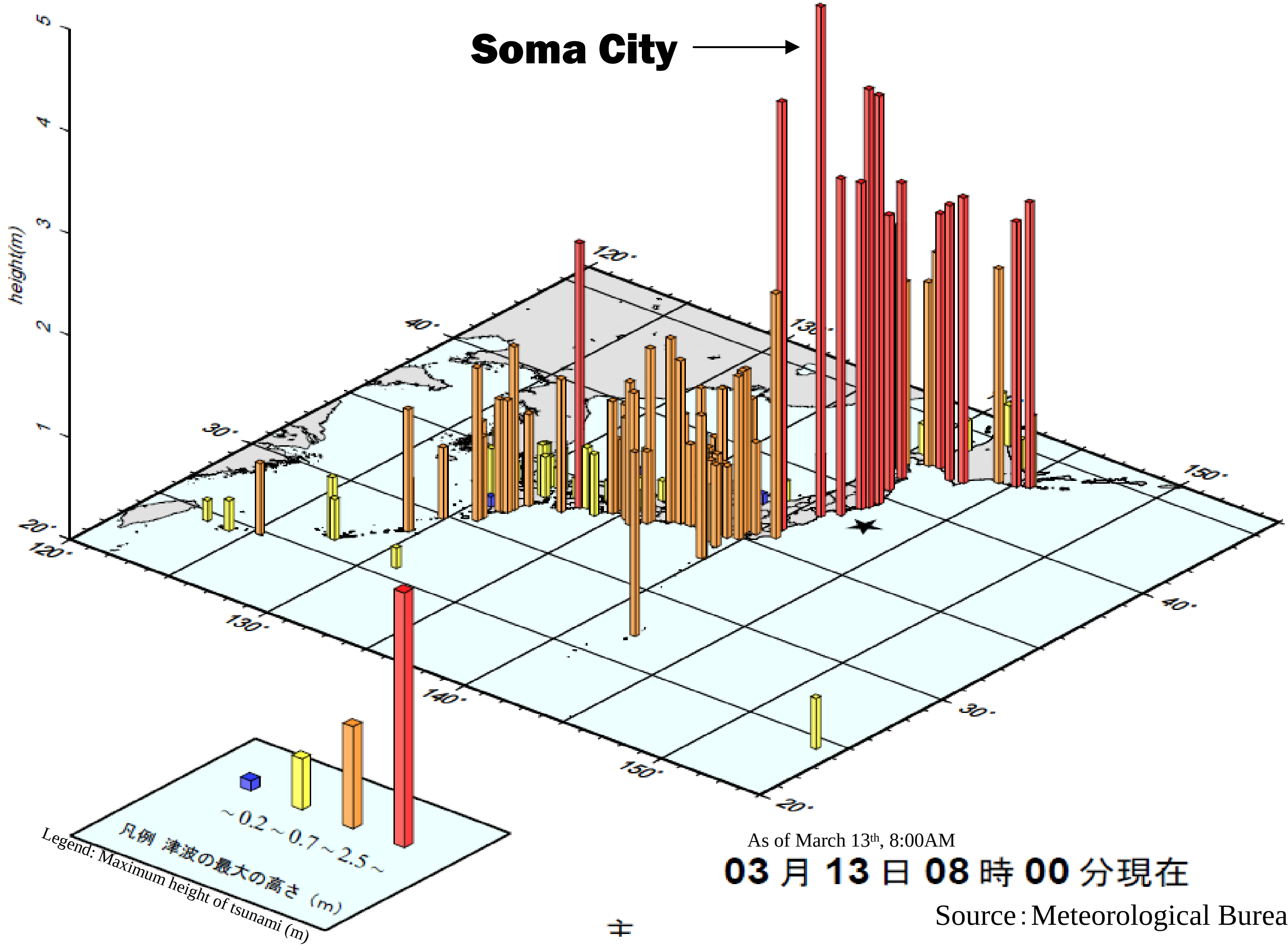
✕ 震源 **hypocenter**

○ 原子力発電所 **Fukushima Dai-ichi and Dai-ni Plants**

Magnitude

After the earthquake, a powerful tsunami occurred along the coasts of Miyagi and Fukushima. At 15:27 of March 11, about 40 minutes after the earthquake, the first wave hit Fukushima Dai-ichi. 8 minutes later (15:35), the even higher 2nd wave hit.

Tsunami height in each location



Soma City →

As of March 13th, 8:00AM

03 月 13 日 08 時 00 分現在

Source：Meteorological Bureau Homepage

Scale of earthquake and tsunami: The earthquake and tsunami that hit Fukushima Dai-ichi were among the fourth largest in the recorded history.

Earthquake Magnitude ＝＞ 4th in recorded history

Rank	Year	Name of Earthquake	Magnitude
1	1960	Chile	9. 5
2	1864	Alaska	9. 2
3	2004	Sumatra	9. 1
4	**2011**	**Tohoku Region Pacific Coast**	**9.0**
4	1952	Kamchatka	9. 0

Tsunami Magnitude*＝＞ 4th in recorded history

Rank	Year	Name of Earthquake	Magnitude
1	1960	Chile	9. 4
2	1837	Valdivia, Chile	9. 3
2	1946	Aleutians	9. 3
4	**2011**	**Tohoku Region Pacific Coast**	**9.1**
4	1964	Alaska	9. 1
6	2004	Sumatra other	9. 0

* Tsunami Magnitude = Calculated from the scale of tsunami caused by the earthquake

Source: Homepage of Laboratory of Seismological Study, Tokyo Univ.

Damage by the earthquake such as the liquefaction and break of infrastructure was larger at Fukushima Dai-ichi (Intensity: upper 6*) than at Dai-ni (lower 6*). One of the major factors which had retarded the accident management at both plants afterwards.

***:** Maximum acceleration at Dai-ichi was 550gal (east to west) and 350gal at Dai-ni (up to down). Both observed at the lowest floors of the reactor buildings.

Damage at Fukushima Dai-ichi

- Road is completely cracked and fissured
- Major bend in guardrail
- Many cracks along the side of the road
- People and vehicles can hardly pass

- Road has caved in for several meters
- Drum can has rolled into the middle of the street
- No cars can pass. People can hardly walk

- Several meters of chasm even at elevated ground

- Ground has caved in

- Gap between building and ground (a depression in ground?)

Damage at Fukushima Dai-ni

Though safety measures to Tsunami were implemented, based on the evaluation by JSCE (Japan Society of Civil Engineers) in 2002, the Tsunami greatly exceeded its assumption (approx. 10m), especially at Fukushima Dai-ichi. 3 times higher than expected.

Design conditions against tsunami to present

* At construction of the plant: The design conditions were determined based on the past tsunami records.

* In 2002: Based on “Tsunami evaluation technique for Nuclear Power Plant” published in the same year by JSCE, the conditions were reviewed, and the safety measures such as to set the seawater pumps in higher place had been implemented.

		At construction	**Review in 2002**	**Tsunami at this time (Height of submergence)**
Fukushima Dai-ichi	Ascent	Altitude (O.P.) +3.1m	**Altitude (O.P.) +5.7m**	On the seaside of main buildings **Altitude (O.P.) +11.5 ~ +15.5m**
	Decline	Same -1.9m	Same -3.6m	
Fukushima Dai-ni	Ascent	Same +3.7m	Same +5.2m	On the seaside area Same +6.5 ~ +7m Concentrated run on south road of main buildings Altitude (O.P.) ＋12 ~ 14.5m
	Decline	Same -1.9m	Same -3.0m	

- **Difference of 5.8 ~ 9.8m from the design condition (about 3 times higher)**
- 1.3 ~ 1.8m of difference at Fukushima Dai-ni

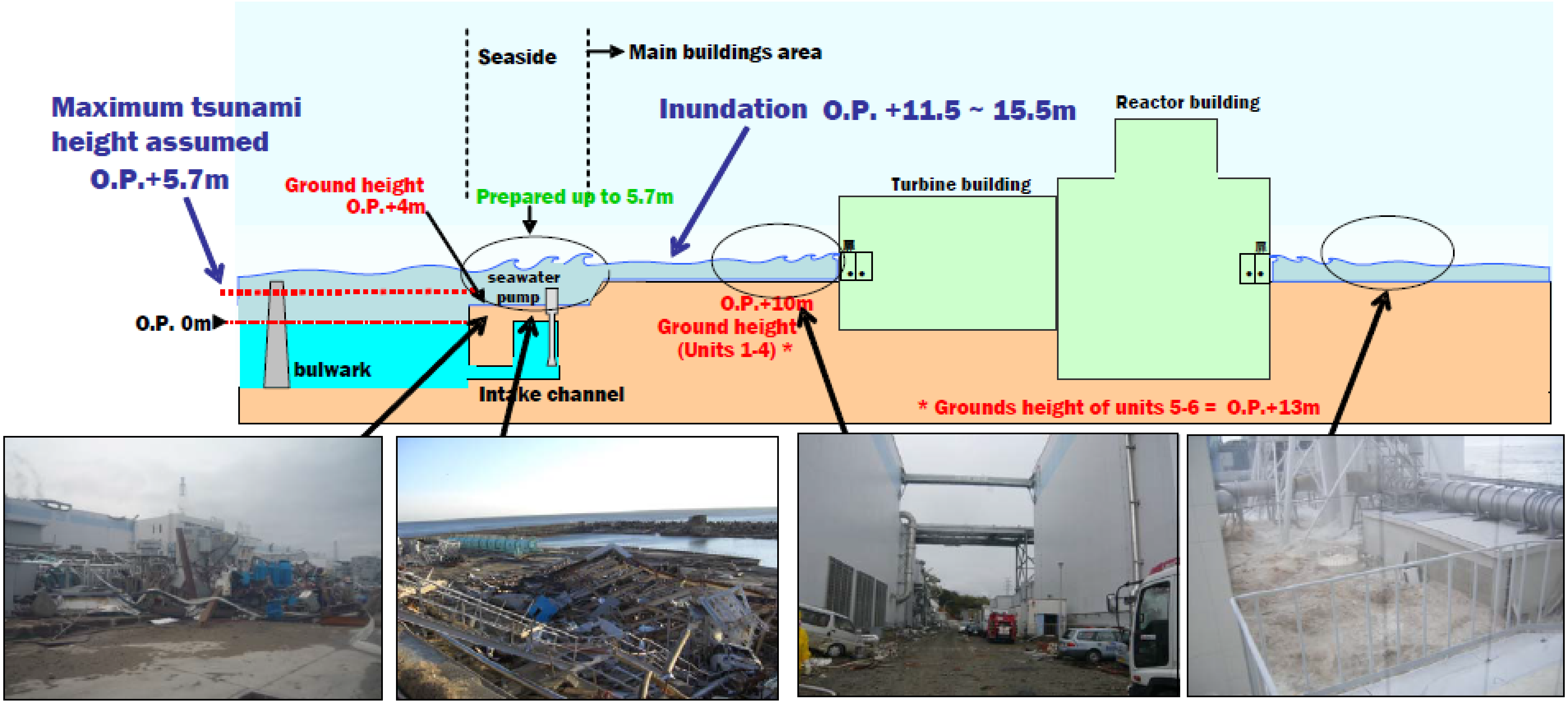
O.P. = Onahama Port Construction Reference Plane
T.P. = Tokyo bay standard sea level
O.P. is 0.727 meters below T.P.

The tsunami swallowed not only the seaside, but the whole area of Dai-ichi, including the mountain side. Both the reactor and turbine buildings were completely inundated. => The safety allowance against tsunami is obviously underestimated.

Maximum tsunami height (estimation)
= + 5.7m

Actual inundation height
= + 11.5 ~ 15.5m

< Ground height and tsunami image at Fukushima Dai-ichi Units 1-4 >



- A heap of rubble in the area of 4m altitude. Hardly transport vehicles, personnel, or supplies.
- Even at an elevation of 10m, cars had drifted. Even on the mountain side of the building, a 5.5m-height tank has been swallowed up, just like a swimming pool.

The moment the tsunami hit: The wave, that reached at the plant, surpassed the reactor building (45 m), and came halfway up the exhaust stack (120 m).

Fukushima Dai-ichi

Exhaust Stack

Nuclear Reactor Building

The Scar of Tsunami: On the south side of the plant, the forestation along the shore has been torn up from their roots.

Before March 11th (Fukushima Dai-ichi Power Plant, south side of unit 4)

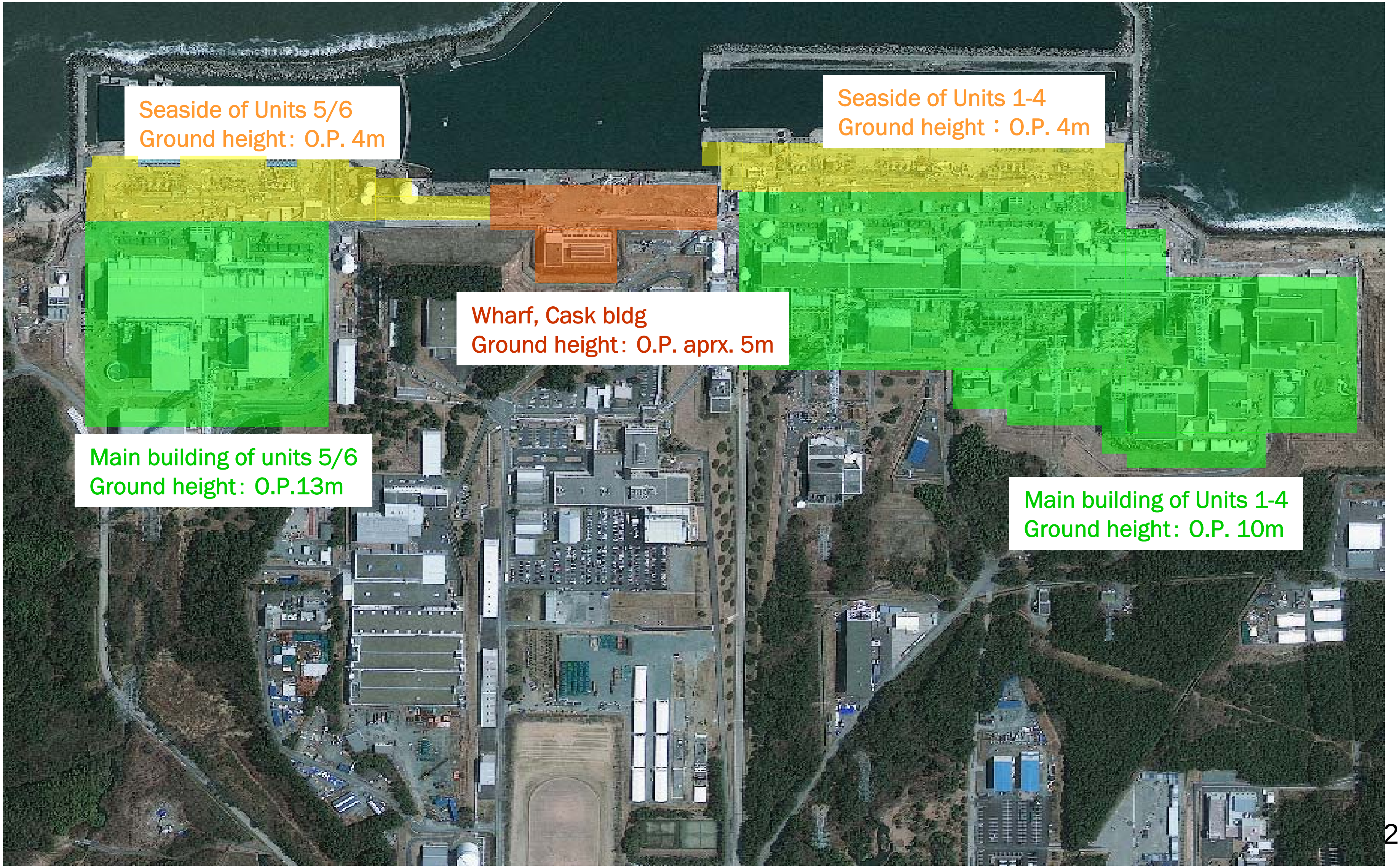
Forestation has been torn up from their roots

After March 11th

Aerial shot of Fukushima Dai-ichi: Of the 6 reactors, the units 1 - 3 were in regular operation. The units 4 - 6 halt for regular inspection.

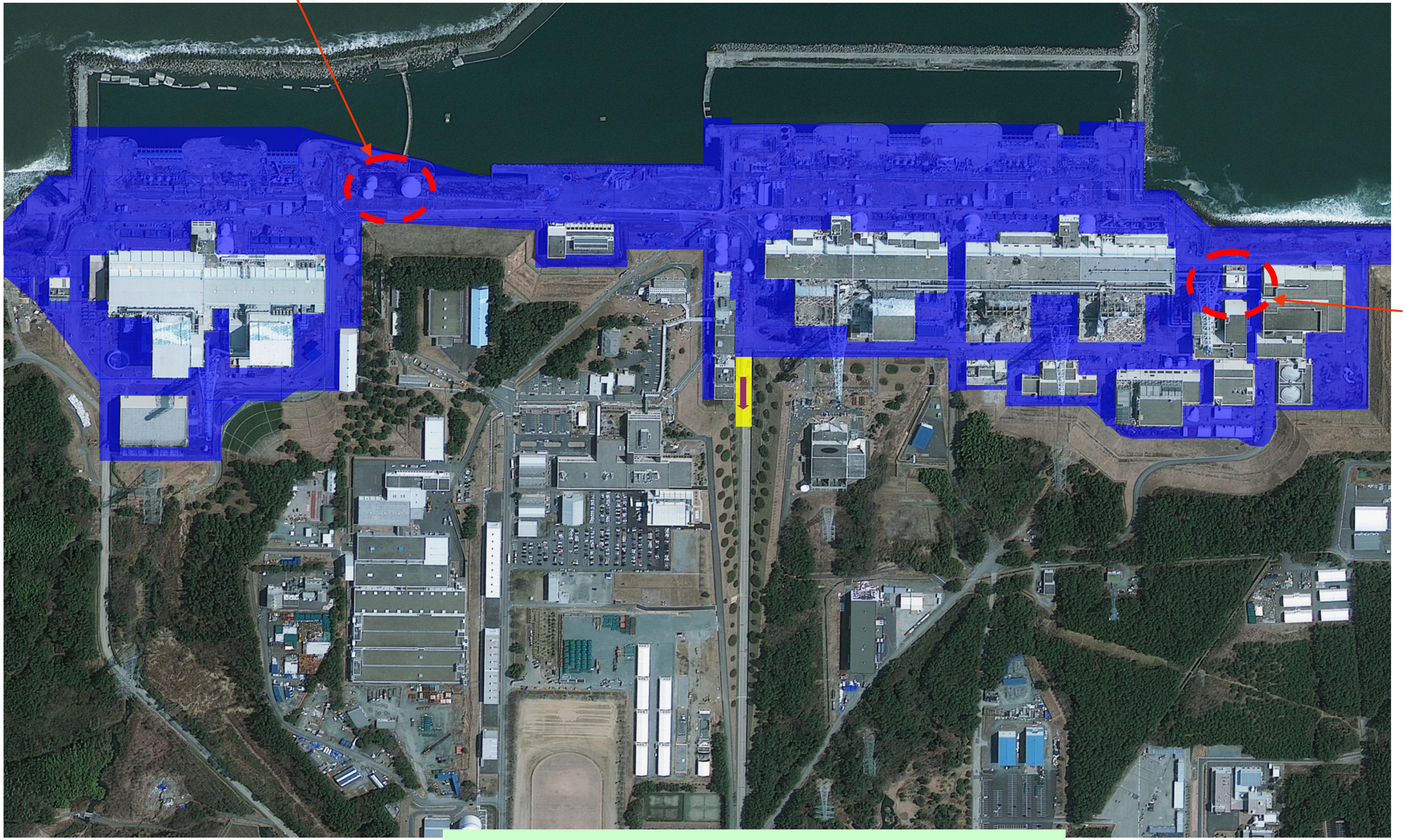
((C) GeoEye

Ground height: Units 1, 2 and 3 (all in operation) are 10m above sea level and at a lower level than Units 5 and 6 (both at 13m).



((C) GeoEye

Units 1-6 of Dai-ichi and the main facilities were all submerged due to the 15.5m tsunami.



Photos of page 27, 28.
(Solid waste storage)

Photos of page
25, 26.
(Near exhaust
stack of Unit 4)

Fukushima Dai-ichi Nuclear Power Plant.
Submerged areas are in blue color

(C) GeoEye

The tsunami easily has swallowed up the heavy fuel tank (5.5m), and the whole yard has become like a swimming pool with full water.

Flooding of the yard at Dai-ichi (near Unit 4 exhaust stack. Ground height O.P.+10m)

Heavy fuel tank (height 5.5m)

3 cars

Date of capture : 2011/3/11 15:42

Same 15:42

Same 15:43

Same 15:43

Heavy fuel tank has been swallowed

Same 15:43

The whole yard has become like a swimming pool with full of water.

Same 15:44

The white car that was on the left side of the picture has been swept aside and is now stuck in the outer wall of the building

Flooding (continued): The 3 vehicles were completely drifted by the tsunami.

Flooding of the yard at Dai-ichi
(near Unit 4 exhaust stack. Ground height O.P.+10m)

Date：2011/3/11 15:44

Same 15:44

Same 15:46

Same 15:49

Same 15:57

Several cars in the first photo have been completely drifted.

One of those vehicles is now stuck into the building's wall

Seaside at the moment the tsunami hit: Tsunami easily overcame the 10m levee, drifted a number of cars, and almost completely swallowed the giant tank.

East side of solid waste storage (southeast seaside of unit 5)

①

②

Tsunami easily flooding over the 10m levee.

③

④

Giant surge tank of photo 3 is submerged up to here.

Cars are drifted from elsewhere

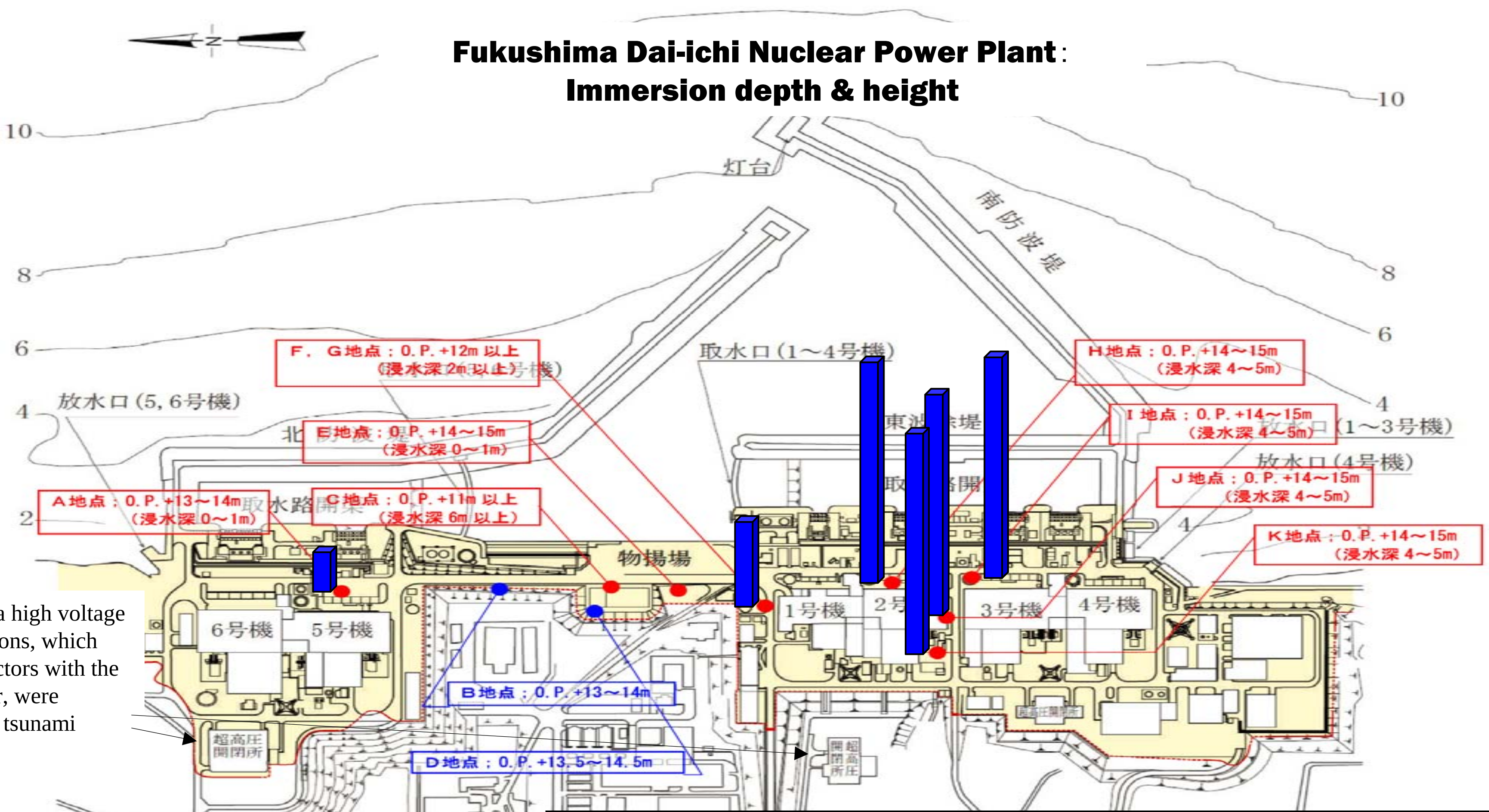
(Continued) The 2 heavy fuel tanks have been drifted onto the road. The side of the surge tank has been bent like a twisted PET bottle.

2 heavy fuel tanks have been drifted, and pushed up towards the roadside.

The entire body of the giant surge tank has been contorted as if a PET bottle is wrenched

The 11.5~15.5m tsunami hit the entire plant with 4-5m of water flooded. As the units 1 - 4 were lower than units 5 & 6 in terms of the ground level, their damage was more serious.

Fukushima Dai-ichi Nuclear Power Plant：Immersion depth & height

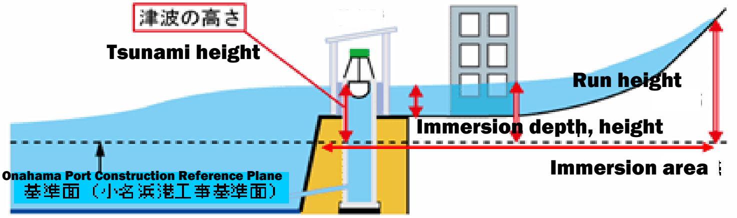


2 out of 3 extra high voltage switching stations, which supply the reactors with the external power, were flooded by the tsunami

Red: Immersion height
(( ) = immersion depth)
Blue: Run height

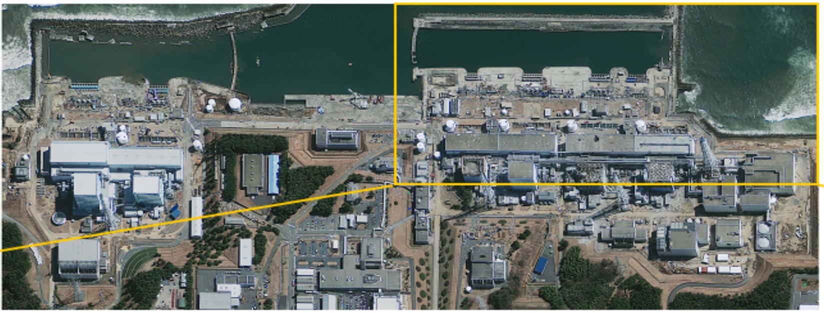
浸水域(破線は推定)

Appendix

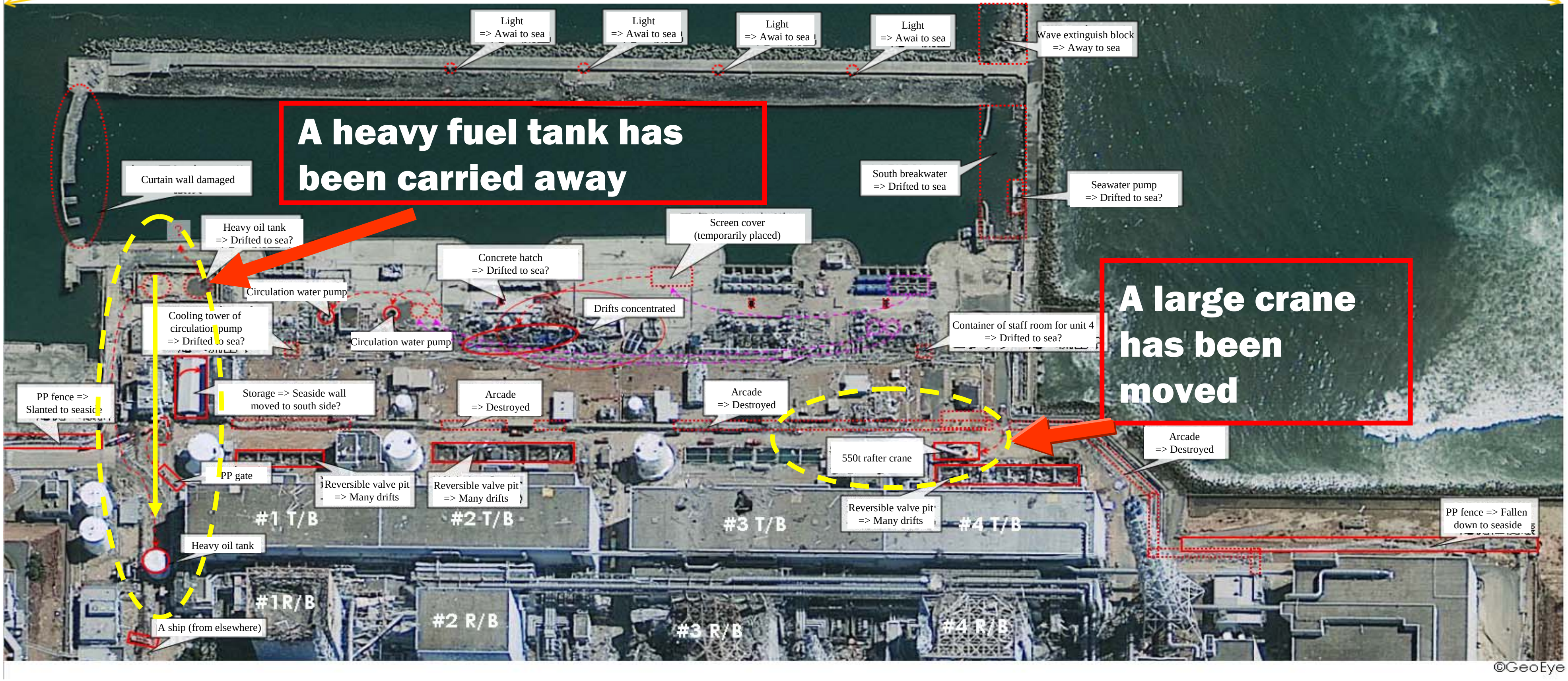


- Immersion height: Height from the O.P. reference plane, at which traces of discoloration or driftage are left in buildings or facilities.
- Immersion depth: Height from the ground level, at which traces of discoloration or driftage are left in buildings or facilities.

Drifted facilities & structures: (1) Seaside of Units 1-4: The heavy fuel tank was carried away, and a large crane was moved. The countless damage and drifts.



Aerial photo of seaside of Fukushima Dai-ichi Units 1-4



A heavy fuel tank has been carried away

A large crane has been moved

Note: Magnified pictures of the heavy fuel tank and the large crane are on the next page.

(Continued) Myriads of rubbles, drifts, and damage made it extremely difficult to transport people and supplies after the tsunami.

A heavy fuel tank has been drifted, and has completely blocked the road.

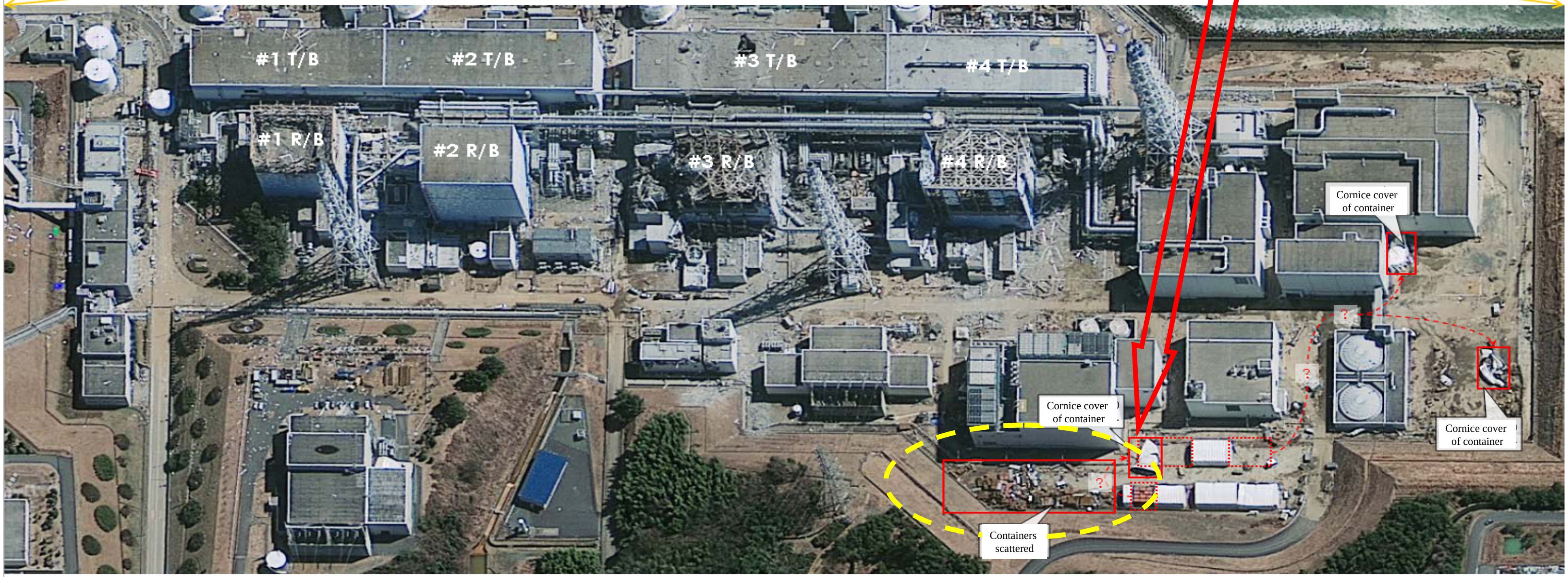
Crane vehicle (45t) and debris have been drifted, and obstructed the access to the building

A drifted car is stuck between the pipes and building.

Drifted facilities & structures: (2) Mountain side of Units 1-4: Container's cornice cover has drifted over one hundred meters, and numerous containers are scattered about.

Places located far from the ocean are also submerged

Aerial photo of the mountain side of Fukushima Dai-ichi Units 1-4



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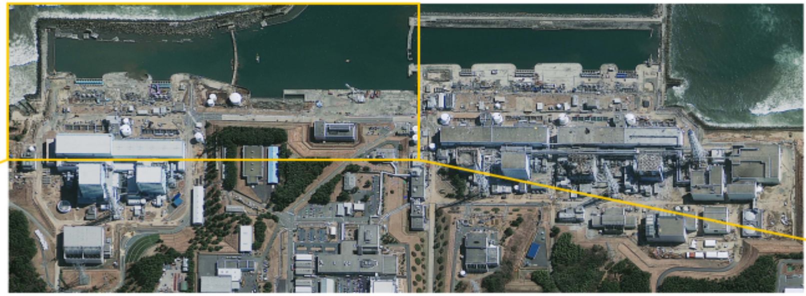
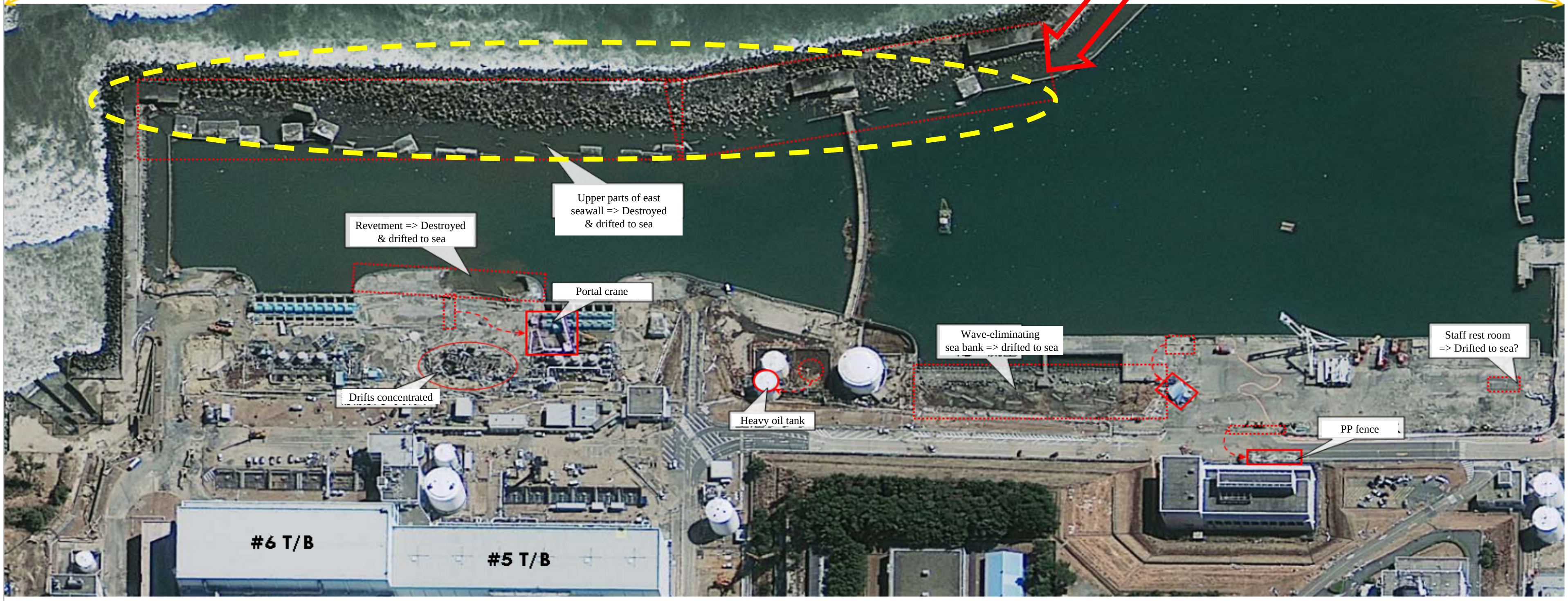
Drifted facilities & structures: (3) Seaside of Units 5 and 6: Even at units 5 and 6 where the ground level was higher, the seawall was damaged and countless tetra pods were stranded on it, making traffic access along the seawall impossible.



Seawall damaged

Aerial photo of seaside of Fukushima Dai-ichi's Unit 5-6



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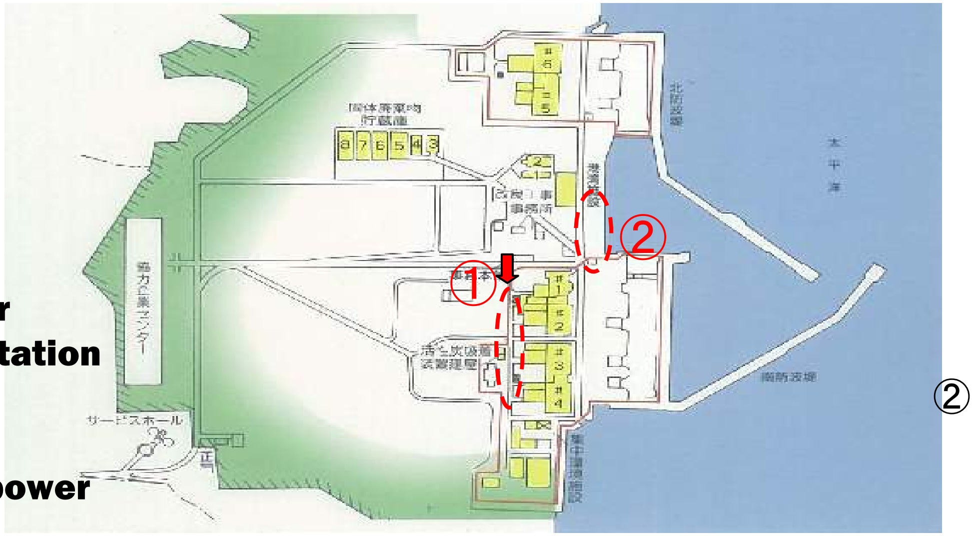
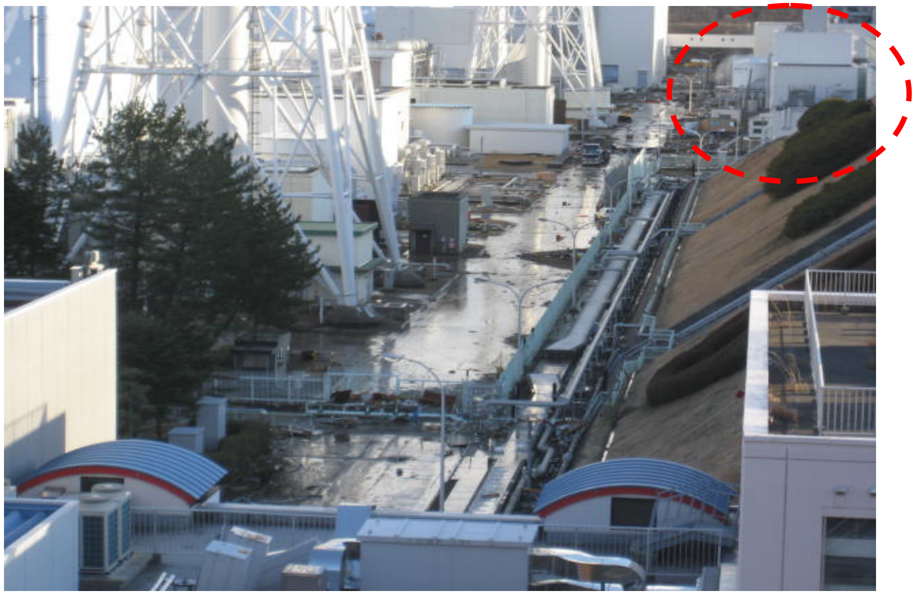
Flooding on the mountain side swallowed the power supply systems of Units 1-4 by salt water. The liquefaction of the roads, landslides, and rubble had made the transportation of people and supplies significantly aggravated and extremely difficult.

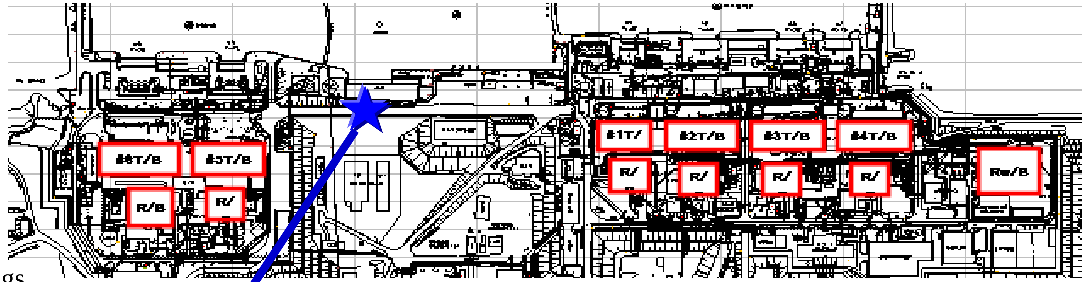


① **A large amount of seawater flowed into the switching station at the mountain side of the exhaust stack , and completely destroyed the power supply systems.**

② **Landslides and rubble by the tsunami made the transportation of people and supplies extremely difficult.**



Damage of Tsunami: An oil fence is stuck into the building. The road is severely liquefied. Along with scattered debris, it is far from passable during the day, and impossible to walk during the night without light.



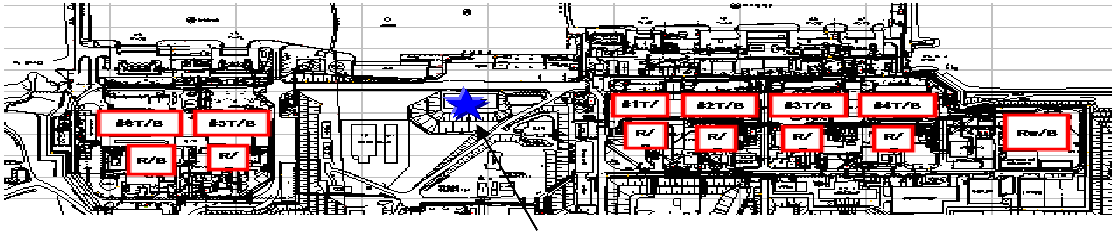
Surroundings of storage/cask buildings

Oil fence is stuck in the building

Several-meter large pieces of asphalt or concrete debris are drifted, fractured, and scattered around.

Road is severely liquefied

Damage of Tsunami: In the storage and cask buildings, a car was swept in and stuck vertically. Heavy debris is strewn over. There is no walking space.

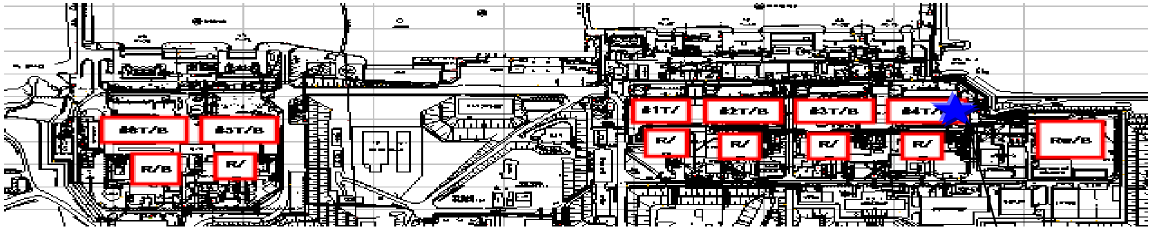


Inside of storage/cask buildings

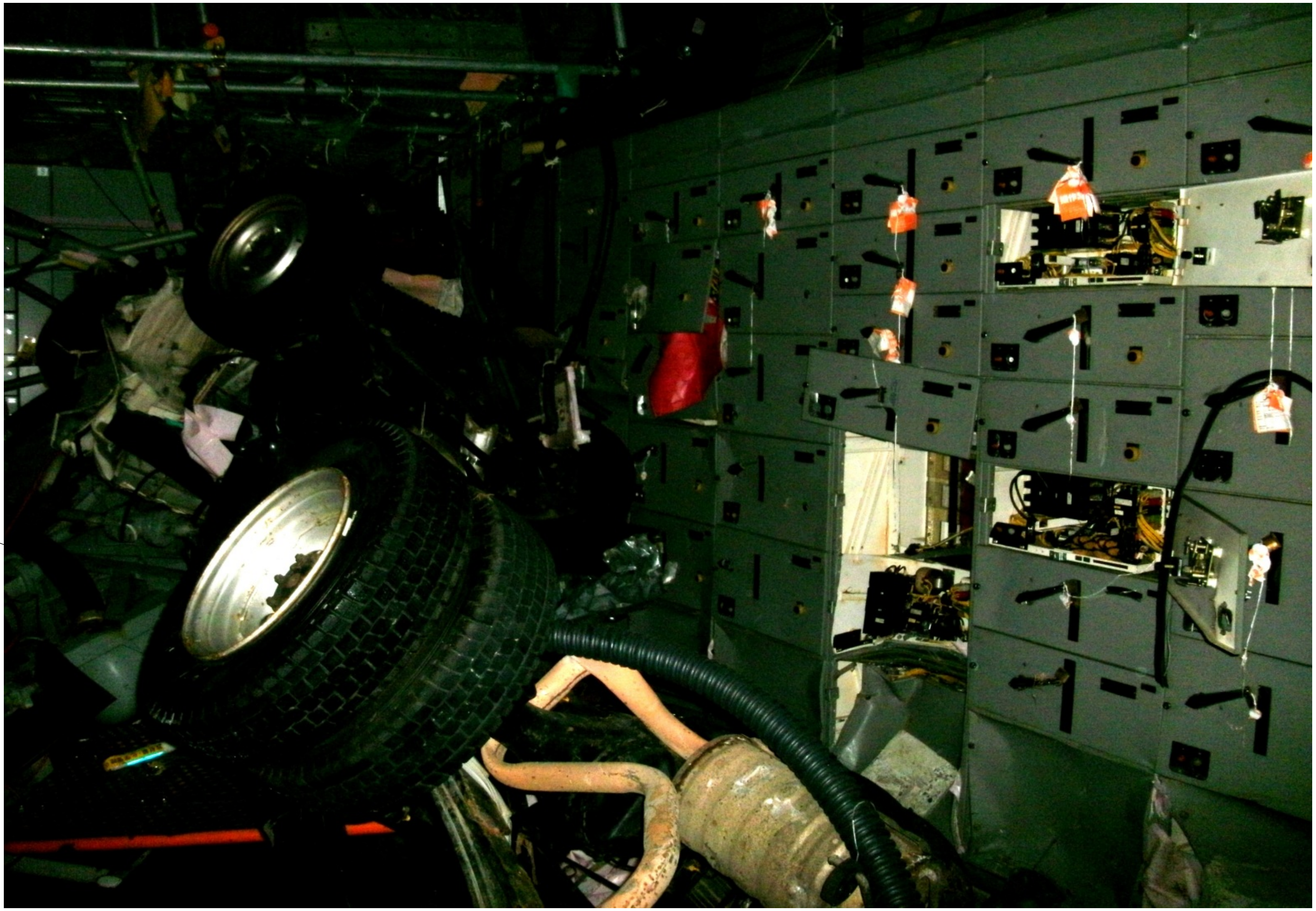
Debris and furniture are completely strewn over the floor. No place for foothold.

A car was swept in and stuck vertically in the ground

Damage of Tsunami: Power boards of Unit 4 turbine building. Tires, vacuums, hoses, and other numerous debris have piled up and scattered around. The boards are inaccessible



Power boards in the turbine building of Unit 4



- **They need to investigate the damage to each power supply system by the earthquake/ tsunami, and take recovery actions.**
- **However, the debris are scattered around, and simply accessing the power board is a challenge.**

Liquefaction, numerous debris, and fractures of roads have made transport of people and supplies extremely difficult. Furthermore, the complete darkness at night has made the work environment extremely hard.

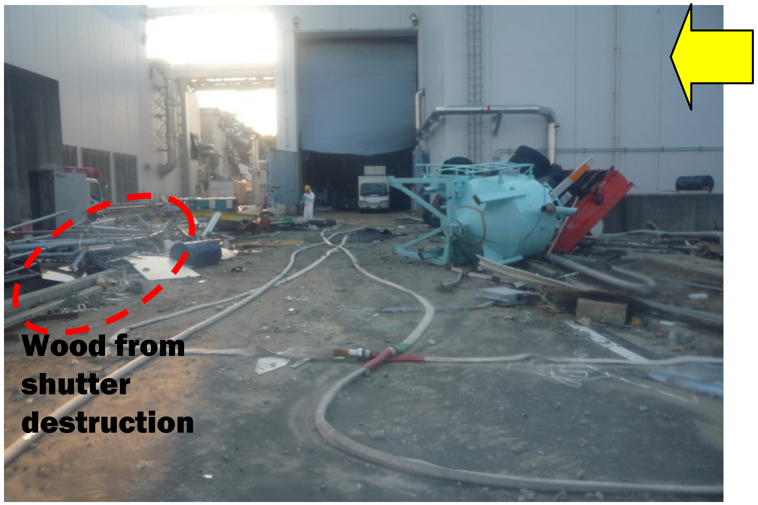
- **Extremely bad access by frequent aftershocks, opened manhole, chasms, cave-ins, and liquefaction of the ground**
- **Complete darkness at night**
- **Access routes were extraordinarily obstructed.**

Cave-ins of roads

Even walking is dangerous, especially so at night.

Obstacles in access route

Access is circumvented by strewn fire hoses. After the explosion, further obstruction by debris, and damaged fire trucks are added.



Access to temporary power supply systems

They used heavy machinery to break down the loading entrance for access to the building.

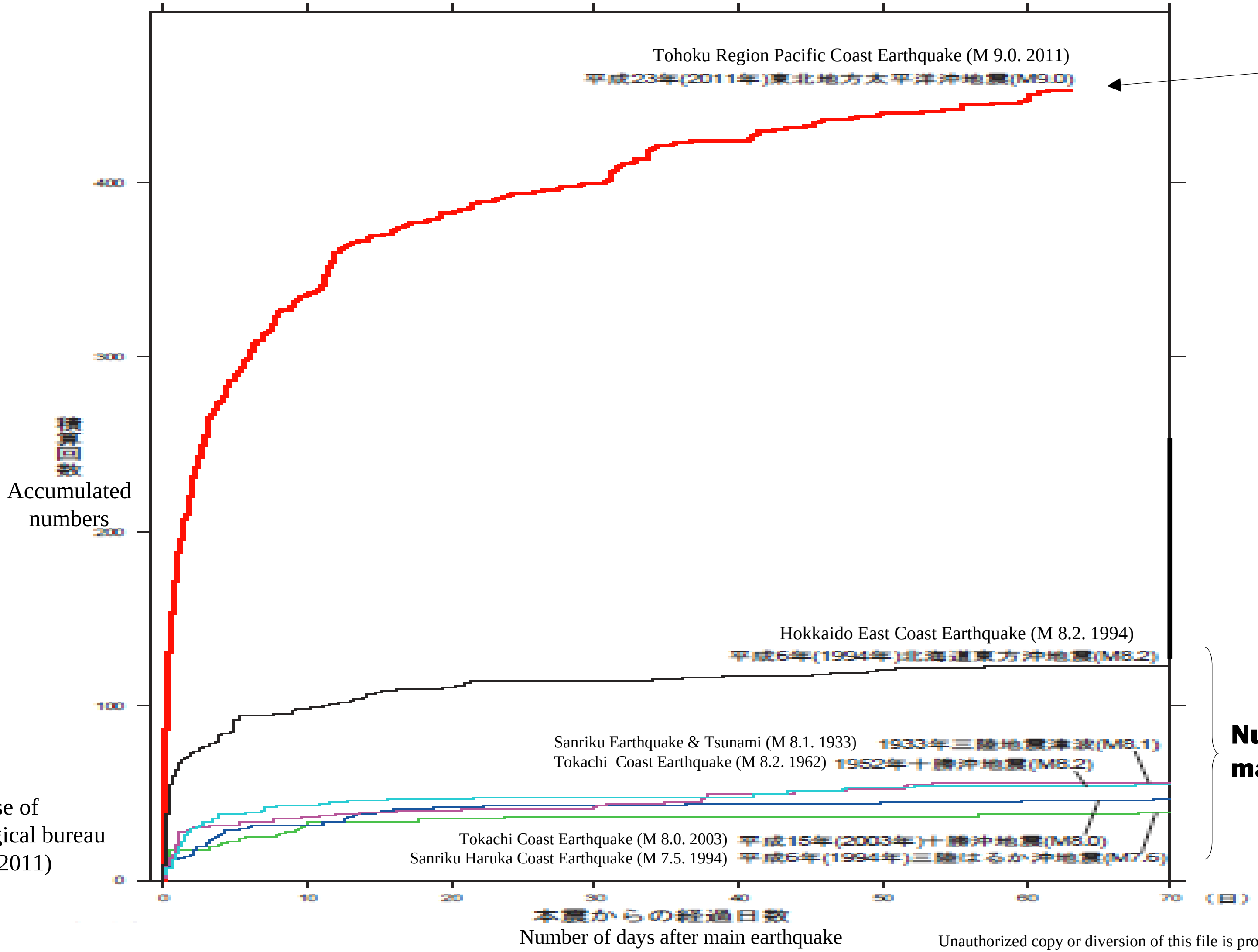
Setting up of makeshift power supply cables

Cables are moved by the staff of not only power company but also other firms.

Furthermore, highly frequent aftershocks significantly interrupted and hindered recovery operations. Compared to the past major earthquakes, about 4 times many aftershocks had occurred.

Number of aftershocks of major earthquakes in ocean areas

(Over 5.0 magnitude, including main earthquake.)



Number of aftershocks of this earthquake on March 11.

Number of aftershocks of major earthquakes in the past

Press release of Meteorological bureau (May 13th, 2011)

With loss of power, in the building was pitch dark, making monitoring the reactor extremely hard. Strewn rubble has further obstructed the field work for recovery.

- Due to power loss, they had to operate under complete darkness in the building.
- Due to power loss, they installed makeshift batteries to monitoring instruments.

Operations in the darkness

Photo of the service building entrance from inside. Debris strewn on the floor.

Makeshift batteries for instruments

Connected makeshift batteries for monitoring instruments.

Monitoring of parameters and data

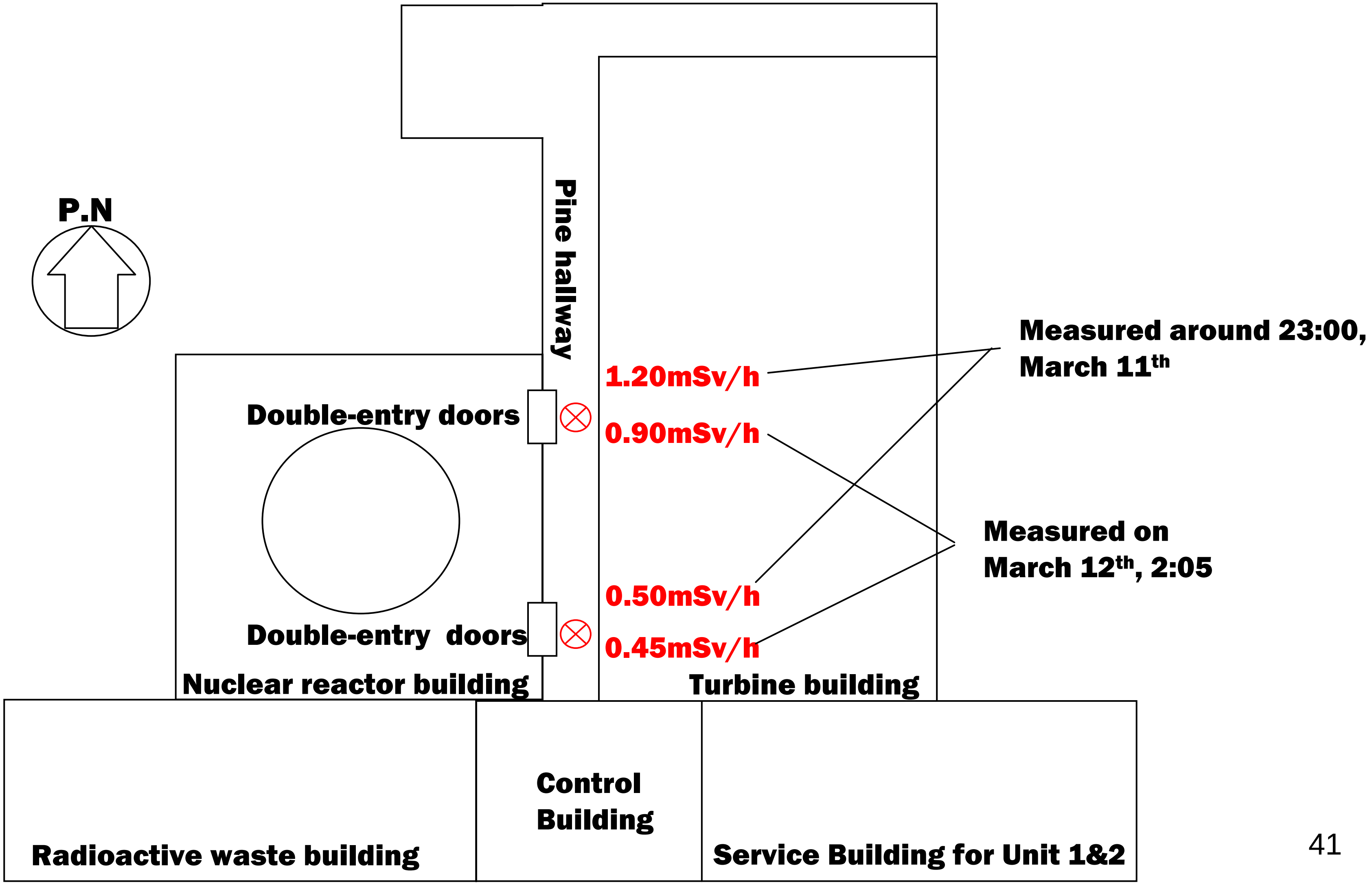
Monitoring parameters in the dark with hand lights.

Direction by Duty Chief

Duty chief at desk in the darkness with full mask.

Furthermore, the radiation levels have continued to rise and interrupted the recovery operations in the fields.

Radiation level in front of the double-entry doors to Unit 1 turbine building along the Pine Hallway (March 11th, 12th)



P.N

Pine hallway

Double-entry doors ⊗

Double-entry doors ⊗

Nuclear reactor building

Turbine building

1.20mSv/h

0.90mSv/h

0.50mSv/h

0.45mSv/h

Measured around 23:00, March 11th

Measured on March 12th, 2:05

Radioactive waste building

Control Building

Service Building for Unit 1&2

Voices of the field staff (1) - The extremely severe and dangerous working environment without any make-up.

- *"…***Power indicators flickered, and they went out one by one in front of my eyes***. At the time I didn't think it was by tsunami, and had no idea what had just occurred."*
- *"…***Unit 2 was pitch dark, Unit 1 had only emergency lighting (dim light).** *I thought we had lost power and were unable to do anything."*
- *"…young operators seemed worried, and wondered* **'if we are unable to operate, and can do nothing, is there a reason for us to be here?', but I begged them to remain.** *I told 2 young trainees to evacuate to the seismic isolation tower, and I asked the remaining others 'is this okay with you all?'"*

- *"… I wrote out the names of people who could go to the vent, and organized so that a shift manager would be allotted.* **As they would be going to a place of very high radiation with fully equipped, I did not send the young people***."*

- *"…***Normally, the cable installation takes 1 to 2 months. That we did it in several hours is killer speed.** *In the pitch dark, we had to find the penetration for installation, or perform terminal processes.* **Normally a machine would be used, but this time a heavy cable was installed by manpower.***"*
- *"***Lots of time was spent with direct communication** *even between headquarters and the field* **as almost all the communication lines were lost.** *For example, it took much time even to send the command "measure resistance by megger".*

Voices of the field staff (2)

- *"…**A considerably large aftershock occurred, and I desperately ran back.**"*

- *"…I placed my foot on the torus, not on the catwalk. Since the valve was on top, **I placed my foot on the torus to check its heat, and (the black boots) melted down.** I determined that it would be safer not to walk there"*

- *"…It was not easy even to go to the reactor building (RCIC room). There were **extra hassles such as 10-15 minutes to put on the protective suit, 30 minutes to work in the field, and took off the suit and went to the operation room for reporting.**"*

- *"…Communication means were unavailable, and **it took me 45-60 minutes just to get to the RCIC room and back.**"*

- *"…**I thought instruments could be revived only with batteries, so all the members were set to looking for some.** Tried to create at least the bare minimum parameters. **It is not something that is usually predicted, but we tried to at least think of something we can do.**"*

- *"… **The battery was very heavy and it was tough to transport. No connection tools, no means of communication. No worse condition than that.**"*

Summary: Earthquake and Tsunami that hit Fukushima Dai-ichi wreaked huge damage to the on-site work environment. It was a major background reason for delay/failure of recovery actions to prevent the core damage and hydrogen explosion.

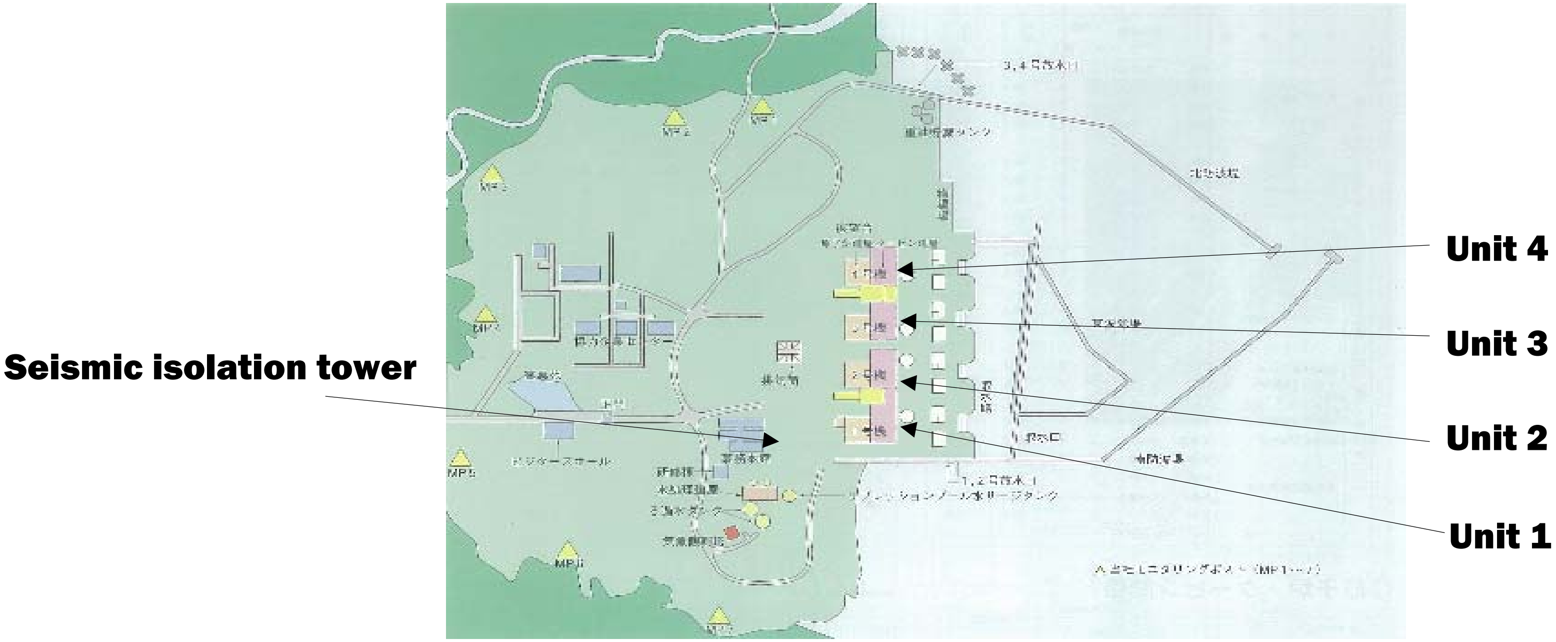
Effects of earthquake & tsunami on the work environment at Fukushima Dai-ichi Units 1-4

- **Darkness**: Almost all inside/outside lights failed due to AC/DC power loss, and the site was plunged into darkness.
- **Loss of command center functions**: Almost all data including the nuclear reactor temperature, pressure, and water level became unavailable at the central control room due to loss of power (gauging and control equipments not working)
- **Communication malfunction, command difficulty**: In addition to the disruption of the lines for fixed phones and cell phones, the PBX for emergency PHS did not function fully due to loss of power. This made communication and commands between the central control room and on-site teams, as well as reporting the plant status and requests for aid to offsite extremely difficult.
- **Difficulty of transporting personnel/supplies**: Due to the combinations of darkness, cave-ins/ shredding/ liquefaction of the roads, myriads of debris, and blockade of electric gates and entrances, the transportation of personnel and supplies was extremely difficult.
- **Extremely brutal work environment**: Interruptions and retreat from operations happened many times at unforeseen points, due to numerous aftershocks and radiation levels that exceeded acceptable safe limits.
- **Limitations in movement and time**: There was a lack of protective gear, masks, individual dosimeters etc, and not enough personnel could work for on-site operations.
- **Shredding/isolation of supplies**: 1 of the 3 fire trucks was damaged by the tsunami, and another was isolated at Unit 5&6 and unable to leave. Eventually only 1 fire truck was available for use at Units 1-4.

Details of the Earthquake and Tsunami on March 11th (at Fukushima Dai-ni)

- Scale and damage caused by earthquake and tsunami
- Its implications of the damage on the plant

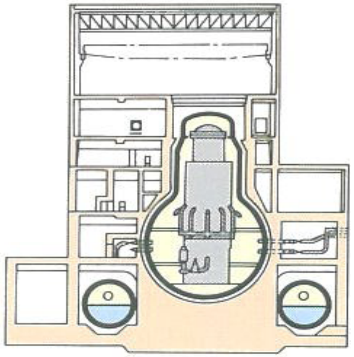
Overview of Fukushima Dai-ni: With a total of 4 nuclear reactors, it was activated in 1982, 11 years after Dai-ichi. At the time of the earthquake, all 4 reactors were in operation.



Location	Unit	Operation started in	PCV type	Output(10,000kW)	Main contractor	Operation status at the time of earthquake
Naraha Town	Unit 1	1982.4	BWR-5	110.0	Toshiba	Under regular operation
	Unit 2	1984.2	BWR-5	110.0	Hitachi	Under regular operation
Tomioka Town	Unit 3	1985.6	BWR-5	110.0	Toshiba	Under regular operation
	Unit 4	1987.8	BWR-5	110.0	Hitachi	Under regular operation

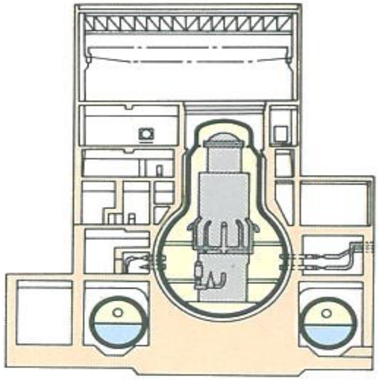
Type of Primary Containment Vessel: Mark II was used at Fukushima Dai-ni, a newer type than that of Dai-ichi.

Fukushima Dai-ichi Unit 1
（Output 460,000kW）
"1971”

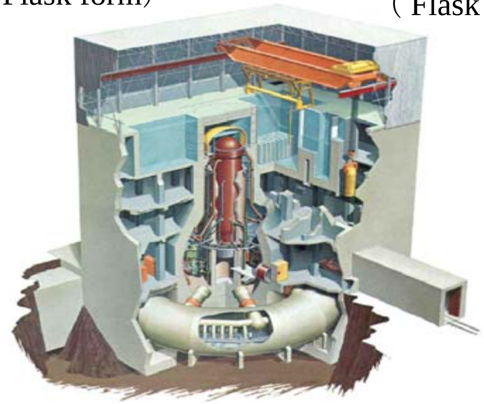


BWR-3
Mark-I
（Flask form）

Dai-ichi Units 2-5
（Output 784,000kW）
"1974～1978”

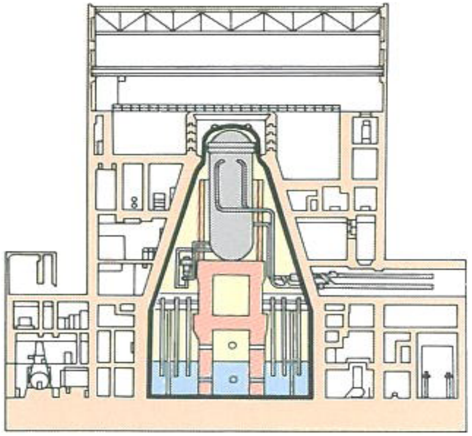


BWR-4
Mark-I
（ Flask form ）



Source：NRC Homepage

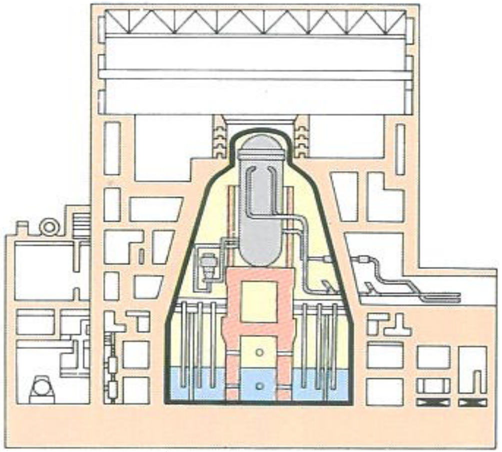
Dai-ichi Unit 6
Fukushima Dai-ni Unit 1
（Output 1,100,000kW）
"1979-1985”



BWR-5
Mark-II
（Circular）

Fukushima Dai-ni Unit 1

Fukushima Dai-ni Units 2-4
（Output 1,100,000kW）
"1984-1994”



BWR-5
Mark-II Improved
（Hangar shape）

Fukushima Dai-ni Unit 3

At Fukushima Dai-ni, compared to the design condition of 5.2m, a 6.5~7m tsunami hit. The difference from the condition is smaller than that at Dai-ichi.

Design conditions against tsunami to present

* At construction of the plant: The design conditions were determined based on the past tsunami records.

* In 2002: Based on "Tsunami evaluation technique for Nuclear Power Plant" published in the same year by JSCE, the conditions were reviewed, and the safety measures such as to set the seawater pumps in higher place had been implemented.

		At construction	**Review in 2002**	**Tsunami at this time (Height of submergence)**
Fukushima Dai-ichi	Ascent	Altitude (O.P.) +3.1m	Altitude (O.P.) +5.7m	On the seaside of main buildings Altitude (O.P.) +11.5 ~ +15.5m
	Decline	Same -1.9m	Same -3.6m	
Fukushima Dai-ni	Ascent	Same +3.7m	**Same +5.2m**	On the seaside area **Same +6.5 ~ +7m** Concentrated run on south road of main buildings Altitude (O.P.) ＋12 ~ 14.5m
	Decline	Same -1.9m	Same -3.0m	

- **Difference of 1.3 ~ 1.8m from the design condition**
- Smaller than that of Dai-ichi (5.8 ~ 9.8m)

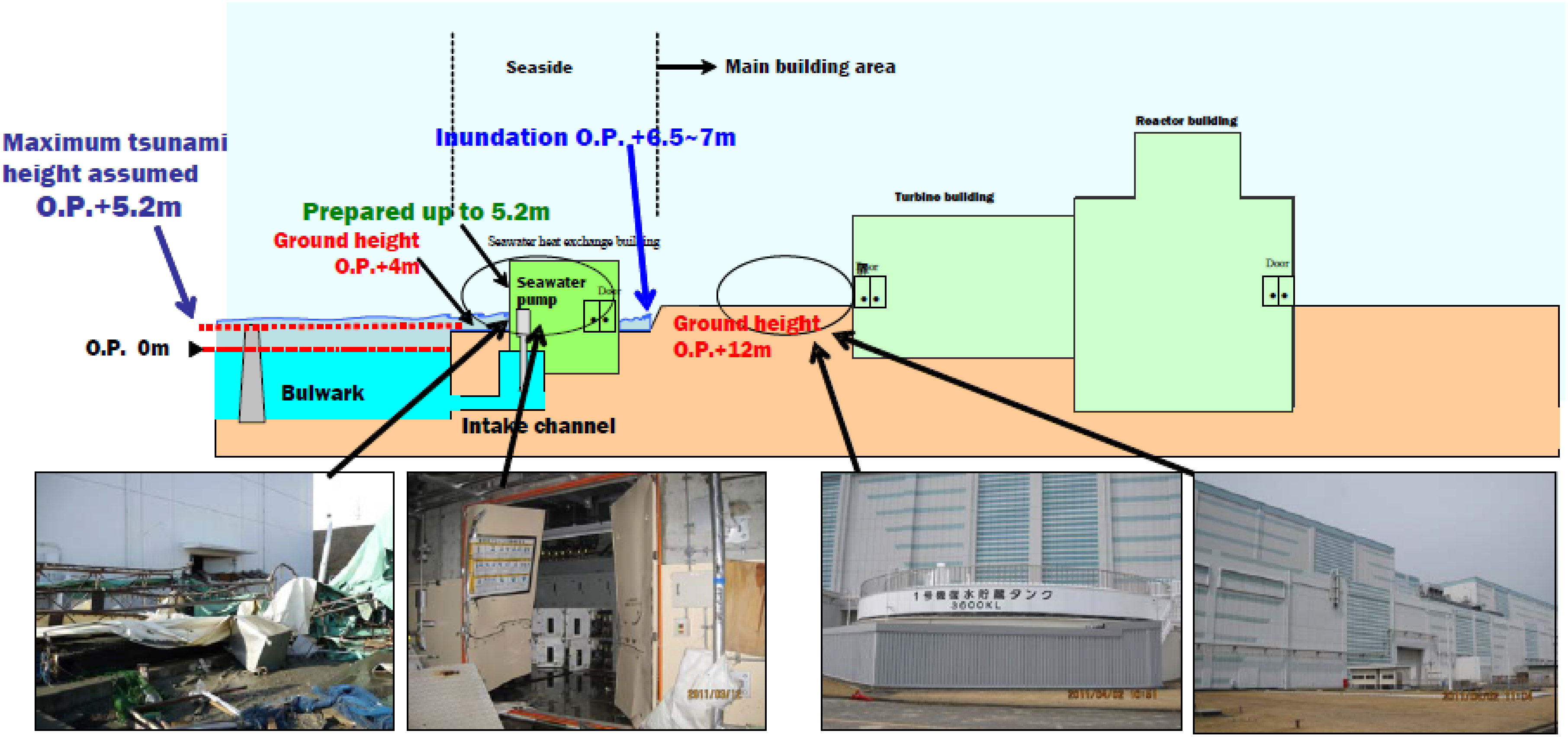
O.P. = Onahama Port Construction Reference Plane
T.P. = Tokyo bay standard sea level
O.P. is 0.727 meters below T.P.

As a result, the tsunami damage at Dai-ni was limited compared to Dai-ichi. The ground heights are either 4m or 12m above sea level. The reactor & turbine buildings were at 12m.

Maximum tsunami height (estimation)
= + 5.2m

Actual inundation height
= + 7m
(14m only at south side of unit 1)

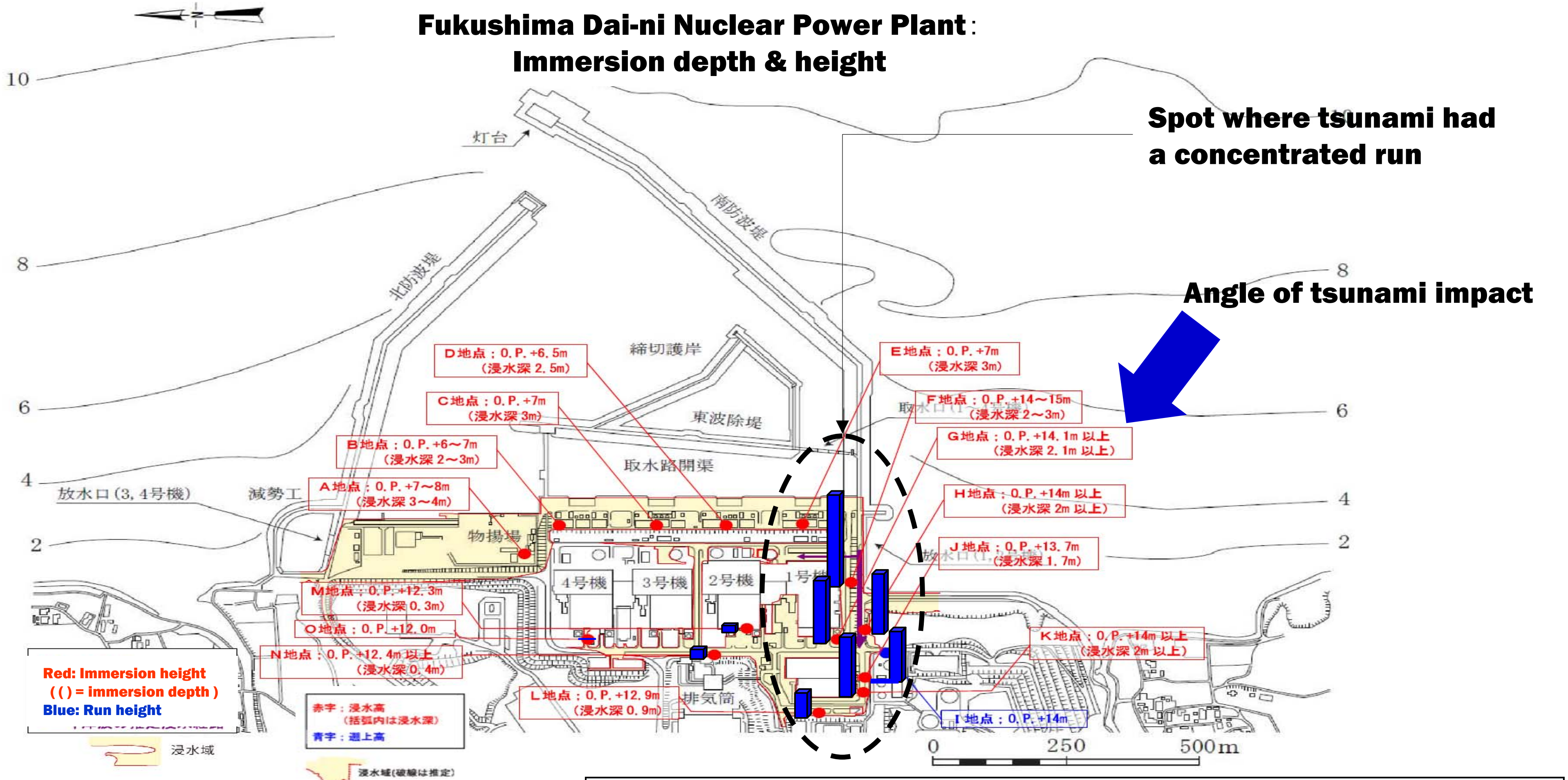
< Ground height and tsunami image at Fukushima Dai-ni Units 1-4 >



- On the sea side, 4m above sea level, debris is scattered as in Dai-ichi, and it is extremely difficult to transport vehicles, personnel, or supplies.
- At 12m above sea level, breakage of buildings, facilities, or scattering of debris can barely be seen.

The immersion height was 7m overall, though it was 14m in the south side of Unit 1, where a concentrated run occurred. Less immersion around the nuclear reactor buildings compared to Dai-ichi.

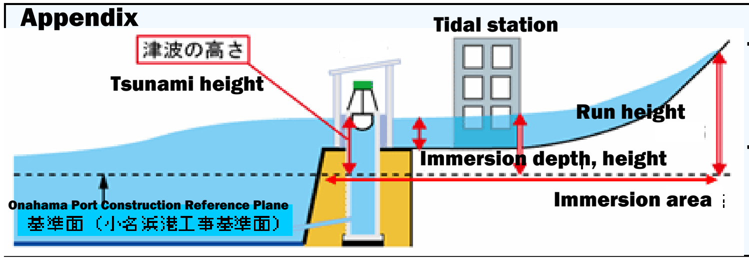
Fukushima Dai-ni Nuclear Power Plant: Immersion depth & height



Spot where tsunami had a concentrated run

Angle of tsunami impact

Appendix

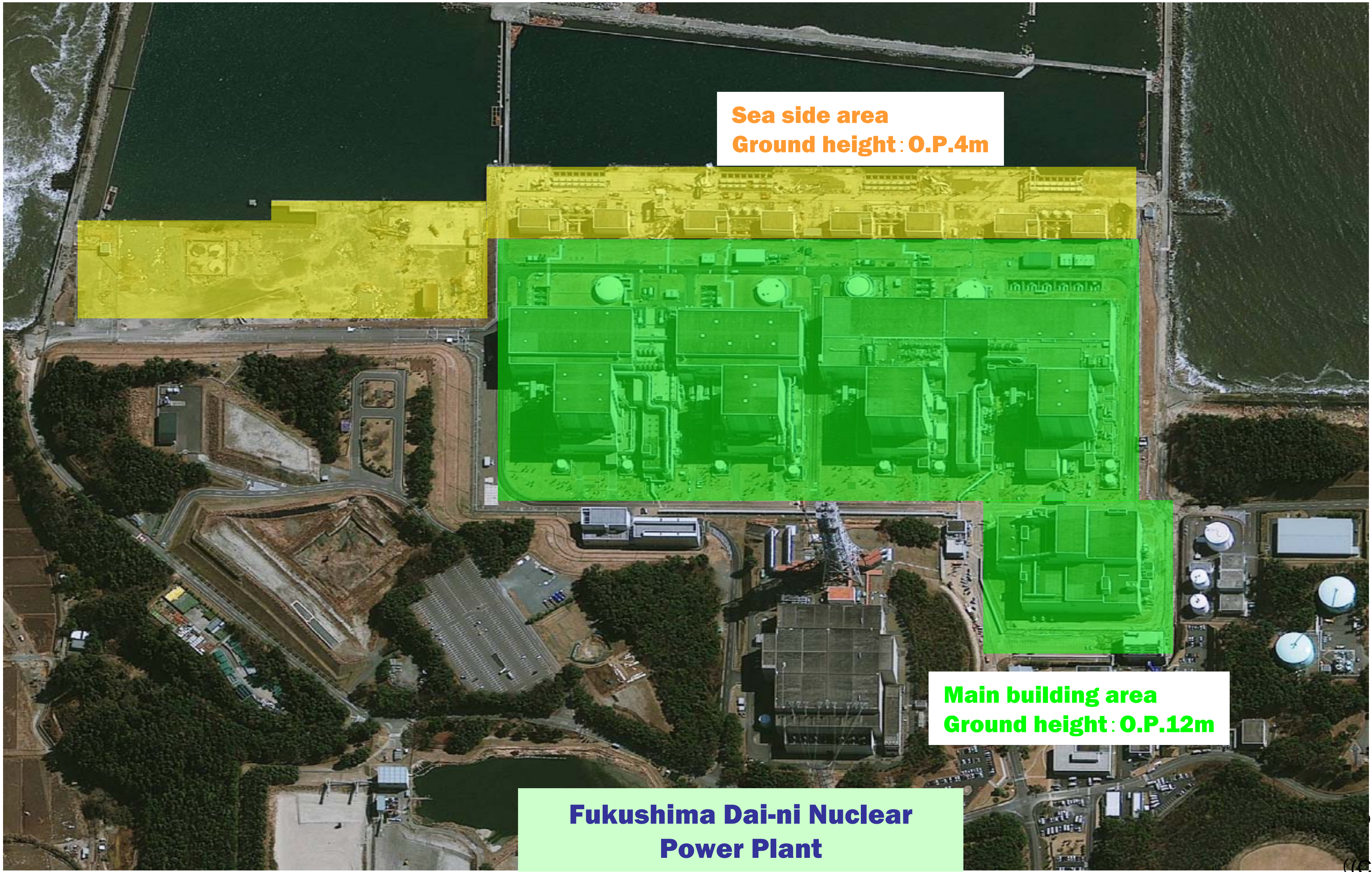


- Immersion height: Height from the <u>O.P. reference plane</u>, at which traces of discoloration or driftage are left in buildings or facilities.
- Immersion depth: Height from the <u>ground level</u>, at which traces of discoloration or driftage are left in buildings or facilities.

Aerial shot of Fukushima Dai-ni before the tsunami: All 4 nuclear reactors were in operation.

(C) GeoEye

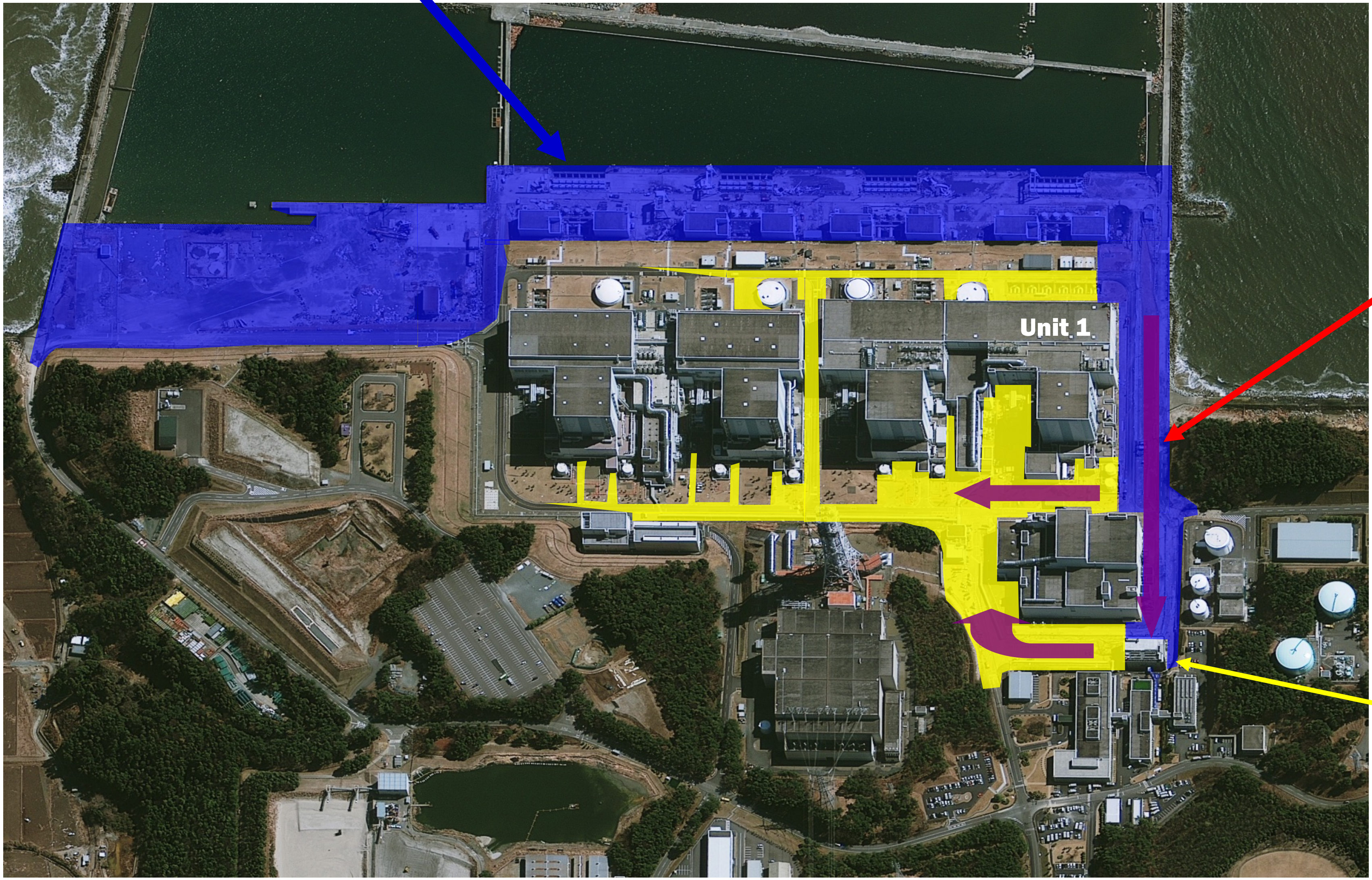
Ground height: – The 4 reactors of Dai-ni were at 12m above sea level. The sea side where the seawater cooling systems are located is at 4m (above sea level). The immersion height was 7m (above sea level).



(C) GeoEye

As the grounds of the reactors are higher than tsunami, direct submersion is limited. However, by the concentrated run of tsunami along the south road of Unit 1, the surrounding area of the nuclear reactors was immersed.

Immersion by tsunami on the seaside is limited

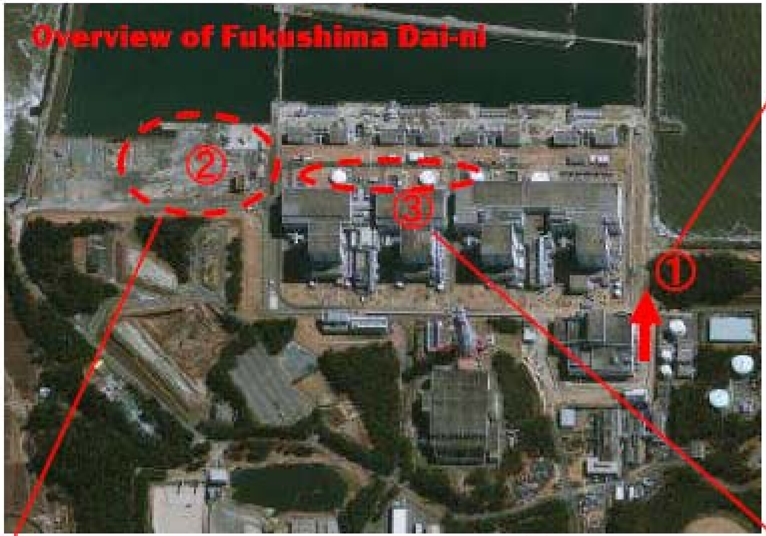


Concentrated run

Seismic Isolation Tower

(C) GeoEye

Damage of tsunami: It is concentrated at the south side of unit 1, along with the concentrated run, and the sea side where the ground level was low.



Overview of Fukushima Dai-ni

① **Climb of tsunami** (south road of Unit 1)

Tsunami, that directly hit Unit 1's south road, ran up to a maximum height of 14m. The water flowed around to the back of the nuclear reactor.

② **Damage at ground height 4m** (Wharf at north of unit 4)

At the sea side, where the grounds were at 4m, heavy damage was caused by the tsunami, and debris is scattered everywhere

③ **No damage at Unit 3 and 4 turbine building**

As the reactor & turbine buildings were at 12m, they were not damaged very much by the 7m tsunami.

Damage of tsunami (continued): Tsunami ran up along the south road and flooded into Unit 1 from the intake duct of its annex building.

① Outside of Unit 1's emergency bellows room

Immersed from the intake louver of the reactor annex building.

② Inside of emergency bellows room

③ Emergency DG control room (System A)

Though immersed, there was no scatter of fixtures and facilities with no numerous debris as was in Dai-ichi.

Fukushima Dai-ichi Power Plant:

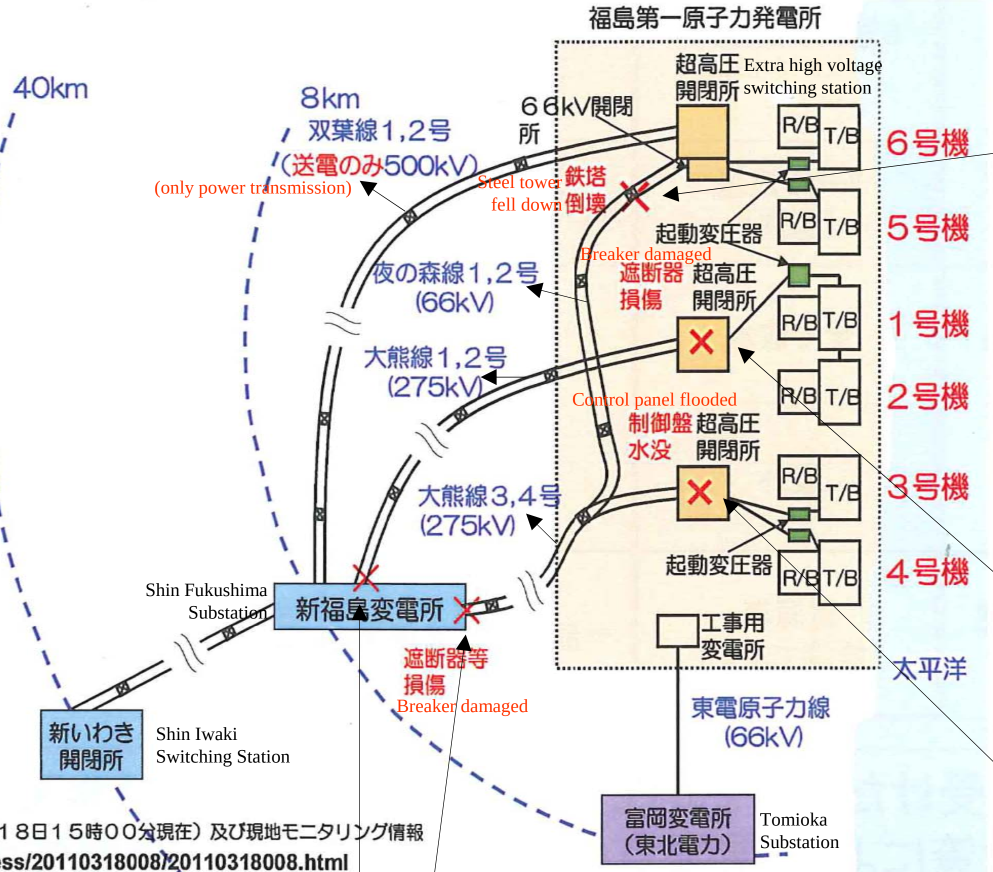
Chronologies and Issues

By the earthquake all external power was lost at Fukushima Dai-ichi. Switching stations and steal towers in the plant, as well as the substations outside were damaged. Furthermore, several power boards were flooded by Tsunami, making the situation worse.

起動変圧器の例

鉄塔の例

開閉所の例



出典：

地震被害情報（第30報）（3月18日15時00分現在）及び現地モニタリング情報

http://www.meti.go.jp/press/20110318008/20110318008.html

東北地方太平洋沖地震に対する原子力発電所の状況について（H23.3.22東京電力　柏崎刈羽原子力発電所）

http://www.tepco.co.jp/nu/kk-np/tiiki/pdf/230325.pdf

Receiving facilities on site (Units 5, 6)
=> Stopped due to earthquake

- Transmission steel tower connected to switching station to activate units 5 and 6 (steel tower no.27): Fallen down by earthquake and unable to receive electricity.

Receiving facilities on site (Units 1-4)
=> Stopped due to earthquake and tsunami

- Extra voltage switching station for Unit 1 and 2: Its breakers were damaged by seismic motion, and disabled to receive electricity.
- Extra voltage switching station for Unit 3 and 4: Control panels were submerged by Tsunami, and disabled to receive electricity.

Transmission from Shin Fukushima substation
=> Stopped due to earthquake

- Facilities such as breakers were damaged by strong seismic motion.
- Stopped transmission lines: 4 lines of 2 systems (275kV) to units 1~4, and 2 lines of 1 system (66kV) to units 5 and 6.

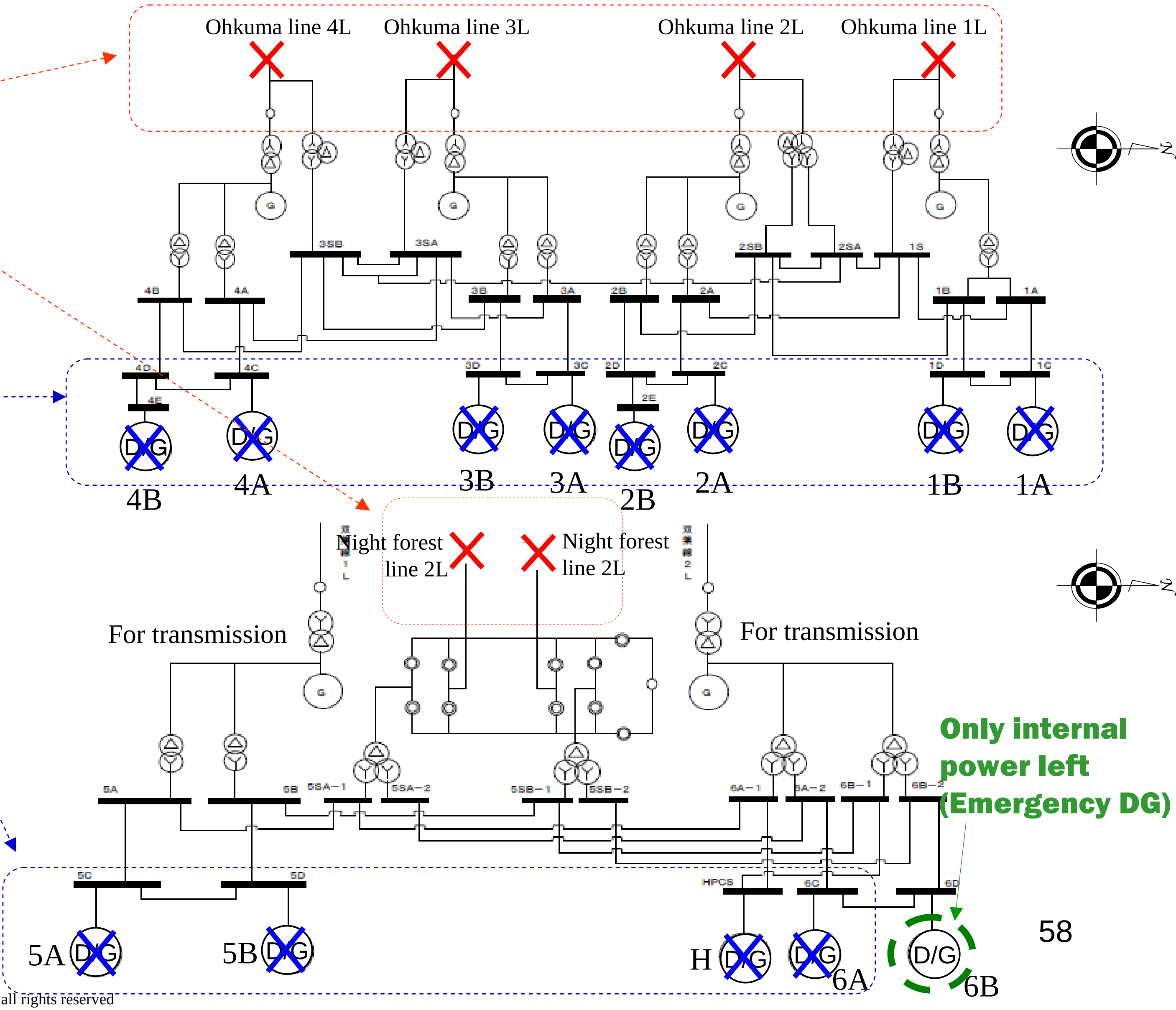
Loss of external/internal power after tsunami: Along with loss of all external power, all internal power sources (emergency DG*) were lost due to submergence except for the one at Unit 6. (*: diesel generator)

External power stopped

- Stopped due to earthquake and subsequent damage (by soil avalanche)

Internal power lost

- After the earthquake, emergency DG supplied power, but lost due to tsunami.
- Only DG (6B) was active.



Only internal power left (Emergency DG)

✗ : Stopped due to earthquake

✗ : Stopped due to tsunami

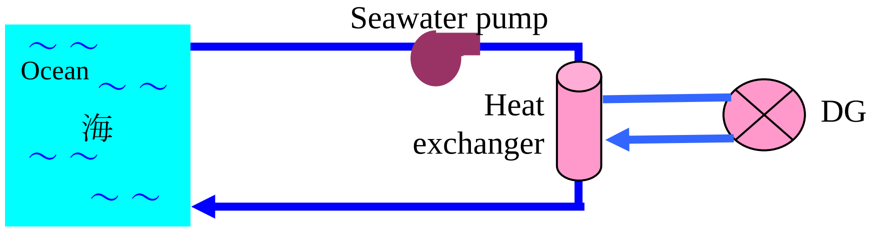
◌ : Active after tsunami

Emergency DG: All 13 units were lost by Tsunami, except for one air cooling DG. The seawater cooling DG were very vulnerable, especially its cooling devices, as located on the seaside and flooded more.

Fukushima Dai-ichi： **DG Systems**

Sea water cooling emergency DG (10 units)

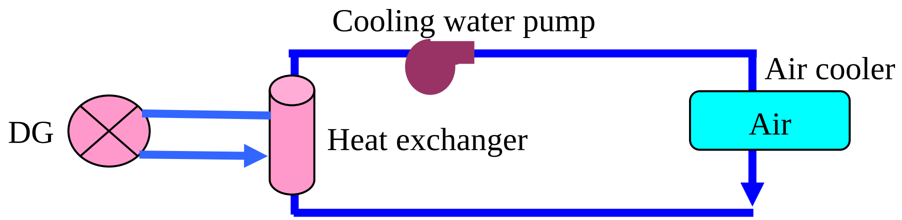
Unit 1A/B, Unit 2A, Unit 3 A/B, Unit 4A, Unit 5A/B, Unit 6A/H



All functions lost after tsunami

Air cooling DG (3 units)

Unit 2B, Unit 4B, Unit 6B



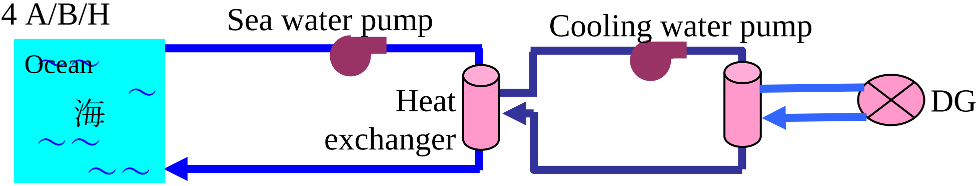
Only Unit 6B retained power

If the cooling system for DG is lost, the entire DG system would be lost even though DG itself is active.

Fukushima Dai-ni

Sea water cooling DG (12 units)

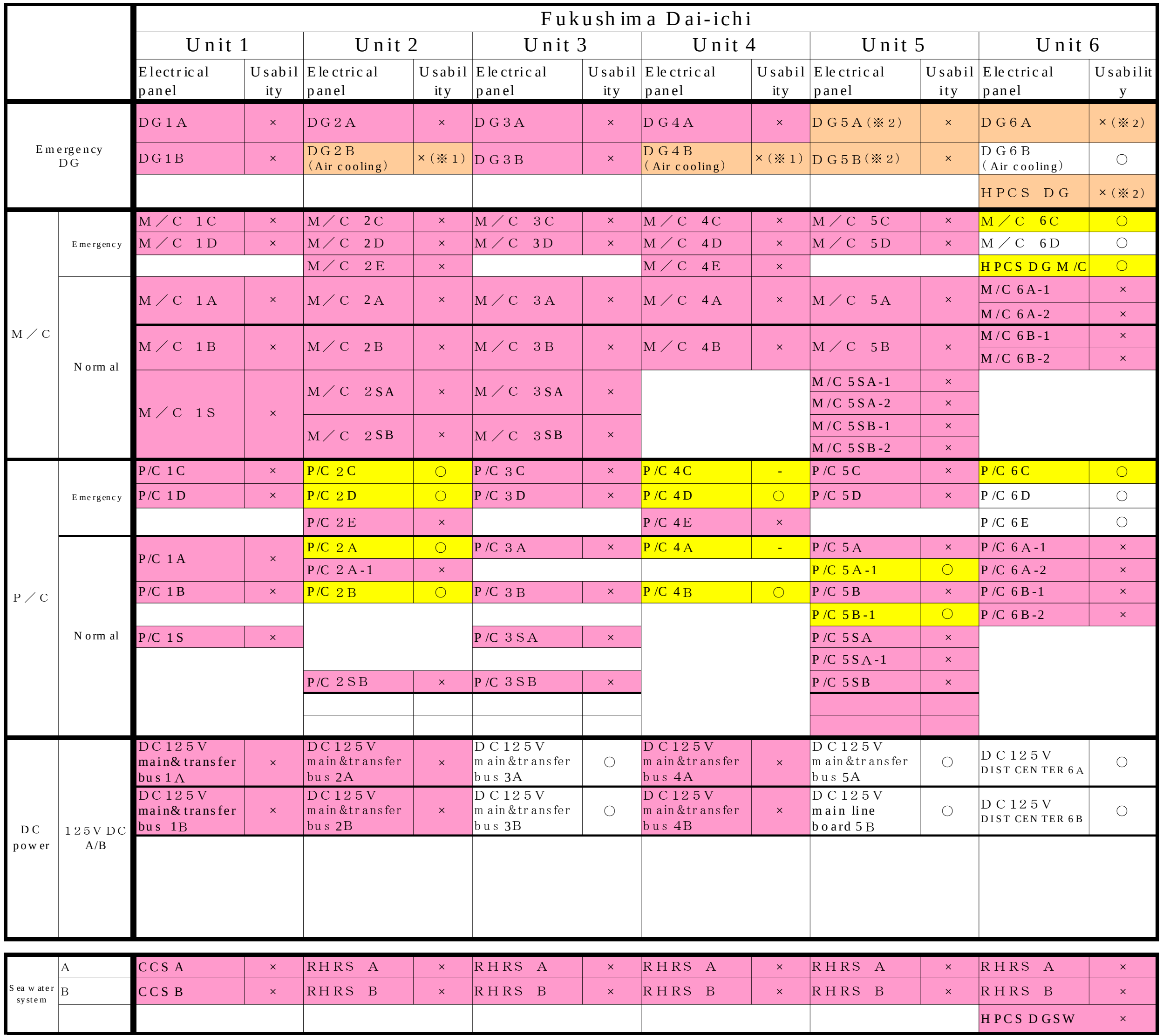
Units 1~4 A/B/H



3 units of Unit 3B/H, Unit 4H retained power.

Loss of power other than external power source: At Units 1-4 where the explosion happened, the emergency DG, M/C electrical boards, and seawater cooling systems were all lost. Only P/C boards in units 2&4, and DC power in unit 3 survived.

Loss of major power supply systems after tsunami



		Fukushima Dai-ichi											
		Unit 1		Unit 2		Unit 3		Unit 4		Unit 5		Unit 6	
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG1A	×	DG2A	×	DG3A	×	DG4A	×	DG5A (※2)	×	DG6A	×(※2)
		DG1B	×	DG2B (Air cooling)	×(※1)	DG3B	×	DG4B (Air cooling)	×(※1)	DG5B (※2)	×	DG6B (Air cooling)	○
												HPCS DG	×(※2)
M/C	Emergency	M/C 1C	×	M/C 2C	×	M/C 3C	×	M/C 4C	×	M/C 5C	×	M/C 6C	○
		M/C 1D	×	M/C 2D	×	M/C 3D	×	M/C 4D	×	M/C 5D	×	M/C 6D	○
				M/C 2E	×			M/C 4E	×			HPCS DG M/C	○
	Normal	M/C 1A	×	M/C 2A	×	M/C 3A	×	M/C 4A	×	M/C 5A	×	M/C 6A-1	×
												M/C 6A-2	×
		M/C 1B	×	M/C 2B	×	M/C 3B	×	M/C 4B	×	M/C 5B	×	M/C 6B-1	×
												M/C 6B-2	×
		M/C 1S	×	M/C 2SA	×	M/C 3SA	×			M/C 5SA-1	×		
										M/C 5SA-2	×		
				M/C 2SB	×	M/C 3SB	×			M/C 5SB-1	×		
										M/C 5SB-2	×		
P/C	Emergency	P/C 1C	×	P/C 2C	○	P/C 3C	×	P/C 4C	-	P/C 5C	×	P/C 6C	○
		P/C 1D	×	P/C 2D	○	P/C 3D	×	P/C 4D	○	P/C 5D	×	P/C 6D	○
				P/C 2E	×			P/C 4E	×			P/C 6E	○
	Normal	P/C 1A	×	P/C 2A	○	P/C 3A	×	P/C 4A	-	P/C 5A	×	P/C 6A-1	×
				P/C 2A-1	×					P/C 5A-1	○	P/C 6A-2	×
		P/C 1B	×	P/C 2B	○	P/C 3B	×	P/C 4B	○	P/C 5B	×	P/C 6B-1	×
										P/C 5B-1	○	P/C 6B-2	×
		P/C 1S	×			P/C 3SA	×			P/C 5SA	×		
										P/C 5SA-1	×		
				P/C 2SB	×	P/C 3SB	×			P/C 5SB	×		
DC power	125V DC A/B	DC125V main&transfer bus 1A	×	DC125V main&transfer bus 2A	×	DC125V main&transfer bus 3A	○	DC125V main&transfer bus 4A	×	DC125V main&transfer bus 5A	○	DC125V DIST CENTER 6A	○
		DC125V main&transfer bus 1B	×	DC125V main&transfer bus 2B	×	DC125V main&transfer bus 3B	○	DC125V main&transfer bus 4B	×	DC125V main line board 5B	○	DC125V DIST CENTER 6B	○
Seawater system	A	CCS A	×	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×
	B	CCS B	×	RHRS B	×	RHRS B	×	RHRS B	×	RHRS B	×	RHRS B	×
												HPCS DGSW	×

🟪 : Lost functions

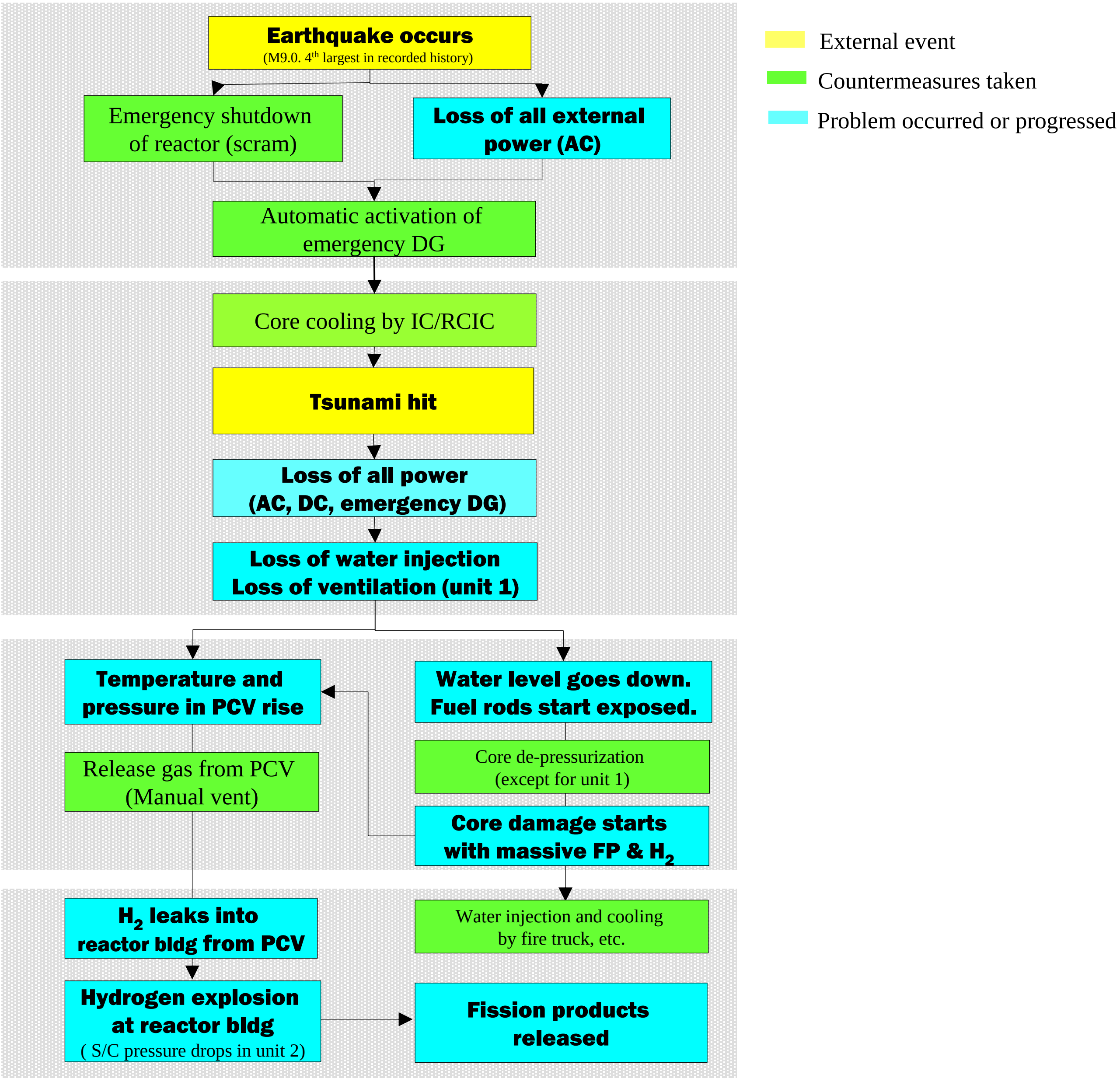
🟨 : Unable to activate due to electrical board and/or cooling system were lost

🟧 : Incoming power was inaccessible due to the loss of electrical supply source

- As to emergency DG, only one at unit 6 survived, and the rest were lost.
- As to metal-clad switching gear (M/C), all M/C were lost except for the one system at unit6.
- As to power center (P/C), all were lost in units 1 ~ 5.
- As to direct current (DC) batteries, all were lost by flooding at units 1, 2, and 4, making functions of central control room and high pressure cooling lost as well.
- As to the seawater cooling systems, all were lost by tsunami.

The accidents in Units 1-3 had progressed in the following manner by the loss of power supply and seawater cooling functions.

Event Progression (Conceptual)



Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by IC/RCIC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection
Loss of ventilation (unit 1)

Temperature and pressure in PCV rise

Release gas from PCV (Manual vent)

H_2 leaks into reactor bldg from PCV

Hydrogen explosion at reactor bldg
(S/C pressure drops in unit 2)

Water level goes down. Fuel rods start exposed.

Core de-pressurization
(except for unit 1)

Core damage starts with massive FP & H_2

Water injection and cooling by fire truck, etc.

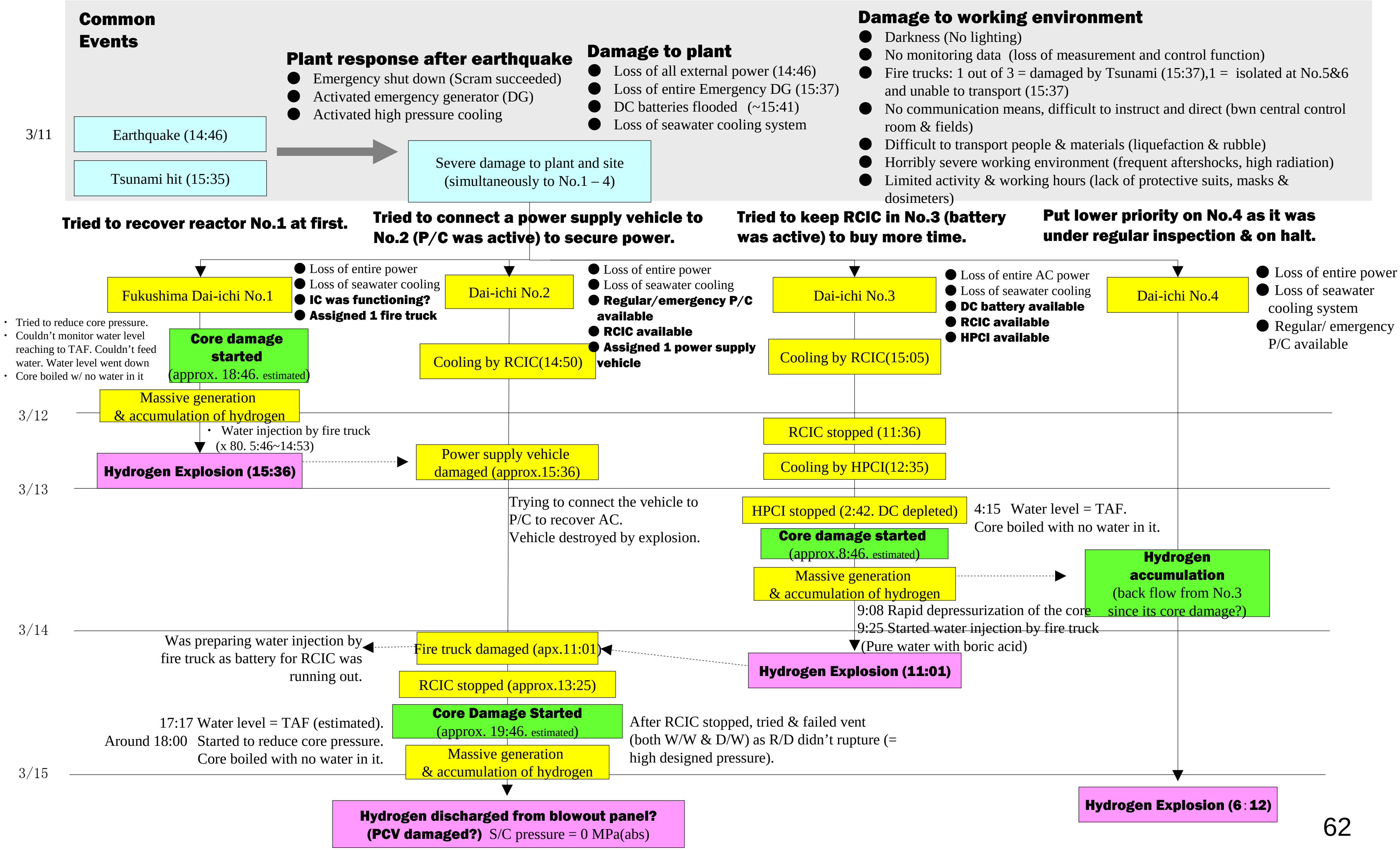
Fission products released

🟨 External event

🟩 Countermeasures taken

🟦 Problem occurred or progressed

Event developments at each plant from earthquake to the explosion are the following.



Common Events

3/11

Earthquake (14:46)

Tsunami hit (15:35)

Severe damage to plant and site (simultaneously to No.1 – 4)

Plant response after earthquake

- ● Emergency shut down (Scram succeeded)
- ● Activated emergency generator (DG)
- ● Activated high pressure cooling

Damage to plant

- ● Loss of all external power (14:46)
- ● Loss of entire Emergency DG (15:37)
- ● DC batteries flooded (~15:41)
- ● Loss of seawater cooling system

Damage to working environment

- ● Darkness (No lighting)
- ● No monitoring data (loss of measurement and control function)
- ● Fire trucks: 1 out of 3 = damaged by Tsunami (15:37),1 = isolated at No.5&6 and unable to transport (15:37)
- ● No communication means, difficult to instruct and direct (bwn central control room & fields)
- ● Difficult to transport people & materials (liquefaction & rubble)
- ● Horribly severe working environment (frequent aftershocks, high radiation)
- ● Limited activity & working hours (lack of protective suits, masks & dosimeters)

Tried to recover reactor No.1 at first.

Fukushima Dai-ichi No.1

- ● Loss of entire power
- ● Loss of seawater cooling
- ● **IC was functioning?**
- ● **Assigned 1 fire truck**

- Tried to reduce core pressure.
- Couldn't monitor water level reaching to TAF. Couldn't feed water. Water level went down
- Core boiled w/ no water in it

Core damage started (approx. 18:46. estimated)

Massive generation & accumulation of hydrogen

3/12

- Water injection by fire truck (x 80. 5:46~14:53)

Hydrogen Explosion (15:36)

3/13

Tried to connect a power supply vehicle to No.2 (P/C was active) to secure power.

Dai-ichi No.2

- ● Loss of entire power
- ● Loss of seawater cooling
- ● **Regular/emergency P/C available**
- ● **RCIC available**
- ● **Assigned 1 power supply vehicle**

Cooling by RCIC(14:50)

Power supply vehicle damaged (approx.15:36)

Trying to connect the vehicle to P/C to recover AC.
Vehicle destroyed by explosion.

3/14

Was preparing water injection by fire truck as battery for RCIC was running out.

Fire truck damaged (apx.11:01)

RCIC stopped (approx.13:25)

Core Damage Started (approx. 19:46. estimated)

17:17 Water level = TAF (estimated).
Around 18:00 Started to reduce core pressure.
Core boiled with no water in it.

After RCIC stopped, tried & failed vent (both W/W & D/W) as R/D didn't rupture (= high designed pressure).

Massive generation & accumulation of hydrogen

3/15

Hydrogen discharged from blowout panel? (PCV damaged?) S/C pressure = 0 MPa(abs)

Tried to keep RCIC in No.3 (battery was active) to buy more time.

Dai-ichi No.3

- ● Loss of entire AC power
- ● Loss of seawater cooling
- ● **DC battery available**
- ● **RCIC available**
- ● **HPCI available**

Cooling by RCIC(15:05)

RCIC stopped (11:36)

Cooling by HPCI(12:35)

HPCI stopped (2:42. DC depleted)

4:15 Water level = TAF.
Core boiled with no water in it.

Core damage started (approx.8:46. estimated)

Massive generation & accumulation of hydrogen

9:08 Rapid depressurization of the core
9:25 Started water injection by fire truck (Pure water with boric acid)

Hydrogen Explosion (11:01)

Put lower priority on No.4 as it was under regular inspection & on halt.

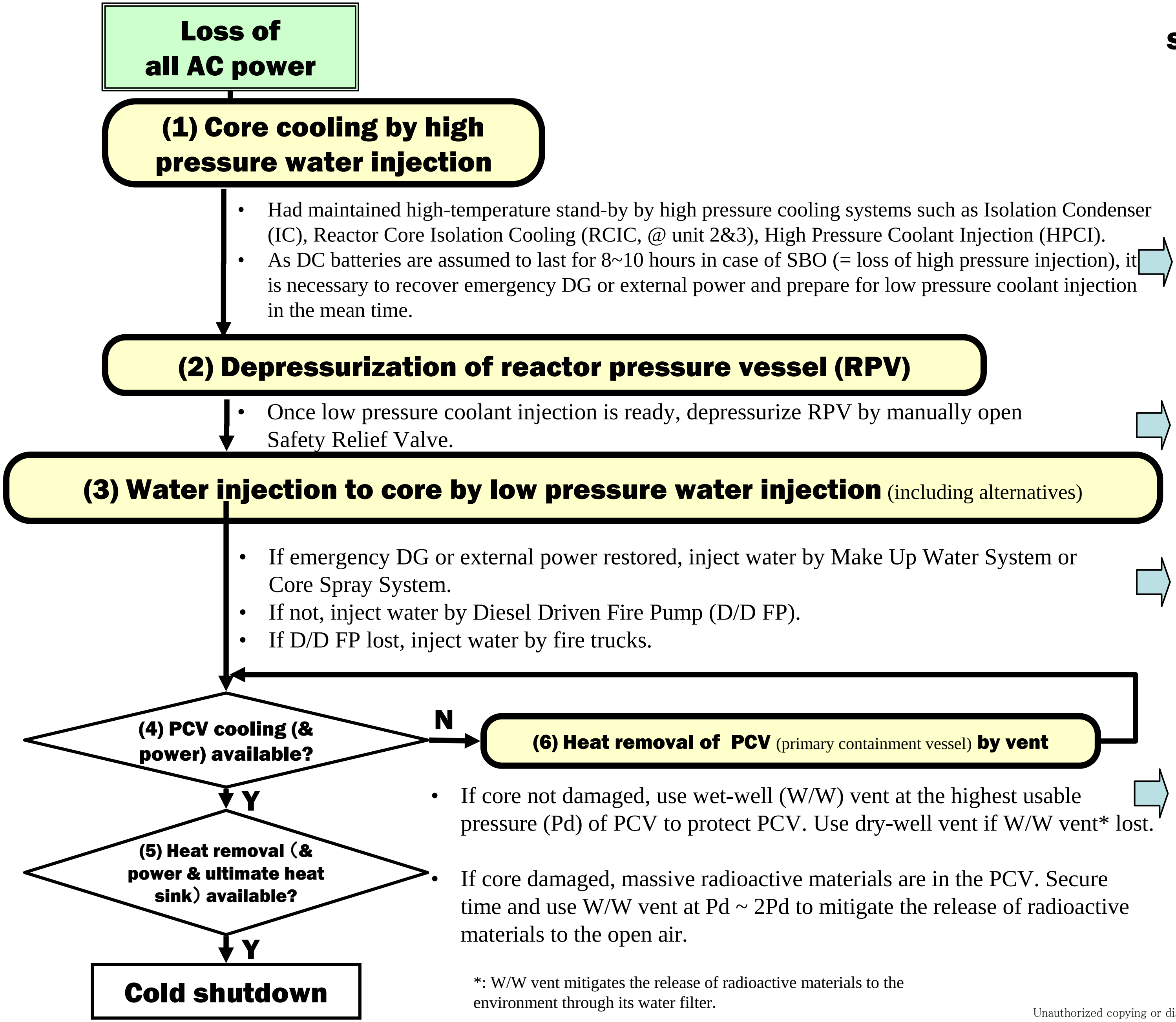
Dai-ichi No.4

- ● Loss of entire power
- ● Loss of seawater cooling system
- ● Regular/ emergency P/C available

Hydrogen accumulation (back flow from No.3 since its core damage?)

Hydrogen Explosion (6:12)

Overview of standard operating procedure in case of Station Black Out (SBO)



Loss of all AC power

(1) Core cooling by high pressure water injection

- Had maintained high-temperature stand-by by high pressure cooling systems such as Isolation Condenser (IC), Reactor Core Isolation Cooling (RCIC, @ unit 2&3), High Pressure Coolant Injection (HPCI).
- As DC batteries are assumed to last for 8~10 hours in case of SBO (= loss of high pressure injection), it is necessary to recover emergency DG or external power and prepare for low pressure coolant injection in the mean time.

(2) Depressurization of reactor pressure vessel (RPV)

- Once low pressure coolant injection is ready, depressurize RPV by manually open Safety Relief Valve.

(3) Water injection to core by low pressure water injection (including alternatives)

- If emergency DG or external power restored, inject water by Make Up Water System or Core Spray System.
- If not, inject water by Diesel Driven Fire Pump (D/D FP).
- If D/D FP lost, inject water by fire trucks.

(4) PCV cooling (& power) available?

(6) Heat removal of PCV (primary containment vessel) **by vent**

- If core not damaged, use wet-well (W/W) vent at the highest usable pressure (Pd) of PCV to protect PCV. Use dry-well vent if W/W vent* lost.
- If core damaged, massive radioactive materials are in the PCV. Secure time and use W/W vent at Pd ~ 2Pd to mitigate the release of radioactive materials to the open air.

(5) Heat removal（& power & ultimate heat sink）available?

Cold shutdown

*: W/W vent mitigates the release of radioactive materials to the environment through its water filter.

Status of safety measures at this time

Fukushima Dai-ichi			Dai-ni
Unit 1	Unit 2	Unit 3	Units 1-4
×	○	○	○
×	△ (Delayed)	△ (Delayed)	○
△ (Delayed or lack of water)			○
△ (Vent delayed)	×	△ (Difficult to keep vent valves open)	○ (PCV cooling available)

○ : Succeeded
△ : Conducted but troubled
× : Failed

Power, coolant, & ventilation functions were all lost due to Tsunami, not earthquake. - Water injected in 15 hrs after the earthquake, ventilation in 24 hrs.

Events

Emergency shutdown of the reactor

3/11 14:46

Earthquake occurred (level 6+)
(M9.0. 4th in recorded history)

- **14:46 Automatic shutdown of the reactor** => 14:52 IC activated automatically & opened/ closed manually.
- **Loss of all external power** => 14:47 Emergency DG activated.

15:35

Tsunami hit
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

Loss of all power & important functions

Simultaneous loss of all power, cooling, & pressure-control functions + darkness & terrible work environment.

- Emergency DG & power panels flooded => **all AC power lost** => Unable to use electrical equipments.
- Battery room submerged => **DC power lost** => Electrical boards, measuring & control facilities lost => **Cooling function lost** (IC, HPCI), **Pressure control function lost** (open SRV remotely etc.)
- Seawater pump lost => **Function for cold-shutdown lost** (ultimate heat sink lost)

Right after tsunami: Isolation Condenser lost
=> Core water level started to drop.

Secure emergency power.

Prepare for coolant injection.

Prepare for ventilation

17:12 Plant manager ordered to consider water injection by fire pump system & fire truck

18:46 Core damage started (estimated)

21:19 Core water level became readable (TAF + 200mm*0)
23:00 Rise in radiation level in turbine bldg confirmed.
Around then, 1st power supply vehicle arrived.

3/12
00:06 Plant manager ordered to prepare vent.
(as Dry-well of PCV pressure possibly over 600k Pa)
01:30 Requested to execute vent & approved by the country.

02:30 Confirmed 'RPV pressure is low & PCV pressure is high'*1.
05:46 Started to inject fresh water by fire trucks.
07:20 RPV damaged. (simulation)

Tried water injection.

Tried ventilation.

Hydrogen built up.

09:04 Workers departed for site for ventilation.
10:17 Started PCV vent.
14:30 PCV vent succeeded (D/W pressure decreased)

14:53 Completed freshwater injection (80,000 l in total).
14:54 Plant manager ordered sea water injection.

15:36 **Reactor building exploded (5th floor)**

Hydrogen Explosion & radiation leak

19:04 Started sea water injection.
20:45 Started sea water injection with boric acid.

*0: Instrument for water level may not have been reliable.

*1: Estimated that the core temperature rose due to core damage, and hydrogen leaked from SRV flange gasket etc.

Implications

All external AC power was lost due to the earthquake.
- The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.

All of AC/DC power was lost due to huge submersion and destruction by Tsunami
- Tsunami submerged and destroyed buildings, tanks, seaside facilities. Debris was strewn all over the inside of buildings and roads, and obstructed recovery work, transportation of staff &supplies (=> work environment degraded).
- Power boards were submerged by Tsunami. Major command functions (lights, measurement, communications) were all lost (=> Core water level, pressure, & temperature could not be measured).
- Emergency DG*2 & electrical panels flooded by tsunami. All AC power lost. (=> could not use electricity)
- Seawater pumps on the seaside were flooded and disabled by Tsunami. Along with all AC power outage, residual heat removal system (water pump, pump cooling device) was lost (=> could not cool the core)

(*2: In Units 5 & 6 (ground height = 13m), 1 emergency DG survived and cold-shutdown achieved. However, units 1-4 (ground height = 10m) lost all of their emergency DG.

With all AC/DC power lost, all functions of core cooling & ventilation were lost.
- Water injection systems to the core & spent fuel pool were lost (=> could not cool the core)
- The electromagnetic / motor-driven valve for AO valve did not function properly. (=> could not control the pressure & heat of RPV & PCV)

Manual for disaster management did not predict simultaneous loss of functions.
- Manual (AM) had assumed SBO (loss of all AC power), but not the simultaneous loss of all AC/DC power & cooling functions.
- Countermeasure, preparation, and training for the simultaneous loss of power, cooling,& vent function were insufficient
- Equipments on site, and dosimeters, masks, & protective gear were lacked.

Combined all of the above together at one time, they could not monitor the plant & recovery actions were delayed even after the core damage started.
- Could not monitor the core water level. (data was read in 6.5 hours after earthquake).
- Delay in securing alternative power (in 8 hours after earthquake).
- Delay in water injection to the core (same, 15 hours later).
- Delay in vent operation to release heat/pressure from highly pressurized PCV (same, 24 hours later).
- Lack of monitoring hydrogen buildup in the building, and countermeasure action (led to explosion).

As a result, the hydrogen accumulated in 5th floor of reactor building & exploded.
- Cladding tube of fuel rods (zirconium) reacted with water & massive hydrogen was generated.
- PCV de-pressurization & cooling delayed. The hydrogen leaked from PCV into the reactor building.
- During recovery work, being unable to detect hydrogen nor comprehend the situation, large quantities of hydrogen accumulated on the 5th floor and exploded.

Chronology of Unit 2

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)** (M9.0. 4th in recorded history)

- ● **14:47 Automatic shutdown of the reactor**.
- ● **Loss of all external power** => Emergency DG automatically activated.

14:50 RCIC activated manually => 14:52 Stopped automatically (high water level = L-8).

- ● 15:01 Sub-criticality of the core confirmed

Loss of all power & seawater cooling functions

15:35 **Tsunami hit** (Tsunami-M9.1. 4th in recorded history) (Immersion height: 11.5~ 15.5m)

15:39 RCIC activated manually.

- ● **15:41 All AC power lost (emergency DG & electrical panel immersed) => Extreme work environment, darkness.** Battery room submerged & **All DC power lost** (some P/C not submerged). => RCIC continued. **Seawater systems submerged & ultimate heat sink lost.** => Function for cold shutdown lost.

17:12 Plant manager ordered to consider water injection by fire truck.

22:00 Core water level became readable (TAF +3400mm)

Secure high pressure cooling.

3/12 2:55 Confirmed RCIC was in operation.
(As RCIC confirmed as working, prioritized ventilation of Unit 1 at first.)

17:30 Plant manager ordered to prepare for PCV vent.

Prepare for low pressure coolant injection.

Prepare for ventilation

3/13 11:00 S/C vent valve (large) opened &vent-line structured.
(As D/W pressure was low, rupture disk did not rupture & ventilation failed).

3/14 11:01 Unit 3 exploded & excitation circuit for electro-magnetic valve damaged. S/C vent valve (large) closed and unable to open again. Also, explosion destroyed the fire truck and makeshift hoses & water injection lines were unusable.

13:25 Reduction trend of reactor's water level confirmed. => Judged as RCIC not working.

17:17 Reactor's water level reached at TAF.

17:17~ Core damage started (estimated)

Core de-pressurized.

LP coolant injection.

Tried & failed ventilation.

Core damage & hydrogen built up.

18:00 Started core de-pressurization (core pressure = 5.4MPa => 19:03 0.63MPa)

18:22 Water level reached at TAF -3700mm. Judged as core was exposed. => Reported to METI.

19:54 Started sea water injection to the core with fire pump system & fire trucks.

21:00 S/C vent valve (small) slightly opened & reconstruction of vent line completed.

22:50 While D/W pressure exceeds maximum usage pressure 427kPa (& kept rising), S/C pressure stayed at 300~400 kPa gage, and both pressures (DW & S/C) did not converge.

23:35 As rupture disk of S/C did not rupture (insufficient pressure), they decided to vent via D/W by opening small valve.

3/15 0:02 Opened D/W vent valve (small) & vent line structured. (but, the valve closed again a few minutes later). (D/W pressure did not drop below 750kPa (abs) & stayed at high level.)

6:00~6:10 **S/C pressure indicated at 0kPa(abs)**

PCV damaged. Radiation leak.

Implications

- ● **All external power was lost due to earthquake**
  - The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.
- ● **All power (DC/AC) was lost due to large scale submersion and destruction caused by tsunami**
  - Could not share the power with other plants due to Tsunami. As debris was strewn all over buildings and road, could not access to the active electrical panel (P/C). This delayed restoration of power.
- ● **'Core cooling' & 'vent' functions were lost due to loss of all power.**
  - Although they had once connected the fire truck to active P/C in order to inject water by CRD & SLC, which were not submerged, the explosion at Unit 1 destroyed the power supply vehicle and cables which became unusable.
  - While RCIC working, they were setting up seawater injection lines with fire truck in case for run-out of RCIC. However, the explosion at Unit 3 destroyed the fire trucks and water injection hoses which became unusable. After that, RCIC stopped & water level started to drop.
  - Reconstruction of seawater injection line was delayed due to frequent aftershocks, and was only completed 3 hrs after RCIC stopped. Furthermore, as fuel for fire trucks ran out, water injection started only 6 hours later & the core was depressurized for about 1 hour.
  - As air compressor not available, they used car batteries to open Safety Relief Valve from the central control room. It took close to 2 hours due to insufficient voltage.
  - While D/W pressure rose, S/C pressure remained at a level insufficient to activate rupture disk. This delayed and obstructed the vent operation either.
- ● **Manual for disaster management did not predict simultaneous loss of functions.**
  - Manual (AM) had assumed SBO (loss of all AC power), but not the simultaneous loss of all AC/DC power & cooling functions.
  - Countermeasure, preparation, and training for the simultaneous loss of power, cooling,& vent function were insufficient
  - Equipments on site, and dosimeters, masks, & protective gear were lacked.
- ● **Combined all of the above together at one time, they could not monitor the plant & recovery actions were delayed even after the core damage started.**
  - Could not monitor the core water level. (data was read in 7 hours after earthquake).
  - Delay & failure of D/W & S/C vent operation (if PCV were damaged.)
  - Lack of monitoring hydrogen buildup in the building, and countermeasure action (if hydrogen explosion occurred).
- ● **As a result, PCV was damaged**
  - Due to high temperatures/ pressure in PCV, the vessel was damaged near S/C (assumed).

Chronology of Unit 3

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)**
(M9.0. 4th in recorded history)

- **14:47 Automatic shutdown of the reactor**. => 15:05 RCIC activated manually => 15:25 RCIC tripped (high water level).
- **Loss of all external power** => 14:48 Emergency DG automatically activated.

15:35 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

Loss of all power & seawater cooling functions

Loss of all AC power + darkness & terrible work environment.

- Emergency DG & power panels flooded => **15:38 all AC power lost** => Unable to use electrical equipments.
- Seawater pump destroyed => **Function for cold-shutdown lost. (ultimate heat sink lost)**
- DC main lines survived. (**Kept supplying DC** power by backup batteries to RCIC, HPCI, measurement instruments).

16:03 Core cooling by RCIC (manually activated)

DC survived then run out.

RCIC/HPCI worked then lost.

Prepare for ventilation

3/12
11:36 RCIC stopped (fire trucks used for Unit 1).
12:35 High pressure water injection (HPCI) automatically activated (water level = low).
17:30 Plant manager ordered to prepare for PCV vent.

3/13
02:42 HPCI stopped (battery depleted).
03:51 Water level indicated as 1600mm below the fuel top (= TAF -1600mm).
04:15 Judged the water level reached at TAF.
05:10 Judged that RCIC failed to inject coolant.
05:15 Plant manager ordered to construct vent line systems.
08:41 Vent line excluding RD had been set up.

08:00 ~ 09:00 Core damage started (estimated)

LP coolant injection.

Conducted PCV ventilation.

Core damage & hydrogen built up.

09:08 Core de-pressurized by SRV (used car batteries of workers).
09:25 Started fresh water injection by fire trucks (with boric acid).
09:36 Confirmed D/W pressure dropped after vent operation.
10:30 Plant manager ordered to prepare sea water injection.
11:17 AO valve of S/C vent closed (pressure of air compressor lowered).
12:20 Fresh water injection completed (since fresh water in fire protection water tank depleted).
12:30 AO valve of S/C vent opened (air compressor changed).
13:12 Started sea water injection by fire trucks (frequent aftershocks delayed its preparation).

3/14
01:10 Seawater injection by fire trucks stopped for replenishing, due to lack of sea water.
03:20 Seawater injection resumed.
05:20 S/C vent AO valve opened. 06:10 Confirmed the AO valve opened.
09:20 Started to supply seawater from the wharf to reverse-valve pit. (retarded by high radiation level & bad transportation)
10:53 7 water supply vehicles (5t) brought in by Self-Defense Force. Placed them to reverse valve pit & re-started fresh water injection.

Implications

- **All external AC power was lost due to the earthquake.**
  - The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.

- **Though All AC power was lost by Tsunami, DC survived.**
  - Tsunami submerged and destroyed buildings, tanks, seaside facilities. Debris was strewn all over the inside of buildings and roads, and obstructed recovery work, transportation of staff &supplies (=> work environment degraded).
  - Emergency DG*2 & electrical panels flooded by tsunami. All AC power lost. (=> could not use electricity)
  - Seawater pumps on the seaside were flooded and disabled by Tsunami. Along with all AC power outage, residual heat removal system (water pump, pump cooling device) was lost (=> could not cool the core)
  - Although the power board in the building was submerged by Tsunami, DC 125V escaped immersion. It powered RCIC, HPCI, lights in the central control room, and measurement instruments of core water level & pressure.
(*2: In Units 5 & 6 (ground height = 13m), 1 emergency DG survived and cold-shutdown achieved. However, units 1-4 (ground height = 10m) lost all of their emergency DG.

- **With all AC power lost & batteries run out, all the core cooling function was lost.**
  - Water injection systems to the core & spent fuel pool were lost (=> could not cool the core)
  - As core pressure rose when RCIC & HPCI stopped, they used Safety Relief Valve to decrease pressure. (Decay heat could not be removed although the water was injected).
  - As HPCI & RCIC stopped with the batteries depleted, core water level was not regained.

- **Manual for disaster management did not predict simultaneous loss of functions.**
  - Manual (AM) had assumed SBO (loss of all AC power), but not the simultaneous loss of all AC/DC power & cooling functions.
  - Countermeasure, preparation, and training for the simultaneous loss of power, cooling,& vent function were insufficient
  - Equipments on site, and dosimeters, masks, & protective gear were lacked.

- **Combined all of the above together at one time, they could not monitor the plant & recovery actions were delayed even after the core damage started.**
  - Delay in recovery actions due to frequent aftershocks.
  - Delay in water injection to the core due to lack of fire trucks.
  - Vent preparation & operation were relatively smooth? (executed in 4 hours since ordered).
  - Lack of monitoring hydrogen buildup in the building, and countermeasure action (led to explosion).

Chronology of Unit 3 (continued)

Events

Hydrogen Explosion & radiation leak

11:01 **Reactor building exploded (4th& 5th floor)**

Fire truck and hoses were destroyed & seawater injection suspended.

16:30 Injection line from the wharf to the core was constructed. Sea water injection resumed.

3/15

07:55 Floating of moisture above the building confirmed.

Implications

● **As a result, the hydrogen accumulated in 5th floor of reactor building & exploded.**

- Cladding tube of fuel rods (zirconium) reacted with water & massive hydrogen was generated.
- PCV de-pressurization & cooling delayed. The hydrogen leaked from PCV into the reactor building.
- During recovery work, being unable to detect hydrogen nor comprehend the situation, large quantities of hydrogen accumulated on the 5th floor and exploded.

Chronology of Unit 4

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)**
(M9.0. 4th in recorded history)

- Under regular inspection from November 30th, 2009, (reactor was on halt). = 1535 rods of spent fuel stored in SFP(97% full).
- **Loss of all external power** => 14:47 Emergency DG automatically activated.
- Water sloshed & spilled over from the pool & water level dropped (approx. 0.5m)

Loss of all power & seawater cooling functions

15:35 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

Loss of all AC power + darkness & terrible work environment.

- Emergency DG & power panels flooded => **all AC power lost** => Unable to use electrical equipments.
- Battery room submerged => **DC power lost** => Electrical board, measurement/ controlling facilities malfunctioned. => **Cooling function lost (RHR).**
- Seawater pump for Fuel Pool Cooling & Filtering (FPC) system damaged. => **Cooling function lost (ultimate heat sink lost)**.

Water level of SFP monitored.

Prepare to maintain water level.

Hydrogen flowed back from Unit 3.

As the pool temperature continued to rise by the decay heat of used fuel, water level in the pool decreased with its water evaporated.

- The water level was estimated to reach to the top of fuel rods around March 20th.
- Since the pool gate was closed before earthquake, the water level was the same as the one at the well side of DS pit. So, it was reasonably expected that the pool gate would open to supply water to SFP from the well side if the water level in SFP continue to drop.

3/14 **04:08 SFP temperature was confirmed as 84 ℃.**
11:01 Unit 3 explosion

Hydrogen Explosion & radiation leak

3/15 06:12 **Huge detonation sound.**
Reactor building severely damaged (4th & 5th floor)

- Pool gate opened due to explosion, and water level recovered up to well level (estimated).

Fire broke out & extinguished.

3/16 09:38 **Fire broke out** from the 3rd floor of the reactor building.
11:00 **Fire extinguished** naturally.
Water level confirmed from helicopter (4-5m above the fuel top)

water injection started.

3/20 08:21 **Started to spray water to the SFP** (continued periodically).

Implications

● **All external power was lost due to earthquake**

- Although one emergency DG started automatically due to the loss of external power, there was no other power source. Drop of water level by sloshing & spillover was predicted.

● **All AC power was lost due to large scale submersion and destruction caused by tsunami.**

- Tsunami submerged and destroyed buildings, tanks, seaside facilities. Debris was strewn all over the inside of buildings and roads, and obstructed recovery work, transportation of staff &supplies (=> work environment degraded).
- Emergency DG & electrical panels flooded by tsunami. All AC power lost. (=> could not use electricity)
- Seawater pumps on the seaside were flooded and disabled by Tsunami. Along with all AC power outage, cooling function for SFP was lost (=> SFP water level drops by evaporation).
- Spent fuel could be damaged if water level continued to drop. But after evaluation, they predicted that the water level would reach at the top of spent fuel on March 20th, (so that they could spend more of their time on other units.)
- They actually measured the water temperature & confirmed it had not reached boiling point (84℃).

● **Manual for disaster management did not predict simultaneous loss of functions.**

- Manual (AM) had assumed SBO (loss of all AC power), but not the simultaneous loss of all AC/DC power & cooling functions.
- Countermeasure, preparation, and training for the simultaneous loss of power, cooling,& vent function were insufficient

● **Nuclear reactor building exploded/damaged.**

- The explosion was not expected, and the cause was not clarified. TEPCO assumed that the hydrogen flowed back from Unit 3 into Unit 4, and exploded.
- Pool gate opened by explosion. Water flowed into the pool from well side. Water level was recovered (assumed).
- Afterward, a fire broke out & was extinguished naturally. Its cause is unknown (could be the hydrogen combustion).
- Lack of monitoring hydrogen buildup in the building, and countermeasure action (led to explosion).

● **Water injection to used fuel pool**

- The actual water level was higher than originally assumed. The water injection to the spent fuel pool was begun on March 20th.

Chronology of Unit 5

(Before earthquake, it had been on halt for regular inspection (pressure 7MPa, water temperature 90℃). Fuel rods were loaded in the core)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)** (M9.0. 4th in recorded history)

- ● **All external power lost.** => 14:47 Emergency DG automatically started.

15:35 **Tsunami hit** (Tsunami-M9.1. 4th in recorded history) (Immersion height: 11.5~ 15.5m)

Loss of all power & seawater cooling functions

- ● Emergency DG stopped => **15:40 All AC power lost** => Unable to use electrical equipments.
- ● Seawater pump lost => **Function for cold shutdown lost (ultimate heat sink lost)**.
- ● DC main line escaped submergence (**DC power supplied by backup batteries**).

3/12
1:40 SRV automatically opened (core pressure 8MPa maintained).
6:06 Core depressurized with opened the valve at top of RPV.
8:13 Started receiving power from emergency DG at Unit 6 via regular cable (DC power maintained).
14:42 Air conditioning system activated manually & air cleaning in central control rooms for units 5&6 resumed.

Supplied AC power from Unit 6.

Water injection to reactor and SFP.

3/13
18:29 Started to supply power to MUWC system from Unit 6's DG via makeshift cables.
20:54 MUWC pump manually activated.
21:01 Stand-by Gas Treatment System (SGTS) manually activated.

3/14
5:00 Core depressurization by opening SRV (continued hereafter).
5:30 Started water injection to the core by MUWC (continued hereafter).
9:27 Water supply to SFP begun (continued hereafter).

3/18
13:30 Holes opened at the roof of reactor building (3 places).

Emergency pump recovered.

Cold shutdown achieved.

3/19
1:55 Makeshift seawater pump for RHR activated by makeshift power from power supply vehicles.
4:22 2nd emergency DG activated at unit 6.
5:00 RHR pump started manually (Started cooling SFP in emergency heat-load mode).

3/20
10:49 RHR stopped manually
12:25 RHR started manually (started core cooling by shut-down cooling system).

14:30 Cold shutdown achieved.

Implications

● **All external power was lost due to earthquake.**

- Just before the earthquake, fuel rods were loaded, and the leakage test of RPV was undergoing (Reactor pressure 7Mpa, water temperature 90℃ (core), 25℃ (SFP).
- Emergency DG activated in accordance to design.

● **AC power at Unit 5 was all lost due to submergence by tsunami & supplied from DG at Unit 6.**

- 2 emergency DG lost due to tsunami. In the early morning of March 12, regular cable was connected between Units 5&6, and DC power supplied from DG at Unit 6.
- With DC power secured, they could monitor parameters in the central control room for recovery actions and countermeasures. Also, by activating emergency ventilation & air conditioning system at Unit 6, work environment in central control rooms of Units 5&6 was improved. (Full masks unnecessary.)
- As all sea water pump system as well as high-voltage power boards were submerged and lost, they structured makeshift cables from Unit 6 to 5, and supplied AC power to equipments for recovery operations at Unit 5.
- With SGTS activated, they maintained negative pressure in the reactor building.

● **Core depressurization succeeded. Started water injection to reactor and spent fuel pool with makeshift power.**

- After earthquake, core pressure first went up by decay heat, then stayed around 8MPa & SRV was automatically opened. They opened the apex valve of RPV to reduce core pressure, which was eventually decreased to atmospheric pressure. Also, through lines for AM, they started to inject water to the nuclear reactor and SFP.

● **Makeshift power recovered & cold shutdown achieved.**

- As water levels of the reactor & SFP were maintained since earthquake, it was very unlikely that hydrogen was being produced. But just in case, they opened 3 passage openings (3.5cm ϕ ~7cm ϕ) in the roof of reactor building by boring machines.
- Regarding RHR, since seawater pumps were lost, they carried in makeshift generator & seawater pump, and connected a makeshift cable from Unit 6 in order to construct RHR system line. With RHR pump activated, they cooled the reactor & SFP alternately.
- After water temperature of SFP dropped, cold shutdown of the core had been achieved.

Chronology of Unit 6

(Before earthquake, it had been on halt for regular inspection. Fuel rods were loaded in the core)

Events

Emergency shutdown of the reactor

3/11 14:46

Earthquake occurred (Level 6+)
(M9.0. 4th in recorded history)

- ● **All external power lost.** => 14:47 Emergency DG automatically started.

15:35

Tsunami hit
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

Loss of all power & seawater cooling functions

- ● 15:36 2 Emergency DG stopped => 1 DG was sound & AC power secured.
- ● Seawater pump lost => **Function for cold shutdown lost (ultimate heat sink lost)**.
- ● DC main line escaped submergence (**DC power supplied by backup batteries**).

Maintained water level of core & SFP.

3/12
6:03 Started to construct power supply line from emergency DG.
8:13 Supplied power from emergency DG to Unit 5 via main cable.
14:42 Activated air conditioning system manually, and started air cleaning for central control rooms of both Units 5&6.

3/13 13:01 Activated MUWP manually. => Started water supply to the core.

3/14 14:13 Started water supply to SFP (continued periodically hereafter).

3/16 13:10 Activated Fuel Pool Cooling & Filtering system manually. (without heat removal function. only circulation).

Emergency pump recovered.

Cold shutdown achieved.

3/18
17:00 Opened passage in the roof of reactor building (3 spots).
19:07 Activated seawater pump for emergency DG.

3/19
4:22 Activated 2 emergency DG.
21:26 Activated makeshift seawater pump for RHR (with makeshift power from supply vehicle).
22:14 Activated RHR manually. (Started cooling SFP in emergency heat loaded mode).

3/20
16:26 Stopped RHR manually (emergency heat loaded mode).
18:48 Activated RHR manually (started core cooling with shutdown cooling system).

19:27 Cold shutdown achieved.

Implications

● **All external power was lost due to earthquake**

- Just before the earthquake, fuel rods were loaded, and the reactor was in the mode of cold shutdown.
- Emergency DG activated in accordance to design.

● **Emergency DG survived & power was secured. However, seawater cooling function was lost.**

- Though 2 emergency DG were lost due to tsunami, one air-cooling DG & emergency power boards survived. Therefore, power source was secured.
- With DG power secured, they could monitor parameters in the central control room for recovery actions and countermeasures for the reactor & SFP. Also, by activating emergency ventilation & air conditioning system, work environment in the central control room was improved. (Full masks unnecessary.)
- All sea water pump system were submerged and lost.
- With SGTS activated, they maintained negative pressure in the reactor building.

● **Maintained water level by injecting water to the core & SFP.**

- They activated Make Up Water Pump system by emergency DG, and injected water to the core & spent fuel pool. After that, they activated Fuel Pool Cooling & Filtering system to circulate the pool water in order to mitigate the rise in water temperature.

● **Makeshift power recovered & cold shutdown achieved.**

- As water levels of the reactor & SFP were maintained since earthquake, it was very unlikely that hydrogen was being produced. But just in case, they opened 3 passage openings (3.5cm ϕ ~7cm ϕ) in the roof of reactor building by boring machines.
- Regarding RHR, they restored seawater pump system with makeshift generator & seawater pump. With RHR pump activated, they cooled the reactor & SFP alternately.
- After water temperature of SFP dropped, cold shutdown of the core had been achieved.

Progression of the accident: The hydrogen was generated by water-zircaloy reaction, accumulated and exploded in 5th floor, leading to the leakage of radioactive material.

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (level 6+)**
(M9.0. 4th in recorded history)

- **14:46 Automatic shutdown of the reactor** => 14:52 IC activated automatically & opened/ closed manually.
- **Loss of all external power** => 14:47 Emergency DG activated.

Loss of all power & important functions

15:35 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

- Emergency DG & power panels flooded => **all AC power lost** => Unable to use electrical equipments.
- Battery room submerged => **DC power lost** => Electrical boards, measuring & control facilities lost => **Cooling function lost** (IC, HPCI), **Pressure control function lost** (open SRV remotely etc.)
- Seawater pump lost => **Function for cold-shutdown lost** (ultimate heat sink lost)

Right after tsunami: Isolation Condenser lost
=> Core water level started to drop.

Secure emergency power.

Prepare for coolant injection.

Prepare for ventilation

17:12 Plant manager ordered to consider water injection by fire pump system & fire truck

18:46 Core damage started (estimated)

21:19 Core water level became readable (TAF + 200mm*0)
23:00 Rise in radiation level in turbine bldg confirmed.
Around then, 1st power supply vehicle arrived.

3/12
00:06 Plant manager ordered to prepare vent.
(as Dry-well of PCV pressure possibly over 600k Pa)
01:30 Requested to execute vent & approved by the country.

02:30 Confirmed 'RPV pressure is low & PCV pressure is high'*1.
05:46 Started to inject fresh water by fire trucks.
07:20 RPV damaged. (simulation)

Tried water injection.

Tried ventilation.

Hydrogen built up.

09:04 Workers departed for site for ventilation.
10:17 Started PCV vent.
14:30 PCV vent succeeded (D/W pressure decreased)

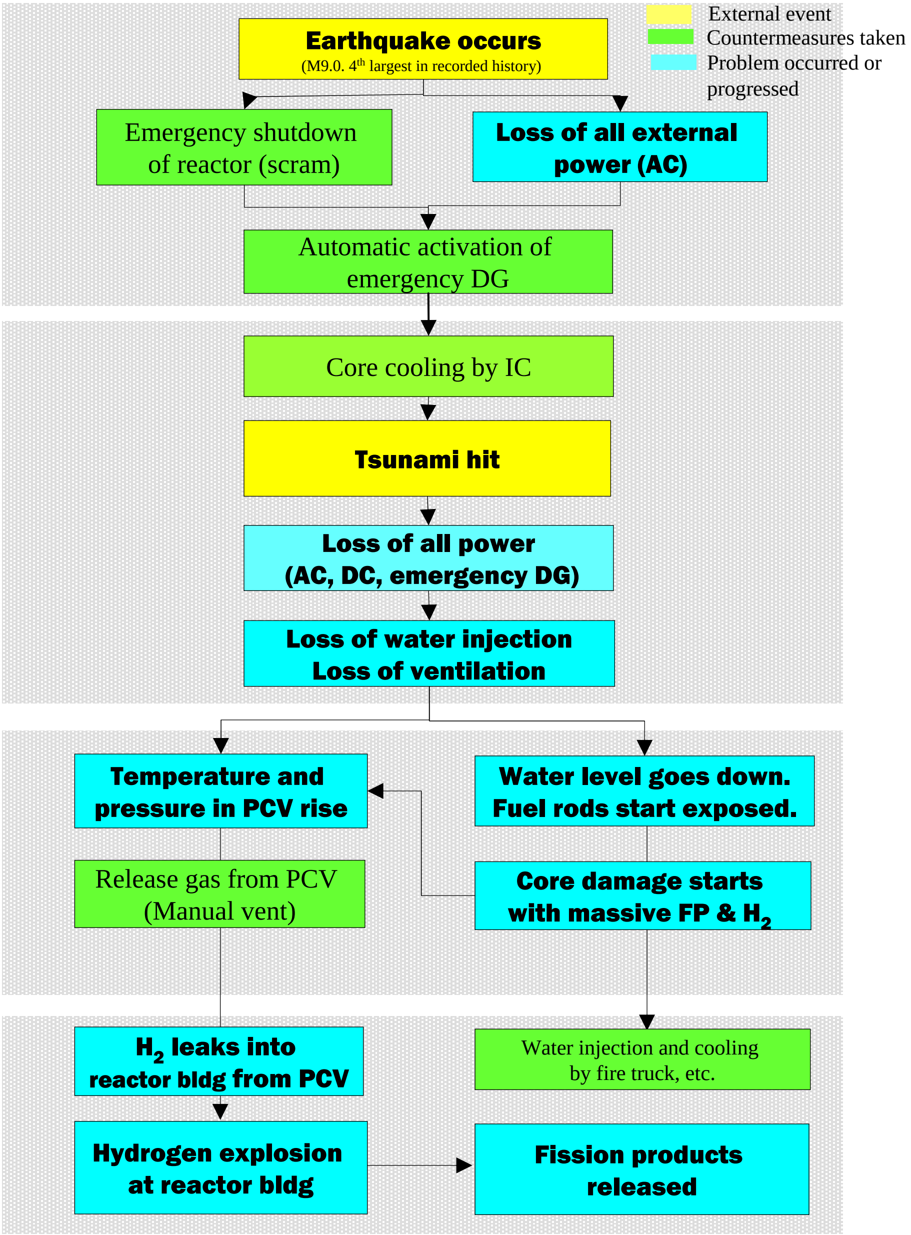
14:53 Completed freshwater injection (80,000 l in total).
14:54 Plant manager ordered sea water injection.

Hydrogen Explosion & radiation leak

15:36 **Reactor building exploded (5th floor)**

19:04 Started sea water injection.
20:45 Started sea water injection with boric acid.

Progression of accident (conceptual)



🟨 External event
🟩 Countermeasures taken
🟦 Problem occurred or progressed

Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by IC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection
Loss of ventilation

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core damage starts with massive FP & H_2

H_2 leaks into reactor bldg from PCV

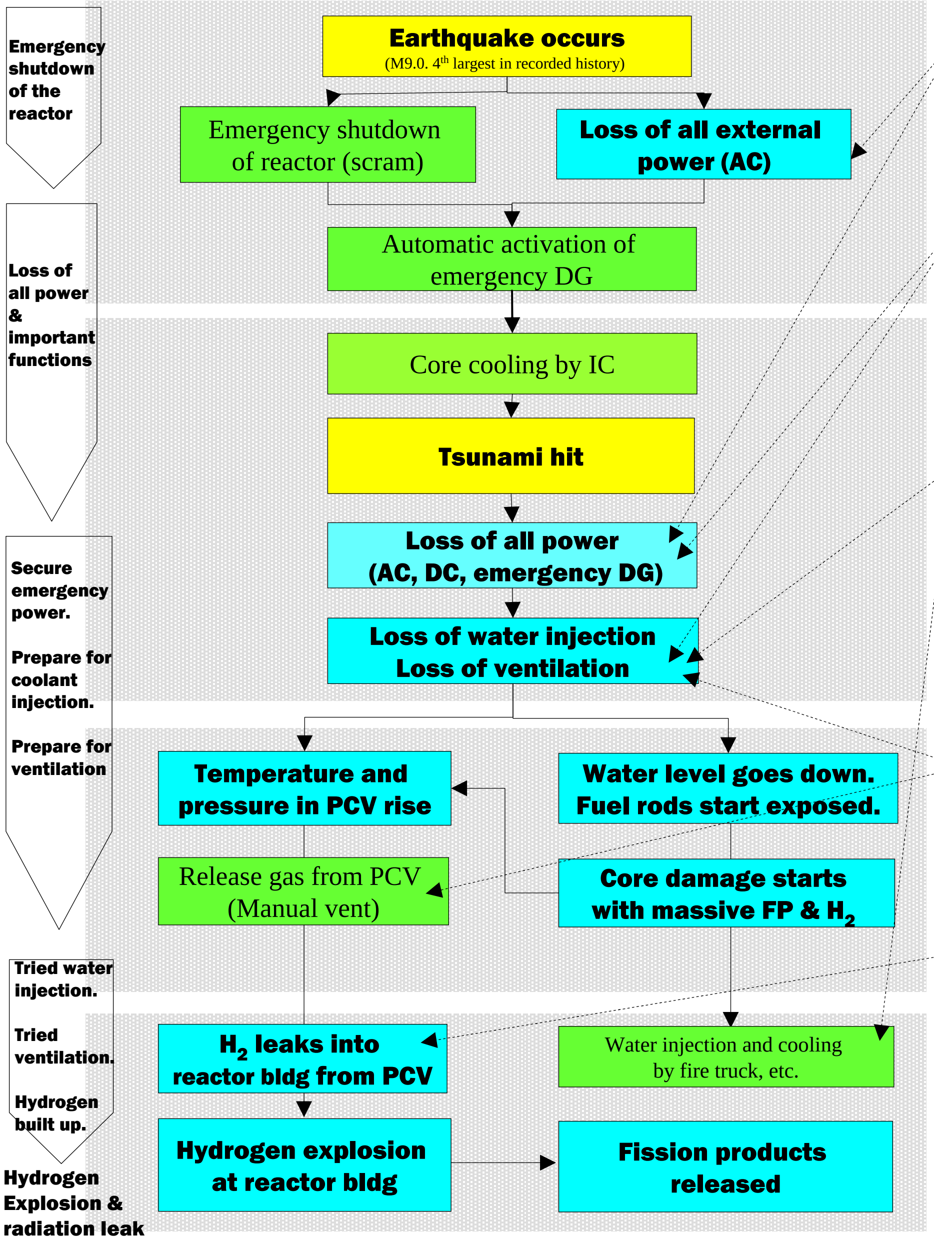
Water injection and cooling by fire truck, etc.

Hydrogen explosion at reactor bldg

Fission products released

Problems deduced from the events: Simultaneous loss of all power and cooling & vent functions had disabled the recovery operations, and taken the 'cool and shut-down the core' function away.

Progression of accident (conceptual)



Emergency shutdown of the reactor

Loss of all power & important functions

Secure emergency power.

Prepare for coolant injection.

Prepare for ventilation

Tried water injection.

Tried ventilation.

Hydrogen built up.

Hydrogen Explosion & radiation leak

Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by IC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection Loss of ventilation

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core damage starts with massive FP & H_2

H_2 leaks into reactor bldg from PCV

Water injection and cooling by fire truck, etc.

Hydrogen explosion at reactor bldg

Fission products released

Problems

AC power was lost over the long-term due to earthquake and tsunami.

- As Unit 2 also lost power, the power could not be shared with Unit 1.
- Due to submergence, there was no electrical panel to be connected with the power supply vehicle.
- Due to extremely bad environment, even after the power supply vehicles arrived, reaching power connection port, and connection itself was difficult.

AM hadn't assumed the simultaneous loss of all AC/DC power (=DC won't be lost for long-term).

- As IC is DC driven, along with DC loss, MSIV was closed (unable to access to internal valves for vent).
- Due to all power loss, they could not remotely open the valves for ventilation.
- There was no specific AM procedure defined for SBO with simultaneous loss of DC (procedure handbook for SBO only assumed that DC power was normal).

Securing alternative cooling water source was insufficient and delayed.

- Due to power loss, core depressurization was delayed (battery depletion, insufficient pressure of air compressor).
- Lack of easy depressurization method under DC loss. Not prepared for working under high radiation (alternative method other than SRV necessary?).
- There was a malfunction in diesel-driven fire extinguishing pump.
- Liquefaction & debris caused extreme difficulty in accessing & constructing external water injection line.
- Insufficient injection ability of external water pump.
- Securing and supplying alternative water source was prolonged.

PCV vent function was lost. Manual ventilation was delayed.

- Lack of easy depressurization method under DC loss. Not prepared for working under high radiation.
- Other than W/W vent, there was no operation procedure or device to prevent fission products from leaking outside, when conducting dry-well vent or other direct ventilation.

Lack of precaution, monitoring, and actions against building explosion (hydrogen explosion).

- No preparation for building ventilation in case of long-term AC power loss.
- No mechanism to detect hydrogen generation.
- No method to release accumulated hydrogen outside of the reactor building.

Emergency facilities at sea side were so vulnerable that they could not do almost anything after the loss of ultimate heat sink.

- Though overall AM procedure of 'high pressure cooling => core depressurization => water injection by low pressure cooling => PCV depressurization" was defined, specific AM/operational procedures in case of simultaneous loss of all power & vent functions were not clearly defined.

Progression of the accident: As the explosion of adjacent units damaged the power supply vehicle & fire truck, the recovery actions delayed, leading to the PCV damage.

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)** (M9.0. 4th in recorded history)

- ● **14**:**47 Automatic shutdown of the reactor.**
- ● **Loss of all external power** => Emergency DG automatically activated.

14:50 RCIC activated manually => 14:52 Stopped automatically (high water level = L-8).

- ● 15:01 Sub-criticality of the core confirmed

Loss of all power & seawater cooling functions

15:35 **Tsunami hit** (Tsunami-M9.1. 4th in recorded history) (Immersion height: 11.5~ 15.5m)

15:39 RCIC activated manually.

- ● **15:41 All AC power lost (emergency DG & electrical panel immersed) => Extreme work environment, darkness.** Battery room submerged & **All DC power lost** (some P/C not submerged). => RCIC continued. **Seawater systems submerged & ultimate heat sink lost.** => Function for cold shutdown lost.

17:12 Plant manager ordered to consider water injection by fire truck.

22:00 Core water level became readable (TAF +3400mm)

Secure high pressure cooling.

Prepare for low pressure coolant injection.

Prepare for ventilation

3/12 2:55 Confirmed RCIC was in operation. **(As RCIC confirmed as working, prioritized ventilation of Unit 1 at first.)**

17:30 Plant manager ordered to prepare for PCV vent.

3/13 11:00 S/C vent valve (large) opened &vent-line structured. (As D/W pressure was low, rupture disk did not rupture & ventilation failed).

3/14 11:01 Unit 3 exploded & excitation circuit for electro-magnetic valve damaged. S/C vent valve (large) closed and unable to open again. Also, explosion destroyed the fire truck and makeshift hoses & water injection lines were unusable.

13:25 Reduction trend of reactor's water level confirmed. => Judged as RCIC not working.

17:17 Reactor's water level reached at TAF.

17:17~ Core damage started (estimated)

Core de-pressurized.

LP coolant injection.

Tried & failed ventilation.

Core damage & hydrogen built up.

18:00 Started core de-pressurization (core pressure = 5.4MPa => 19:03 0.63MPa)

18:22 Water level reached at TAF -3700mm. Judged as core was exposed. => Reported to METI.

19:54 Started sea water injection to the core with fire pump system & fire trucks.

21:00 S/C vent valve (small) slightly opened & reconstruction of vent line completed.

22:50 While D/W pressure exceeds maximum usage pressure 427kPa (& kept rising), S/C pressure stayed at 300~400 kPa gage, and both pressures (DW & S/C) did not converge.

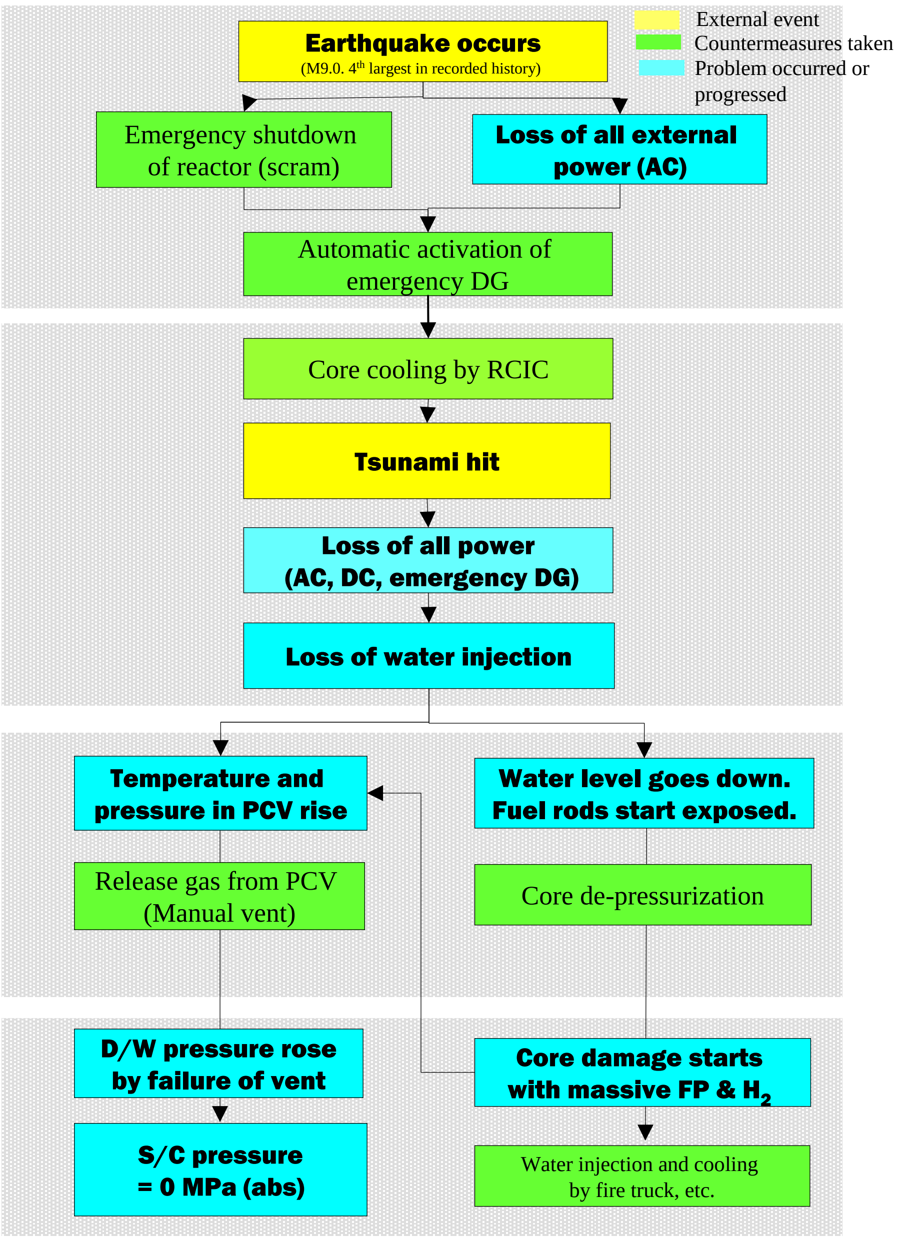
23:35 As rupture disk of S/C did not rupture (insufficient pressure), they decided to vent via D/W by opening small valve.

PCV damaged. Radiation leak.

3/15 0:02 Opened D/W vent valve (small) & vent line structured. (but, the valve closed again a few minutes later). (D/W pressure did not drop below 750kPa (abs) & stayed at high level.)

6:00~ 6:10 **S/C pressure indicated at 0kPa(abs)**

Progression of accident (conceptual)



🟨 External event
🟩 Countermeasures taken
🟦 Problem occurred or progressed

Earthquake occurs (M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by RCIC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core de-pressurization

D/W pressure rose by failure of vent

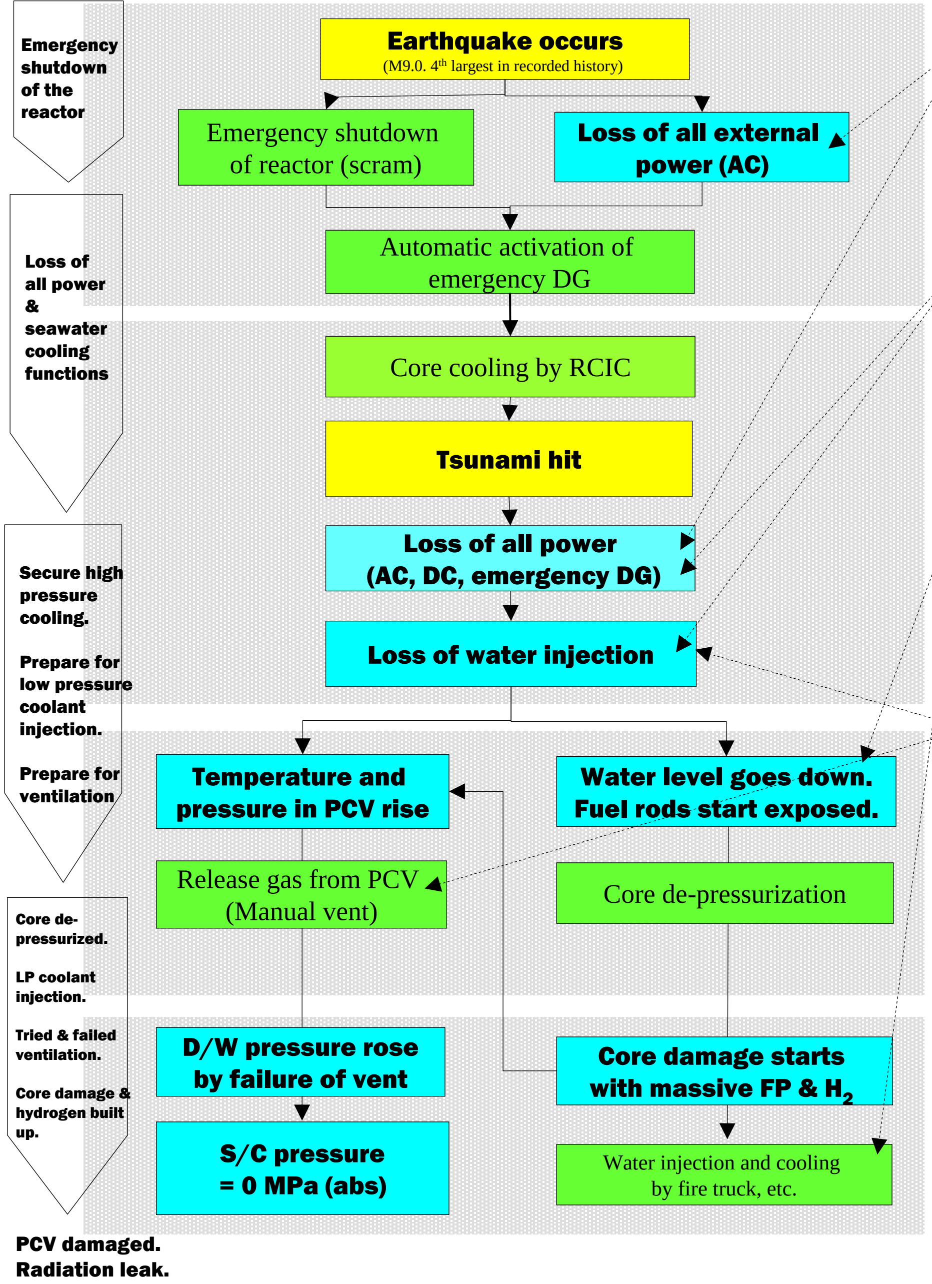
Core damage starts with massive FP & H_2

S/C pressure = 0 MPa (abs)

Water injection and cooling by fire truck, etc.

Problems deduced from the events at Fukushima Dai-ichi Unit 2

Progression of accident (conceptual)



Emergency shutdown of the reactor

Loss of all power & seawater cooling functions

Secure high pressure cooling.

Prepare for low pressure coolant injection.

Prepare for ventilation

Core de-pressurized.

LP coolant injection.

Tried & failed ventilation.

Core damage & hydrogen built up.

PCV damaged. Radiation leak.

Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by RCIC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core de-pressurization

D/W pressure rose by failure of vent

Core damage starts with massive FP & H_2

S/C pressure = 0 MPa (abs)

Water injection and cooling by fire truck, etc.

Problems

AC power was lost over the long-term due to earthquake and tsunami.

- As Unit 1 also lost power, the power could not be shared with Unit 2.
- Though some electrical panels had survived, it was so difficult to access the building due to obstacles such as numerous debris that the recovery of power was delayed.
- As the power supply vehicle was destroyed by the explosion at Unit 1, they could not use the vehicle to power the survived panel.

AM hadn't assumed the simultaneous loss of all AC/DC power (=DC won't be lost for long-term).

- It was not assumed that the all batteries (DC) were submerged and lost spontaneously (lead to the loss of monitoring function such as water level, status of RCIC etc).
- Due to all power loss, they could not remotely open the valves for ventilation.
- There was no specific AM procedure defined for SBO with simultaneous loss of DC (procedure handbook for SBO only assumed that DC power was normal).

Securing alternative cooling water source was insufficient and delayed.

- Due to power loss, core depressurization was delayed (battery depletion, insufficient pressure of air compressor).
- The fire truck and hoses were destroyed by the explosion at Unit 3.
- Liquefaction & debris, combined with frequent aftershocks, caused extreme difficulty in accessing & constructing external water injection line.

PCV vent function was lost. Manual ventilation was delayed.

- Due to the explosion at Unit 3, the large valve of PCV vent line was closed and unable to be opened any more. The operation to open small valve was also delayed.
- Even when dry-well (D/W) pressure exceeded the activation pressure of rupture disk (destruction valve), wet well (W/W) pressure was below the activation pressure. So the rupture disk did not activate and continued to be so. After a while, as the pressure of suppression chamber (S/C) dropped, there was a possibility of PCV damage.
- It is necessary to review the activation pressure of rupture disk.

Emergency facilities at sea side were so vulnerable that they could not do almost anything after the loss of ultimate heat sink.

- Though overall AM procedure of 'high pressure cooling => core depressurization => water injection by low pressure cooling => PCV depressurization" was defined, specific AM/operational procedures in case of simultaneous loss of all power & vent functions were not clearly defined.

Progression of the accident: Loss of important functions and delay in recovery actions lead to the explosion.

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)** (M9.0. 4th in recorded history)

- **14：47 Automatic shutdown of the reactor**. => 15:05 RCIC activated manually => 15:25 RCIC tripped (high water level).
- **Loss of all external power** => 14:48 Emergency DG automatically activated.

Loss of all power & seawater cooling functions

15:35 **Tsunami hit** (Tsunami-M9.1. 4th in recorded history) (Immersion height: 11.5~ 15.5m)

Loss of all AC power + darkness & terrible work environment.

- Emergency DG & power panels flooded => **15:38 all AC power lost** => Unable to use electrical equipments.
- Seawater pump destroyed => **Function for cold-shutdown lost. (ultimate heat sink lost)**
- DC main lines survived. (**Kept supplying DC** power by backup batteries to RCIC, HPCI, measurement instruments).

16:03 Core cooling by RCIC (manually activated)

DC survived then run out.

RCIC/HPCI worked then lost.

Prepare for ventilation

3/12
11:36 RCIC stopped (fire trucks used for Unit 1).
12:35 High pressure water injection (HPCI) automatically activated (water level = low).
17:30 Plant manager ordered to prepare for PCV vent.

3/13
02:42 HPCI stopped (battery depleted).
03:51 Water level indicated as 1600mm below the fuel top (= TAF -1600mm).
04:15 Judged the water level reached at TAF.
05:10 Judged that RCIC failed to inject coolant.
05:15 Plant manager ordered to construct vent line systems.
08:41 Vent line excluding RD had been set up.

08：00 ~ 09：00 Core damage started (estimated)

LP coolant injection.

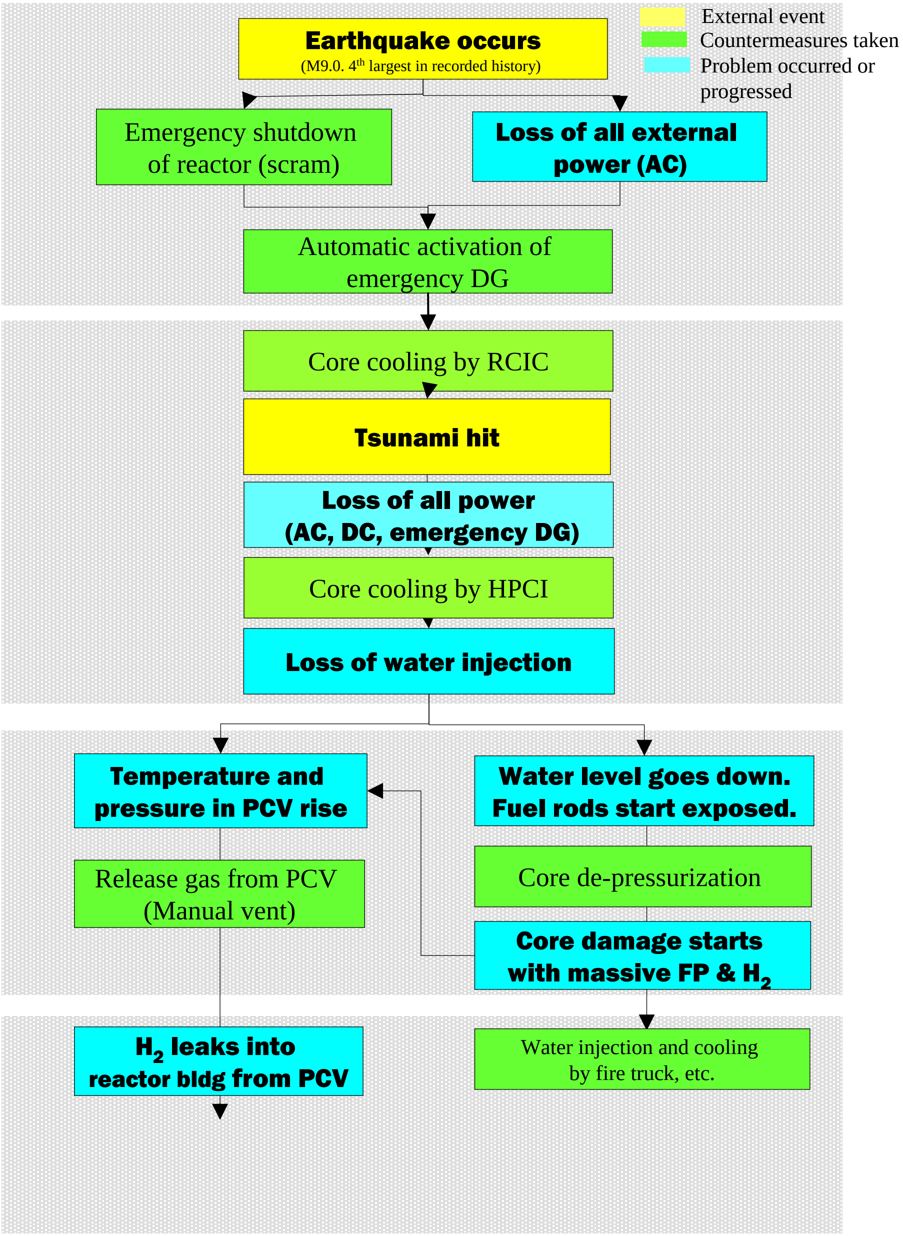
Conducted PCV ventilation.

Core damage & hydrogen built up.

09:08 Core de-pressurized by SRV (used car batteries of workers).
09:25 Started fresh water injection by fire trucks (with boric acid).
09:36 Confirmed D/W pressure dropped after vent operation.
10:30 Plant manager ordered to prepare sea water injection.
11:17 AO valve of S/C vent closed (pressure of air compressor lowered).
12:20 Fresh water injection completed (since fresh water in fire protection water tank depleted).
12:30 AO valve of S/C vent opened (air compressor changed).
13:12 Started sea water injection by fire trucks (frequent aftershocks delayed its preparation).

3/14
01:10 Seawater injection by fire trucks stopped for replenishing, due to lack of sea water.
03:20 Seawater injection resumed.
05:20 S/C vent AO valve opened. 06:10 Confirmed the AO valve opened.
09:20 Started to supply seawater from the wharf to reverse-valve pit. (retarded by high radiation level & bad transportation)
10:53 7 water supply vehicles (5t) brought in by Self-Defense Force. Placed them to reverse valve pit & re-started fresh water injection.

Progression of accident (conceptual)



🟨 External event
🟩 Countermeasures taken
🟦 Problem occurred or progressed

Earthquake occurs (M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by RCIC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Core cooling by HPCI

Loss of water injection

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core de-pressurization

Core damage starts with massive FP & H_2

H_2 leaks into reactor bldg from PCV

Water injection and cooling by fire truck, etc.

Events

Hydrogen Explosion & radiation leak

3/15

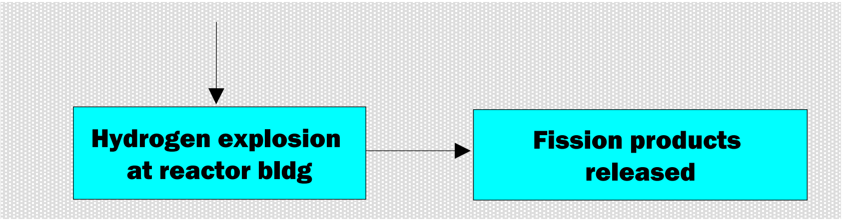
11:01 **Reactor building exploded (4th& 5th floor)**

Fire truck and hoses were destroyed & seawater injection suspended.

16:30 Injection line from the wharf to the core was constructed. Sea water injection resumed.

07:55 Floating of moisture above the building confirmed.

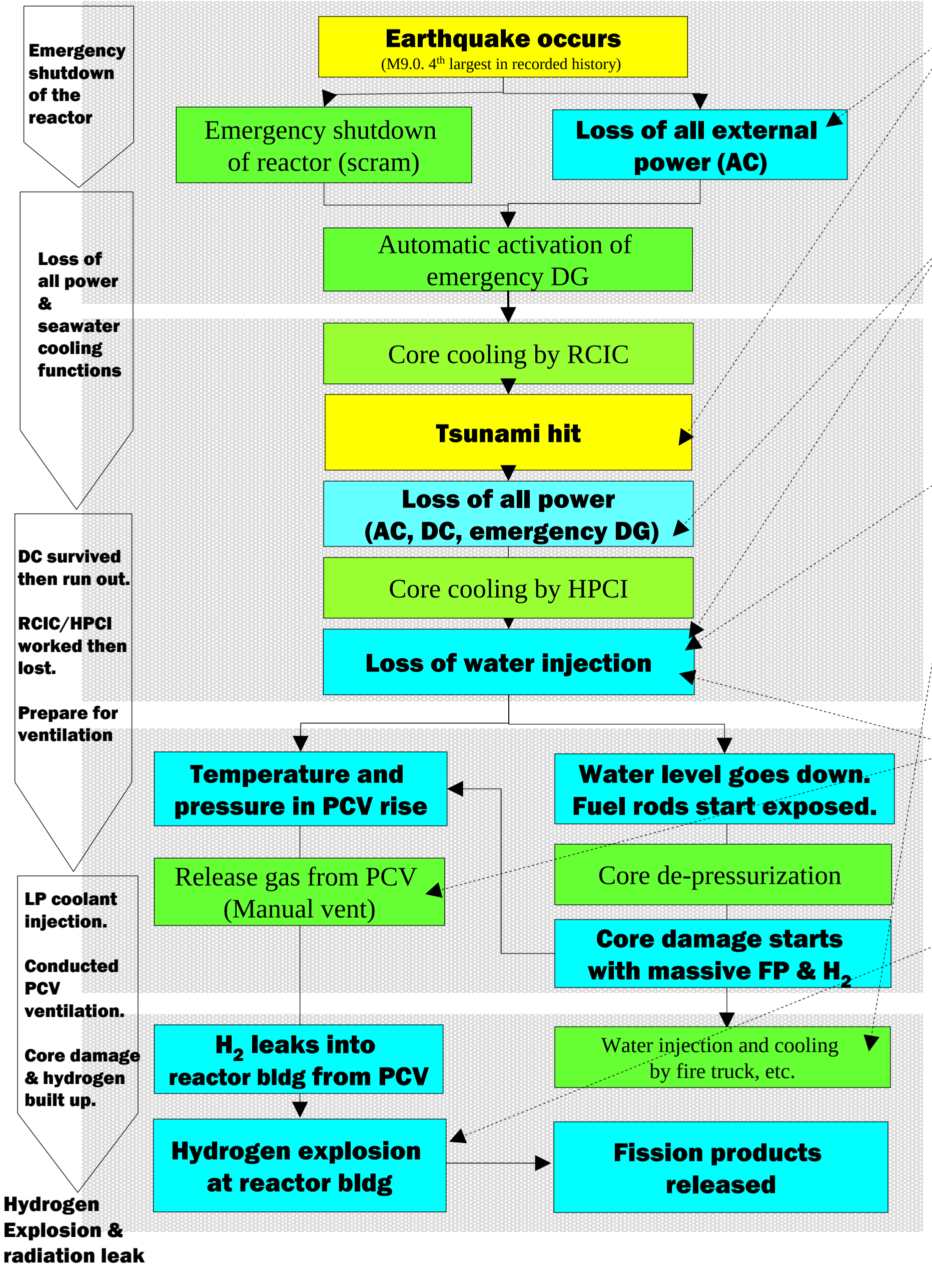
Progression of accident (conceptual)



Extremely Confidential

Problems deduced from the events at Fukushima Dai-ichi Unit 3

Progression of accident (conceptual)



Emergency shutdown of the reactor

Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Loss of all power & seawater cooling functions

Core cooling by RCIC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

DC survived then run out.

RCIC/HPCI worked then lost.

Prepare for ventilation

Core cooling by HPCI

Loss of water injection

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Core de-pressurization

Release gas from PCV (Manual vent)

LP coolant injection.

Conducted PCV ventilation.

Core damage & hydrogen built up.

Core damage starts with massive FP & H_2

Water injection and cooling by fire truck, etc.

H_2 leaks into reactor bldg from PCV

Hydrogen explosion at reactor bldg

Fission products released

Hydrogen Explosion & radiation leak

Problems

AC power was lost over the long-term due to earthquake and tsunami.

- As Unit 2 & 4 also lost power, the power could not be shared with Unit 3.
- Due to submergence of electrical panel, the loss of all AC power was prolonged.
- Due to extremely bad environment, even after the power supply vehicles arrived, reaching power connection port, and connection itself was difficult.

AM hadn't assumed the simultaneous loss of all AC/DC power (=DC won't be lost for long-term).

- As batteries were not submerged, the high pressure cooling system worked for a while. However, with batteries depleted, water injection function was lost.
- Due to all power loss, they could not remotely open the valves for SRV ventilation.
- There was no specific AM procedure defined for SBO with simultaneous loss of DC (procedure handbook for SBO only assumed that DC power was normal).

Securing alternative cooling water source was insufficient and delayed.

- As the batteries were insufficient, they collected and brought in individual car batteries to open SRV. This had delayed the depressurization.
- It took much time to procure alternative fire trucks other than the one used at Unit 1, which was only available then.
- Water injection was delayed due to insufficient seawater source and lack of fire trucks.
- Liquefaction & debris caused extreme difficulty in transporting fire trucks & constructing external water injection line/hose.

PCV vent function was lost. Manual ventilation was delayed.

- Lack of easy depressurization method under DC loss. Not prepared for working under high radiation.
- Other than suppression pool scrubbing, there was no operation procedure or device to prevent fission products from leaking outside, when conducting dry-well vent or other direct ventilation.

Lack of precaution, monitoring, and actions against building explosion (hydrogen explosion).

- No preparation for building ventilation in case of long-term AC power loss.
- No mechanism to detect hydrogen generation.
- No method to release accumulated hydrogen outside of the reactor building.

Emergency facilities at sea side were so vulnerable that they could not do almost anything after the loss of ultimate heat sink.

- Though overall AM procedure of 'high pressure cooling => core depressurization => water injection by low pressure cooling => PCV depressurization" was defined, specific AM/operational procedures in case of simultaneous loss of all power & vent functions were not clearly defined.

Progression of the accident: Loss of SFP cooling function raised water temperature, and the hydrogen flowed into the reactor building from Unit 3, leading to the explosion.

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)**
(M9.0. 4th in recorded history)

- Under regular inspection from November 30th, 2009, (reactor was on halt). = 1535 rods of spent fuel stored in SFP(97% full).
- **Loss of all external power** => 14:47 Emergency DG automatically activated.
- Water sloshed & spilled over from the pool & water level dropped (approx. 0.5m)

Loss of all power & seawater cooling functions

15:35 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

Loss of all AC power + darkness & terrible work environment.

- Emergency DG & power panels flooded => **all AC power lost** => Unable to use electrical equipments.
- Battery room submerged => **DC power lost** => Electrical board, measurement/ controlling facilities malfunctioned. => **Cooling function lost (RHR).**
- Seawater pump for Fuel Pool Cooling & Filtering (FPC) system damaged. => **Cooling function lost (ultimate heat sink lost)**.

Water level of SFP monitored.

Prepare to maintain water level.

Hydrogen flowed back from Unit 3.

As the pool temperature continued to rise by the decay heat of used fuel, water level in the pool decreased with its water evaporated.

- The water level was estimated to reach to the top of fuel rods around March 20th.
- Since the pool gate was closed before earthquake, the water level was the same as the one at the well side of DS pit. So, it was reasonably expected that the pool gate would open to supply water to SFP from the well side if the water level in SFP continue to drop.

3/14 **04:08 SFP temperature was confirmed as 84 ℃.**
11:01 Unit 3 explosion

Hydrogen Explosion & radiation leak

3/15 06:12 **Huge detonation sound.**
Reactor building severely damaged (4th & 5th floor)

- Pool gate opened due to explosion, and water level recovered up to well level (estimated).

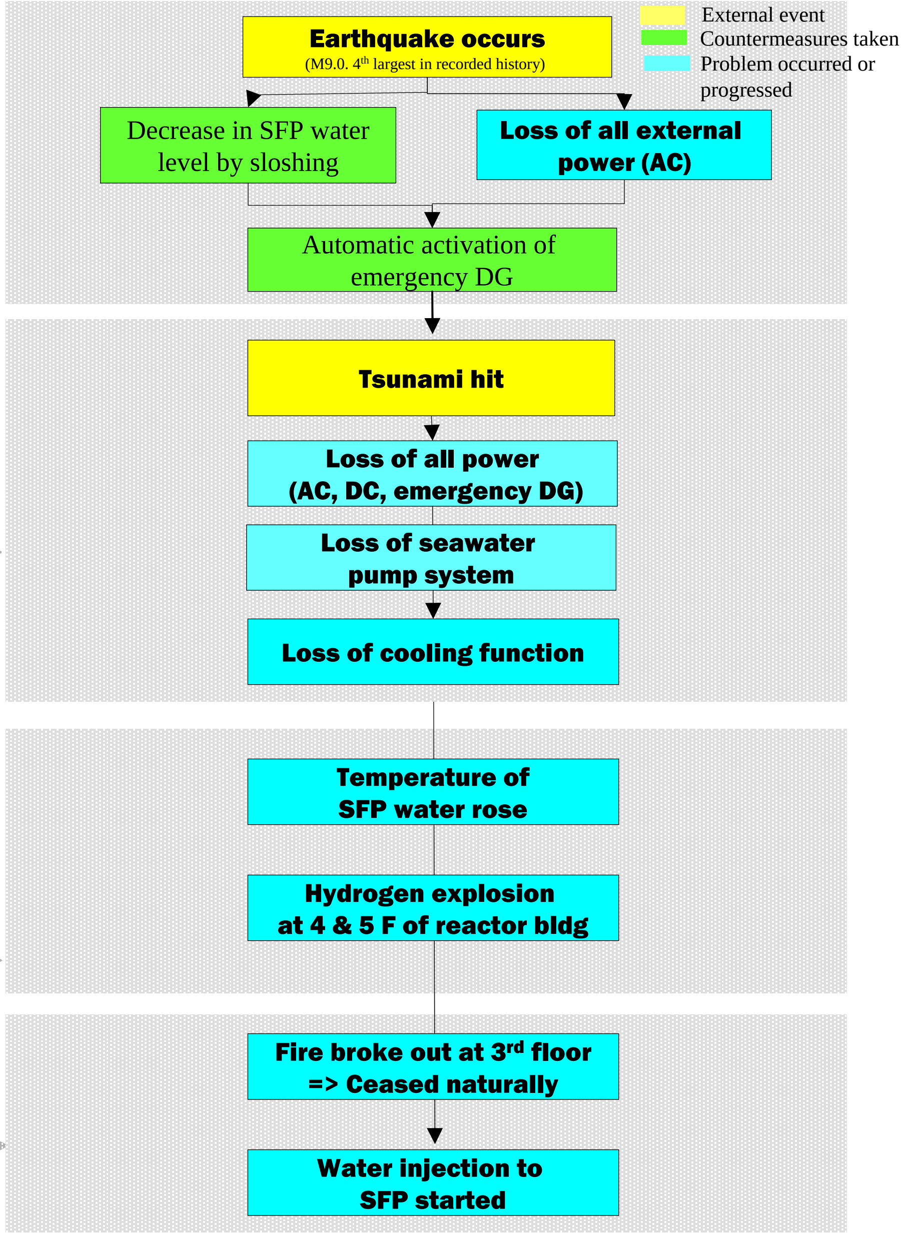
Fire broke out & extinguished.

3/16 09:38 **Fire broke out** from the 3rd floor of the reactor building.
11:00 **Fire extinguished** naturally.
Water level confirmed from helicopter (4-5m above the fuel top)

water injection started.

3/20 08:21 **Started to spray water to the SFP** (continued periodically).

Progression of accident (conceptual)



🟨 External event
🟩 Countermeasures taken
🟦 Problem occurred or progressed

Earthquake occurs
(M9.0. 4th largest in recorded history)

Decrease in SFP water level by sloshing

Loss of all external power (AC)

Automatic activation of emergency DG

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of seawater pump system

Loss of cooling function

Temperature of SFP water rose

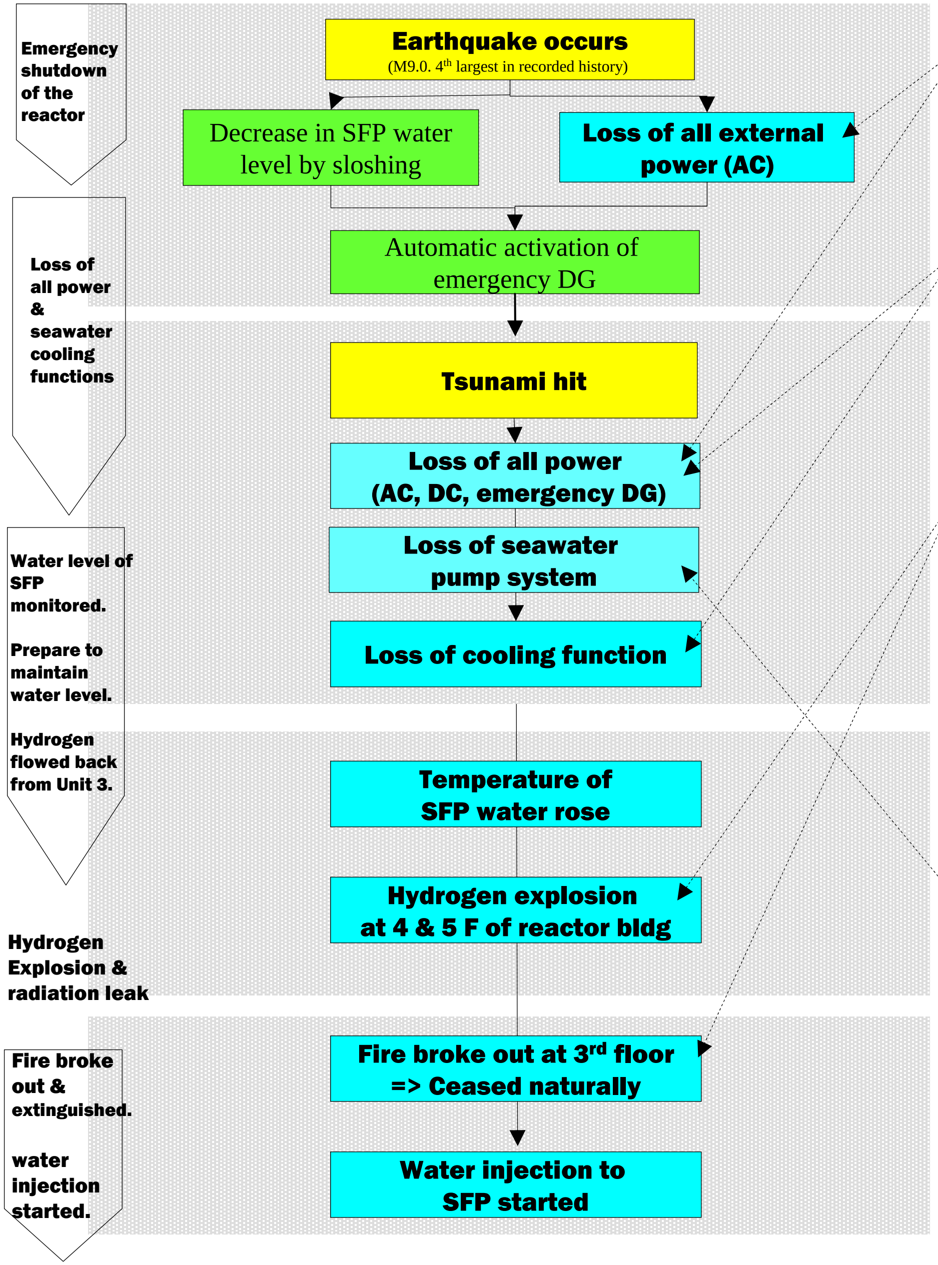
Hydrogen explosion at 4 & 5 F of reactor bldg

Fire broke out at 3rd floor => Ceased naturally

Water injection to SFP started

Problems deduced from the events at Fukushima Dai-ichi Unit 4

Progression of accident (conceptual)



Emergency shutdown of the reactor

Earthquake occurs
(M9.0. 4th largest in recorded history)

Decrease in SFP water level by sloshing

Loss of all external power (AC)

Automatic activation of emergency DG

Loss of all power & seawater cooling functions

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of seawater pump system

Loss of cooling function

Water level of SFP monitored.

Prepare to maintain water level.

Hydrogen flowed back from Unit 3.

Temperature of SFP water rose

Hydrogen Explosion & radiation leak

Hydrogen explosion at 4 & 5 F of reactor bldg

Fire broke out & extinguished.

water injection started.

Fire broke out at 3rd floor => Ceased naturally

Water injection to SFP started

Problems

AC power was lost over the long-term due to earthquake and tsunami.

- As Unit 3 also lost power, the power could not be shared with Unit 4.
- Although one emergency DG survived and was activated, there was no additional power source.
- Drop in water level by sloshing was expected.

AM hadn't assumed the simultaneous loss of all AC/DC power (=DC won't be lost for long-term).

- There was no specific AM procedure defined for SBO with simultaneous loss of DC (procedure handbook for SBO only assumed that DC power was normal).
- Countermeasures, preparation, and training in case of simultaneous loss of power, cooling & vent functions were inadequate.

The building explosion (hydrogen explosion).

- Although it was an unexpected explosion and the reason was unknown, TEPCO assumed that the hydrogen generated in Unit 3 had flowed into Unit 4 through the pipelines for stand-by gas treatment system (SGTS), and exploded. (No damage of fuel rods in SFP of Unit 4).
  => Radiation levels of radiation removal filters for SGTS were a couple of ten times higher at the exhaust side than at the intake side.
- Cause of fire was also unknown. It could be caused by the combustion of hydrogen.
- No preparation for building ventilation in case of long-term AC power loss.
- No mechanism to detect hydrogen generation.
- No method to release accumulated hydrogen outside of the reactor building.

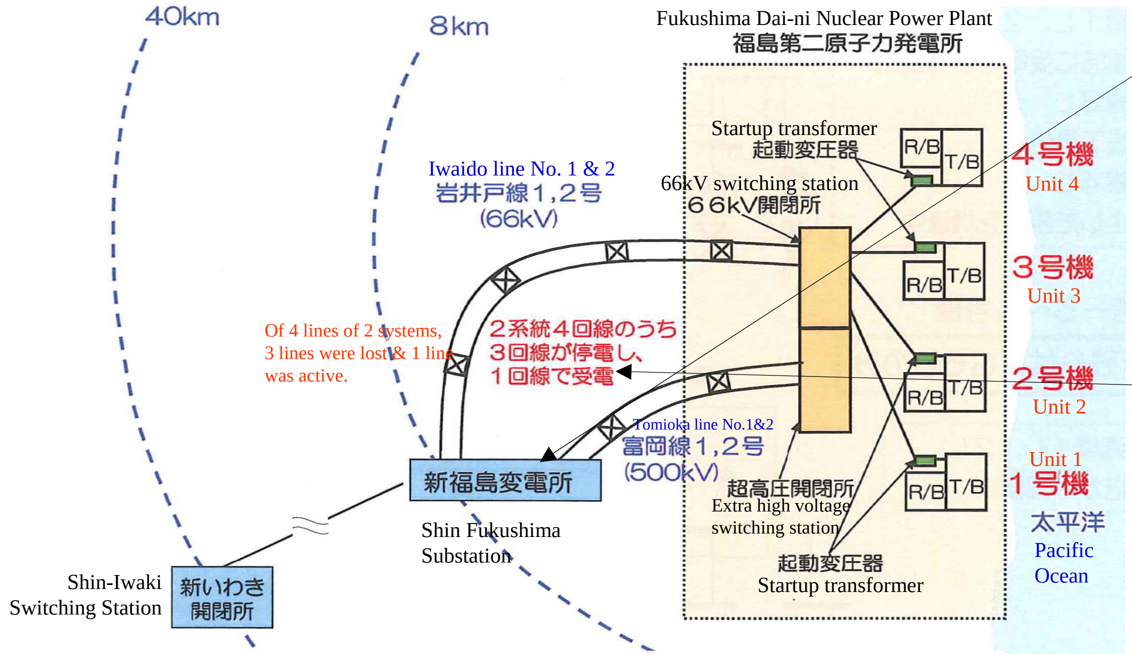
Emergency facilities at sea side were so vulnerable that they could not do almost anything after the loss of ultimate heat sink.

- Due to submergence of the seawater cooling pumps, combined with loss of all AC power, SFP cooling function was lost.

Fukushima Dai-ni Power Plant:

Chronologies and Issues

Damage to external power: At Fukushima Dai-ni, 3 out of 4 external power lines were lost due to the damage of transforming equipments at substations.



出典：
東北地方太平洋沖地震に対する原子力発電所の状況について（H23.3.22東京電力　柏崎刈羽原子力発電所）
http://www.tepco.co.jp/nu/kk-np/tiiki/pdf/230325.pdf

Status of Nuclear Power Plants after Tohoku Region Pacific Coast Earthquake (March, 22, 2011. TEPCO)

Supply route of external power

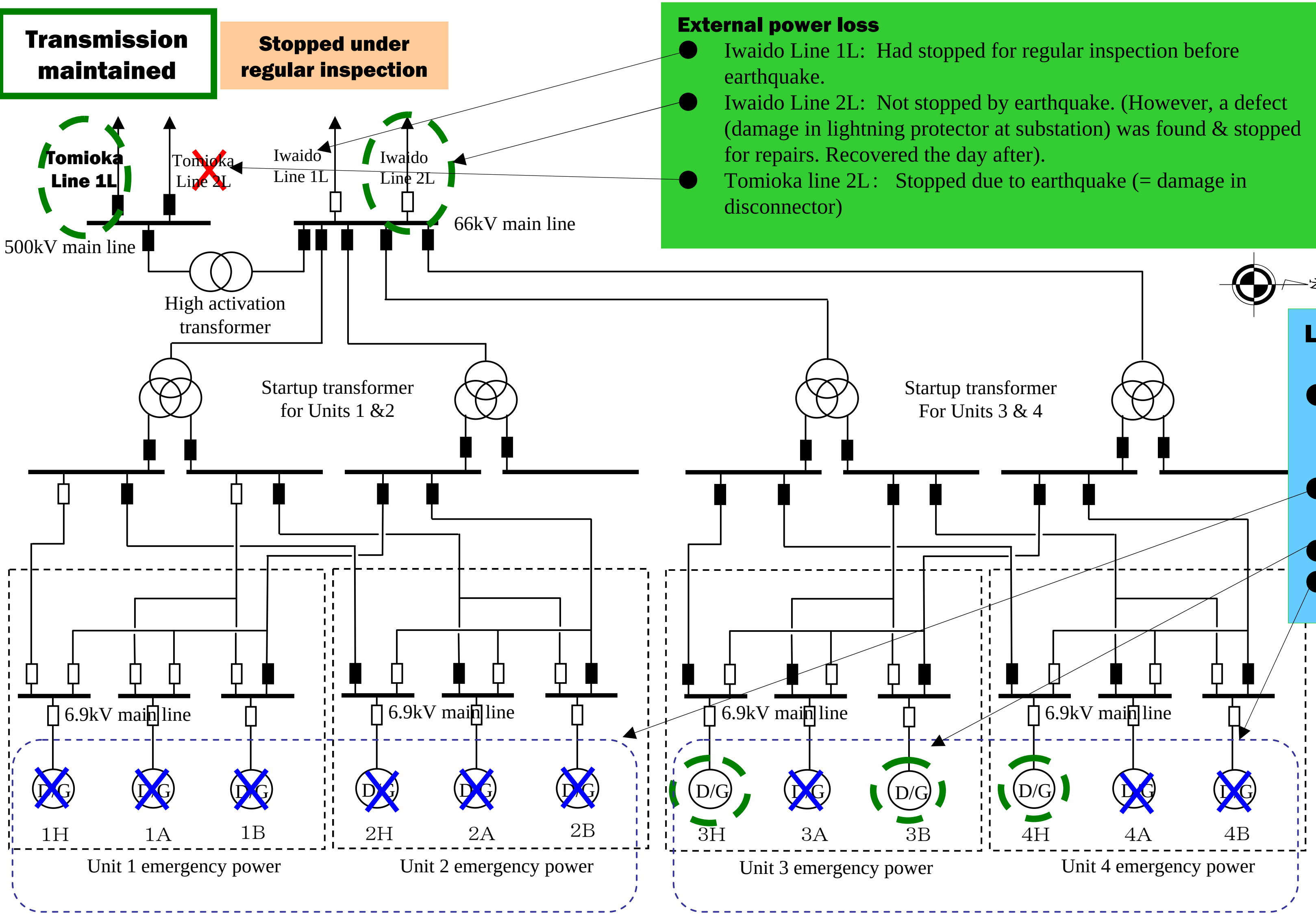
- Fukushima Dai-ni usually receives power from Shin-Fukushima substation, 8 km away from the plant.

Power supply from the substation => 3 out of 4 lines were down due to earthquake

- Facilities such as breakers were damaged by strong seismic motion at Shin Fukushima substation.
- 2 out of 4 transmission lines* to Dai-ni Units 1-4 were stopped.
(*: 2 lines of 1 systems (500 kV), and 2 lines of 1 system (66kV)).

  (1 line (66kV) already on halt before earthquake).

Loss of external and internal power after tsunami: At Fukushima Dai-ni, 1 external power line and 3 internal power lines (emergency DG) survived.



External power loss

- Iwaido Line 1L: Had stopped for regular inspection before earthquake.
- Iwaido Line 2L: Not stopped by earthquake. (However, a defect (damage in lightning protector at substation) was found & stopped for repairs. Recovered the day after).
- Tomioka line 2L : Stopped due to earthquake (= damage in disconnector)

Loss of emergency DG

- 3 emergency DG's were placed in each unit.
- Units 1&2: All lost due to tsunami.
- Unit 3: 1 unit lost, 2 sound.
- Unit 4: 2 lost, 1 sound.

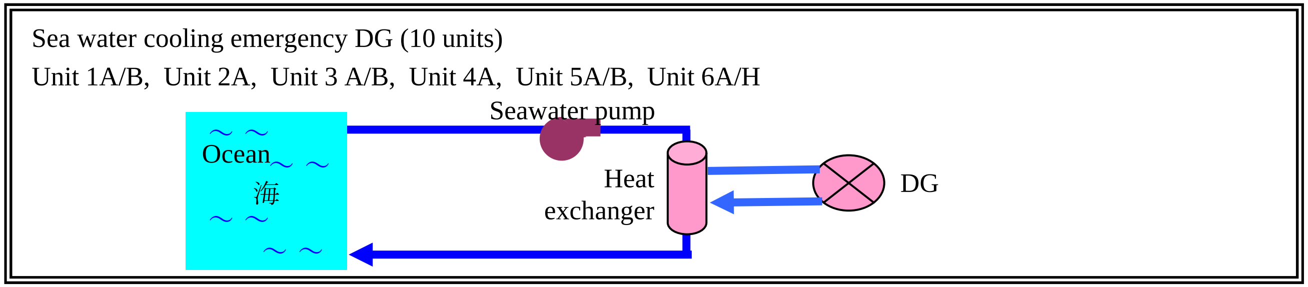
✗ : Stopped due to earthquake

✗ : Stopped due to tsunami

○ : Active after tsunami

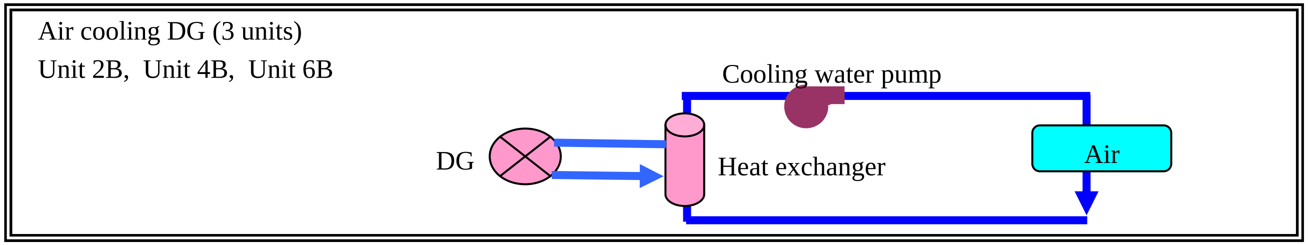
Emergency DG: 3 out of 12 emergency DG survived at Fukushima Dai-ni. At Dai-ichi, all but one at Unit 6 were lost.

Fukushima Dai-ichi: DG systems


Sea water cooling emergency DG (10 units)

Unit 1A/B, Unit 2A, Unit 3 A/B, Unit 4A, Unit 5A/B, Unit 6A/H

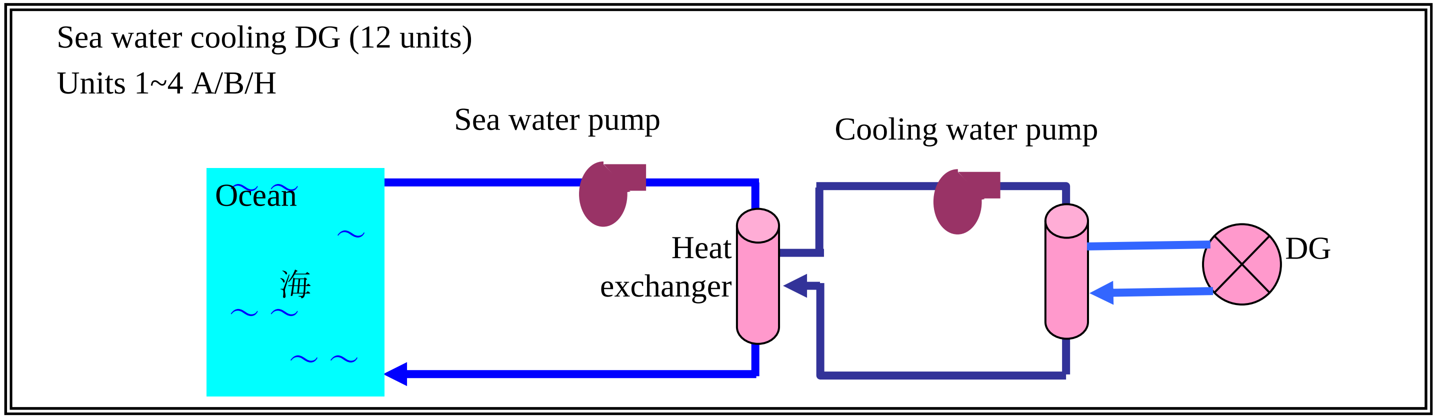
All units lost their functions after tsunami


Air cooling DG (3 units)

Unit 2B, Unit 4B, Unit 6B

Only Unit 6B functioned.

Fukushima Dai-ni: DG systems


Sea water cooling DG (12 units)

Units 1~4 A/B/H

Only Unit 3B, 3H and Unit 4H functioned.

If the cooling system for DG is lost, the entire DG system would be lost even though DG itself is active.

Loss of power other than external power: At Fukushima Dai-ni, as the flooding damage to reactor/turbine buildings was limited, the damage to electrical panels (MC, PC), DC power, and seawater systems were less than that of Dai-ichi.

Loss of major power supply systems after tsunami

		Fukushima Dai-ichi											
		Unit 1		Unit 2		Unit 3		Unit 4		Unit 5		Unit 6	
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG1A	×	DG2A	×	DG3A	×	DG4A	×	DG5A(※2)	×	DG6A	×(※2)
		DG1B	×	DG2B (Air cooling)	×(※1)	DG3B	×	DG4B (Air cooling)	×(※1)	DG5B(※2)	×	DG6B (Air cooling)	○
												HPCS DG	×(※2)
M/C	Emergency	M/C 1C	×	M/C 2C	×	M/C 3C	×	M/C 4C	×	M/C 5C	×	M/C 6C	○
		M/C 1D	×	M/C 2D	×	M/C 3D	×	M/C 4D	×	M/C 5D	×	M/C 6D	○
				M/C 2E	×			M/C 4E	×			HPCS DG M/C	○
	Normal	M/C 1A	×	M/C 2A	×	M/C 3A	×	M/C 4A	×	M/C 5A	×	M/C 6A-1	×
												M/C 6A-2	×
		M/C 1B	×	M/C 2B	×	M/C 3B	×	M/C 4B	×	M/C 5B	×	M/C 6B-1	×
												M/C 6B-2	×
		M/C 1S	×	M/C 2SA	×	M/C 3SA	×			M/C 5SA-1	×		
										M/C 5SA-2	×		
				M/C 2SB	×	M/C 3SB	×			M/C 5SB-1	×		
										M/C 5SB-2	×		
P/C	Emergency	P/C 1C	×	P/C 2C	○	P/C 3C	×	P/C 4C	-	P/C 5C	×	P/C 6C	○
		P/C 1D	×	P/C 2D	○	P/C 3D	×	P/C 4D	○	P/C 5D	×	P/C 6D	○
				P/C 2E	×			P/C 4E	×			P/C 6E	○
	Normal	P/C 1A	×	P/C 2A	○	P/C 3A	×	P/C 4A	-	P/C 5A	×	P/C 6A-1	×
				P/C 2A-1	×					P/C 5A-1	○	P/C 6A-2	×
		P/C 1B	×	P/C 2B	○	P/C 3B	×	P/C 4B	○	P/C 5B	×	P/C 6B-1	×
										P/C 5B-1	○	P/C 6B-2	×
		P/C 1S	×			P/C 3SA	×			P/C 5SA	×		
										P/C 5SA-1	×		
				P/C 2SB	×	P/C 3SB	×			P/C 5SB	×		
DC power	125VDC A/B	DC125V main&transfer bus 1A	×	DC125V main&transfer bus 2A	×	DC125V main&transfer bus 3A	○	DC125V main&transfer bus 4A	×	DC125V main&transfer bus 5A	○	DC125V DIST CENTER 6A	○
		DC125V main&transfer bus 1B	×	DC125V main&transfer bus 2B	×	DC125V main&transfer bus 3B	○	DC125V main&transfer bus 4B	×	DC125V main line board 5B	○	DC125V DIST CENTER 6B	○
Sea water system	A	CCS A	×	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×
	B	CCS B	×	RHRS B	×	RHRS B	×	RHRS B	×	RHRS B	×	RHRS B	×
												HPCS DGSW	×

		Fukushima Dai-ni							
		Unit 1		Unit 2		Unit 3		Unit 4	
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG1A	×	DG2A	×(※2)	DG3A	×(※2)	DG4A	×(※2)
		DG1B	×	DG2B	×(※2)	DG3B	○	DG4B	×(※2)
		DG1H	×	DG2H	×(※2)	DG3H	○	DG4H	○
M/C	Emergency	M/C 1C	×	M/C 2C	○	M/C 3C	○	M/C 4C	○
		M/C 1D	○	M/C 2D	○	M/C 3D	○	M/C 4D	○
		M/C 1H	×	M/C 2H	○	M/C 3H	○	M/C 4H	○
	Normal	M/C 1A-1	○	M/C 2A-1	○	M/C 3A-1	○	M/C 4A-1	○
		M/C 1A-2	○	M/C 2A-2	○	M/C 3A-2	○	M/C 4A-2	○
		M/C 1B-1	○	M/C 2B-1	○	M/C 3B-1	○	M/C 4B-1	○
		M/C 1B-2	○	M/C 2B-2	○	M/C 3B-2	○	M/C 4B-2	○
		M/C 1SA-1	○			M/C 3SA-1	○		
		M/C 1SA-2	○			M/C 3SA-2	○		
		M/C 1SB-1	○			M/C 3SB-1	○		
		M/C 1SB-2	○			M/C 3SB-2	○		
P/C	Emergency	P/C 1C-1	×	P/C 2C-1	○	P/C 3C-1	○	P/C 4C-1	○
		P/C 1C-2	×	P/C 2C-2	×	P/C 3C-2	×	P/C 4C-2	×
		P/C 1D-1	○	P/C 2D-1	○	P/C 3D-1	○	P/C 4D-1	○
	Normal	P/C 1D-2	×	P/C 2D-2	×	P/C 3D-2	○	P/C 4D-2	×
		P/C 1A-1	○	P/C 2A-1	○	P/C 3A-1	○	P/C 4A-1	○
		P/C 1A-2	○	P/C 2A-2	○	P/C 3A-2	○	P/C 4A-2	○
		P/C 1B-1	○	P/C 2B-1	○	P/C 3B-1	○	P/C 4B-1	○
		P/C 1B-2	○	P/C 2B-2	○	P/C 3B-2	○	P/C 4B-2	○
		P/C 1SA	○			P/C 3SA	○		
		P/C 1SB	○			P/C 3SB	○		
DC power	125VDC A/B	DC125V main line boardA	○	DC125V main&transfer bus A	○	DC125V main&transfer bus A	○	DC125V main&transfer bus A	○
		DC125V main line board B	○	DC125V main&transfer bus B	○	DC125V main&transfer bus B	○	DC125V main&transfer bus B	○
Sea water system	A	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×
	B	RHRS B	×	RHRS B	×	RHRS B	○	RHRS B	×
		HPCSS	×	HPCSS	×	HPCSS	○	HPCSS	○

🟪 : Lost functions

🟨 : Unable to activate due to electrical board and/or cooling system were lost

🟧 : Incoming power was inaccessible due to the loss of electrical supply source

Chronology of Fukushima Dai-ni Unit 1 (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)**
(M9.0. 4th in recorded history)

- **14:48 Reactor automatically shutdown.** All control rods inserted. Main turbines automatically shut down. Core water level was low (L-3). 1 transmission system (500kV) stopped. External power secured with remaining 1 system.
- 15:00 Core sub criticality confirmed.

Loss of emergency equipments by tsunami

15:22 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 12~ 14.5m)

15:33 Water circulation pump (C) manually stopped.
15:34 Emergency DG (A), (B), (H) automatically activated => But stopped immediately due to tsunami.
15:36 MSIV all closed manually.
RCIC manually activated (for water injection to nuclear reactor).
15:40 After RCIC pump automatically stopped (core water level (L-8)),water level continuously maintained with RCIC.
15:55 Started core depressurization by SRV & continued hereafter.

Maintained core pressure & water level.

De-pressurized RPV.

Started core cooling.

- **17:35 Warning of 'dry-well (D/W) pressure is high'. => Automatic activation signal for ECCS pump transmitted.**

17:53 D/W cooling system manually activated.

3/12
0:00 Started water injection to the core by MUWC.
3:50 Started rapid core depressurization.
4:56 Rapid core depressurization completed.
4:58 RCIC manually stopped.
6:20 Cooling of suppression chamber (S/C) by MUWC using flammability control system (FCS).
7:10 Conducted D/W spray by MUWC (continued arbitrarily henceforth).
7:37 Conducted S/C spray by MUWC (continued arbitrarily henceforth).
7:45 Stopped S/C cooling by FCS cooling water (MUWC).
10:21 Started construction of PCV pressure resistance vent line.
18:30 Construction of the above vent line completed.

Restored power supply & emergency equipments.

Cold shutdown.

3/13
20:17 Activated RHRS (B) pump manually (power supplied through makeshift cable).
21:03 Activated RHRC (D) pump manual (power supplied through makeshift cable).

3/14
1:24 Activated RHR(B) pump manually (S/C cooling mode started).
1:44 Activated Emergency Equipment Cooling Water system (EECW) manually (power supplied by high-voltage power supply vehicle).
3:39 Started RHR(B) S/C spray mode.
10:05 Water injected to the core with RHR(B) LPCI mode.
10:15 Confirmed that S/C water temperature was below 100℃.
16:30 Started water injection to SFP by FWMUW.

17:00 Cold shutdown achieved.

Implications

- **Nuclear reactor automatically shutdown due to earthquake**
  - The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.
  - Since external power survived, normal/emergency power source were secured.
- **Due to submergence by Tsunami, emergency DG, emergency power, & sea water pump systems were lost.**
  - As the annex of reactor building & seawater heat exchange building were submerged, emergency power systems (M/C, P/C) became unavailable.
  - Emergency DG were active before Tsunami. After Tsunami, all emergency DG were lost, since all the Emergency Equipment Cooling Water pumps, DG units & cooling pumps were flooded & lost their functions.
- **Maintained core pressure & water level with SRV and RCIC.**
  - Regarding reactor pressure control, since water condenser was unusable because of the loss of water circulation pump (main steam could not be condensed), they closed all MSIV and depressurized the core by SRV (as defined in the AM manual).
  - With all MSIV closed, they manually activated RCIC to inject water to the core.
  - Since the pressure of RPV & S/C was reaching to the warning range, they rapidly de-pressurized the core by SRV, and prepared water injection by MUMC (i.e. prepare for low pressure cooling), then stopped RCIC.
- **Warning of high pressure in Dry Well.**
  - Warning was alerted as D/W pressure rose very high. This is because SRV was opened (i.e. main steam flew into S/C from core) and the loss of RHR (i.e. PCV residual heat could not be removed).
  - Automatic activation signal for ECCS pump was transmitted because of high pressure in D/W. As the cooling pumps for RHR (B,C) were lost, RHR(B,C) was stopped manually after automatic activation. Other ECCS pumps could not be activated.
- **Prepared to cool S/C & D/W of PCV as well as ventilation.**
  - For S/C cooling, they injected water to S/C through drain line from FCS cooling device, and sprayed water on to S/C & D/W by MUWC periodically.
  - Though they had structured the pressure resistance vent line to prepare for the rise in PCV pressure, it had not reached to 310 kPa (= maximum designed pressure of PCV).
- **Achieved cold shutdown with the recovery of emergency cooling pump systems.**
  - They recovered cooling function of RHR systems & emergency DG with power supply vehicles & makeshift cables which were supplied power from the external power line of the radioactive waste processing building. With RHR (B) activated manually, they started S/C cooling.
  - Using LPCI line of RHR (B) system and SRV, they cooled the core with the heat exchanger of RHR and achieved cold shutdown.

Chronology of Fukushima Dai-ni Unit 2 (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46

Earthquake occurred (Level 6+)
(M9.0. 4th in recorded history)

- **14:48 Reactor automatically shutdown.** All control rods inserted. Main turbines automatically shut down. Core water level was low (L-3). 1 transmission system (500kV) stopped. External power secured with remaining 1 system.
- 15:01 Core sub criticality confirmed.

Loss of emergency equipments by tsunami

15:22

Tsunami hit
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 12~ 14.5m)

15:34 Emergency DG (H) automatically activated => But stopped immediately due to tsunami.
15:34 MSIV all closed manually.
15:35 Activated RHR (B) manually. => 15:38 stopped.
Stopped circulation water pump ((C) manually, (A, B) automatically).
15:41 Emergency DG (A)(B) automatically activated. => Sopped immediately due to Tsunami.

Maintained core pressure & water level.

De-pressurized RPV.

Started core cooling.

15:41 Started core depressurization by SRV & continued hereafter.
15:43 RCIC manually activated (for water injection to nuclear reactor). Continued hereafter.
- **18:50 Warning of 'dry-well (D/W) pressure is high'. => Automatic activation signal for ECCS pump transmitted.**

20:02 D/W cooling system manually activated.

3/12

4:50 Started water injection to the core by MUWC.
4:53 RCIC automatically stopped (since core pressure went down).
6:30 Cooling of suppression chamber (S/C) by MUWC using flammability control system (FCS).
7:11 Conducted D/W spray by MUWC (continued arbitrarily henceforth).
7:35 Conducted S/C spray by MUWC (continued arbitrarily henceforth).
Activated RHR (B) manually. => Cooled S/C.
7:52 Stopped S/C cooling by FCS cooling water (MUWC).
10:33 Started construction of PCV pressure resistance vent line.
10:58 Construction of the above vent line completed.

Restored power supply & emergency equipments.

Cold shutdown.

3/14

3:20 Activated EECW (B) manually (power supplied through makeshift cable).
3:51 Activated RHRS (B) pump manually (power supplied through makeshift cable).
5:52 Activated RHRC (D) pump manual (power supplied through makeshift cable).
7:13 Activated RHR(B) pump manually (S/C cooling mode started).
7:50 Started RHR(B) S/C spray mode.
10:48 Water injected to the core with RHR(B) LPCI mode.
15:52 Confirmed that S/C water temperature was below 100℃.

18:00 Cold shutdown achieved.

Implications

● **Nuclear reactor automatically shutdown due to earthquake**
- The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.
- Since external power survived, normal/emergency power source were secured.

● **Due to submergence by Tsunami, emergency power & sea water pump systems were lost.**
- As the seawater heat exchange building was submerged, its emergency power systems (P/C) became unavailable.
- Emergency DG were active before Tsunami. However, all the Emergency Core Cooling System (ECCS) pump & emergency DG were lost, since all the Emergency Equipment Cooling Water (EECW) pumps were flooded & lost their functions with the seawater heat exchange building flooded.

● **Maintained core pressure & water level with SRV and RCIC.**
- Regarding reactor pressure control, since water condenser was unusable because of the loss of water circulation pump (main steam could not be condensed), they closed all MSIV and depressurized the core by SRV (as defined in the AM manual).
- With all MSIV closed, they manually activated RCIC to inject water to the core.
- As the core pressure dropped by SRV, RCIC stopped automatically. Then they changed to water injection by MUWC, following the AM manual.

● **Warning of high pressure in Dry Well.**
- Warning was alerted as D/W pressure rose very high. This is because SRV was opened (i.e. main steam flew into S/C from core) and the loss of RHR (i.e. PCV residual heat could not be removed).
- Automatic activation signal for ECCS pump was transmitted because of high pressure in D/W. As the EECW pumps were lost, the ECCS pumps were stopped manually.

● **Prepared to cool S/C & D/W of PCV as well as ventilation.**
- For S/C cooling, they injected water to S/C through drain line from FCS cooling device, and sprayed water on to S/C & D/W by MUWC periodically.
- Though they had structured the pressure resistance vent line to prepare for the rise in PCV pressure, it had not reached to 310 kPa (= maximum designed pressure of PCV).

● **Achieved cold shutdown with the recovery of emergency cooling pump systems.**
- They recovered cooling pump function of RHR (B) systems & emergency DG with power supply vehicles & makeshift cables, which were supplied power from the external power line in the radioactive waste processing building, as well as from the emergency power source in the heat exchange building at Unit 3. With RHR (B) activated manually, they started S/C cooling.
- Using LPCI line of RHR (B) system and SRV, they cooled the core with the heat exchanger of RHR and achieved cold shutdown.

Chronology of Fukushima Dai-ni Unit 3 (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)**
(M9.0. 4th in recorded history)

● **14:48 Reactor automatically shutdown.** All control rods inserted. Main turbines automatically shut down. Core water level was low (L-3). 1 transmission system (500kV) stopped. External power secured with remaining 1 system.

● 15:05 Core sub criticality confirmed.

Loss of emergency equipments (system-A) by tsunami

15:22 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 12~ 14.5m)

15:34 Stopped water circulation pump (C) manually.
15:35 Emergency DG (A), (B), (H) automatically activated. => DG (A) stopped immediately due to tsunami.
15:36 Activated RHR(B) manually. (Started S/C cooling).
15:37 Closed all MSIV manually.
15:38 Stopped water circulation pump (B) manually.
15:46 Started core depressurization with SRV & continued henceforth.

Maintained core pressure & water level.

De-pressurized RPV.

Started core cooling.

16:06 Activated RCIC manually (water injection to reactor). Water level adjustment continued.
16:48 Stopped water circulation pump (A) manually.

● **19:46 Warning of 'dry-well (D/W) pressure is high'. => Automatic activation signal for ECCS pump transmitted.**
=> As the RHRC(A,C), RHRS(A,C), EECW(A) pumps were not available, they switched off the automatic activation function of RHR(A,C) pump & LPCS pump in advance.
Then, they changed RHR(B) from S/C cooling mode to LPCI mode.

20:07 Switch RHR(B) from LPCI to S/C cooling mode.
20:12 Activated D/W cooling system automatically.
22:53 Started water injection to the core by MUWC.
23:11 Stopped RCIC manually (due to drop in nuclear reactor pressure).

Used power supply & emergency equipments (system-B).

Cold shutdown.

3/12
0:06 Started to construct the RHR(B) reactor shutdown cooling system (SHC).
1:23 RHR(B) manually stopped (to prepare for SHC mode).
2:39 RHR(B) manually activated (S/C cooling mode started).
2:41 RHR(B) S/C spray mode started.
7:59 RHR(B) manually stopped (stopped S/C cooling & spray mode).
9:37 RHR(B) manually activated (SHC mode started).
12:08 Started to structure PCV pressure resistant vent line.
12:13 The construction of the vent line above completed.

12:15 Cold shutdown achieved.

Implications

● **Nuclear reactor automatically shutdown due to earthquake**
- The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.
- Since external power survived, normal/emergency power source were secured.

● **Due to submergence by Tsunami, emergency power (A) & sea water pump systems (A) were lost.**
- Due to Tsunami, emergency power systems (some P/C) in the heat exchange building became unavailable.
- Emergency DG were active before Tsunami. However, the Emergency Core Cooling System (ECCS) (A) pump & emergency DG (A) were lost, since the Emergency Equipment Cooling Water (EECW) (A) pumps were lost with the seawater heat exchange building partially flooded,.

● **Maintained core pressure & water level with SRV and RCIC.**
- Regarding reactor pressure control, since water condenser was unusable because of the loss of water circulation pump (main steam could not be condensed), they closed all MSIV and depressurized the core by SRV (as defined in the AM manual).
- With all MSIV closed, they manually activated RCIC to inject water to the core.
- As the core pressure dropped by SRV, they prepared low-pressure cooling system, MUWC, at first. Then they stopped RCIC manually.

● **Warning of high pressure in Dry Well.**
- Warning was alerted as D/W pressure rose very high. This is because SRV was opened with main steam flowing into S/C.
- Automatic activation signal for ECCS pump was transmitted because of high pressure in D/W. As the EECW pumps (A) were lost, they had switched off its automatic activation function beforehand. The ECCS pumps (B) were cooling S/C normally.

● **Achieved cold shutdown.**
- Using Residual Heat Removal (RHR) pump (B), which was active, after setting up the SHC systems, they injected the water to the core & achieved cold shutdown.

Chronology of Fukushima Dai-ni Unit 4 (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6+)**
(M9.0. 4th in recorded history)

- **14:46 Reactor automatically shutdown.** All control rods inserted. Main turbines automatically shut down. Core water level was low (L-3). 1 transmission system (500kV) stopped. External power secured with remaining 1 system.
- 15:05 Core sub criticality confirmed.

Loss of emergency equipments by tsunami

15:22 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 12~ 14.5m)

15:33 Water circulation pump (C) manually stopped
15:34 Emergency DG (A)(B)(H) automatically started => DG (A)(B) stopped immediately due to tsunami.
15:35 Water circulation pumps (A)(B) automatically stopped.
15:36 All MSIV manually closed. RHR (B) manually activated => 15:41 automatically stopped.
15:37 RHR (A) manually activated => 15:38 manually stopped.
15:46 Core depressurization begun by SRV & pressure adjustment continued henceforth.
15:54 RCIC manually activated (Water injection to core) & continued.

Maintained core pressure & water level.

De-pressurized RPV.

Started core cooling.

- **19:02 Warning of 'dry-well (D/W) pressure is high'. => Automatic activation signal for ECCS pump transmitted.**

=> As RHRC(A,B,C,D), RHRS(A,B,C,D) & EECW(A,B) pumps were not usable, they switched off the automatic activation function of the ECCS pumps in advance.

19:14 D/W cooling system automatically activated.

3/12
0:16 RCIC automatically stopped (due to drop in core pressure drop). Started water injection to the core by MUWC begun.
7:23 Started S/C cooling by FCS cooling system (MUWP).
7:35 Conducted S/C spray by MUWC.
11:17 Switched water injection to the core from MUWC to HPCS.
11:44 Started to construct PCV pressure resistance vent line.
11:52 Construction of the line above completed.
13:48 Stopped core water injection by HPCS (hereafter, conducted as needed).

Restored power supply & emergency equipments.

Cold shutdown.

3/14
11:00 EECW(B) manually activated (powered from power supply vehicle).
13:07 RHRS(D) pump manually activated (powered through makeshift cable).
14:56 RHRC(B) pump manually activated (powered through makeshift cable).
15:42 RHR(B) manually activated (S/C cooling mode begun).
16:02 RHR(B) S/C spray mode begun
18:58 Injected water to the core with RHR(B)LPCI mode.

3/15
7:15 Cold shutdown achieved.

Implications

● **Nuclear reactor automatically shutdown due to earthquake**

- The reactor reacted (scrammed) to earthquake in accordance with the design. No major problems found.
- Since external power survived, normal/emergency power source were secured.

● **Due to submergence by Tsunami, emergency power & sea water pump systems were lost.**

- As the seawater heat exchange building was submerged, its emergency power systems (P/C) became unavailable.
- Emergency DG were active after core scram. However, emergency DG (A, B) were lost, since all the Emergency Equipment Cooling Water (EECW) pumps were lost their functions. Since emergency DG (H) was active, power source for core cooling was secured.

● **Maintained core pressure & water level with SRV and RCIC.**

- Regarding reactor pressure control, since water condenser was unusable because of the loss of water circulation pump (main steam could not be condensed), they closed all MSIV and depressurized the core by SRV (as defined in the AM manual).
- With all MSIV closed, they manually activated RCIC to inject water to the core.
- As the core pressure dropped by SRV, RCIC stopped automatically. Then they changed to water injection by MUWC, following the AM manual.

● **Warning of high pressure in Dry Well.**

- Warning was alerted as D/W pressure rose very high. This is because SRV was opened (i.e. main steam flew into S/C from core) and the loss of RHR (i.e. PCV residual heat could not be removed).
- Automatic activation signal for ECCS pump was transmitted because of high pressure in D/W. As the EECW pumps were lost, they had switched off its automatic activation function beforehand.

● **Prepared to cool S/C & D/W of PCV as well as ventilation.**

- For S/C cooling, they injected water to S/C through drain line from FCS cooling device, and sprayed water on to S/C by MUWC periodically.
- Though they had structured the pressure resistance vent line to prepare for the rise in PCV pressure, it had not reached to 310 kPa (= maximum designed pressure of PCV).

● **Achieved cold shutdown with the recovery of emergency cooling pump systems.**

- They recovered cooling system of RHR with makeshift cables, connected to the emergency power system in the seawater heat exchange building at Unit 3, as well as recovered cooling system of emergency DG with high voltage power supply vehicles. With RHR (B) activated manually, they started S/C cooling.
- Using LPCI line of RHR (B) system and SRV, they cooled the core with the heat exchanger of RHR and achieved cold shutdown.

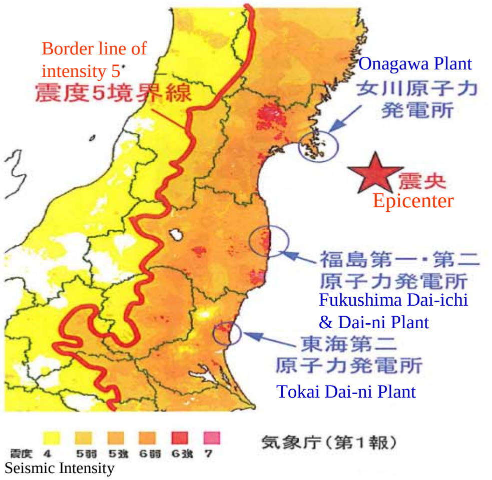
Other Plants
(Onagawa, Tokai Dai-ni Power Plant)

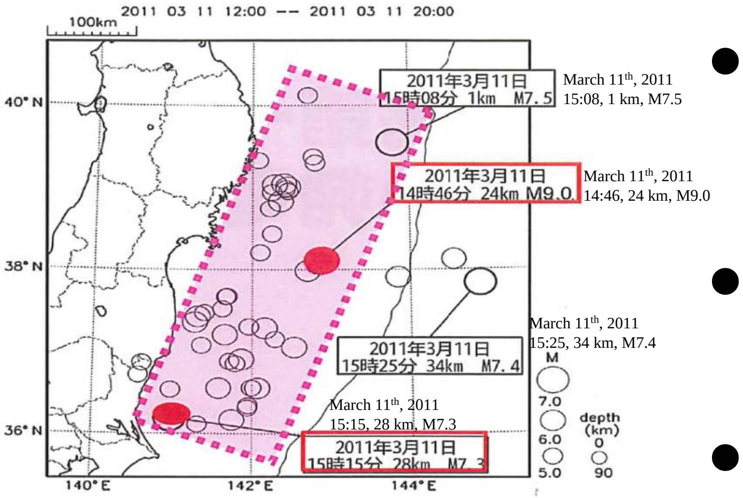
Chronologies and Issues

Location of earthquake and power plants are as below. The earthquake was around level 6 in all locations. Some locations in Dai-ichi and Onagawa have exceeded "Ss*".

(*: Ss = Standard seismic movement)

Tohoku Area Pacific Coast Earthquake: Data & Scale





(refer to JMA 5th report)

震源域はJNESで加筆

	Fukushima Dai-ichi	Fukushima Dai-ni	Onagawa	Tokai Dai-ni
Seismic Intensity	**6+** (Ohkuma town, Futaba town)	**6+** (Taruha town, Tomioka town)	**6-** (Onagawa town)	**6-** (Tokai town)
Maximum Acceleration	**550 gal** (East-west, Unit 2)	**305 gal** (Vertical, Unit 1)	**607 gal** (South-north, Unit 2)	**225 gal** (East-west)
Comparison to Ss	**Some periodic band had exceeded Ss.**	Below Ss.	**Some periodic band had exceeded Ss.** (March 11 & aftershock in April 7)	Below Ss.

- In terms of the distance from epicenter, Onagawa power plant is the closest. Following in order are Fukushima Dai-ichi, Dai-ni, and Tokai Dai-ni.
- Regarding the seismic intensity, all plants have recorded around level 6, and there are no major differences.
- Maximum acceleration of seismic motion at nuclear reactors: Onagawa was the largest with 607 gal. Followed by Fukushima Dai-ichi (500 gal). The smallest was Tokai Dai-ni (225 gal).
- Standard seismic movement (Ss): Some locations in Onagawa and Dai-ichi had exceeded Ss.

  - In some places at Onagawa, Ss were exceeded even in aftershocks of April 7th.

Damage of important facilities for reactor safety has not been found with this earthquake, but the fatal accident and damage did happen at some other facilities. At Onagawa, a fire at Unit 1 and shutdown of external access were reported.

< Major damage of facilities reported >

	Damage of facilities	Other damage
Fukushima Dai-ichi	▪ Unit 1: Air conditioning duct damaged. ▪ Unit 2: Leak of non-radioactive steam from electric boiler. ▪ Unit 5: Supports for moisture separator came off. Small-diameter pipe around the separator ruptured. ▪ Unit 6: Slide vestiges on low pressure turbine rotor. ▪ Fire protection pipe of transformer damaged. Water leakage from the connection pipe of pure water tank. ▪ Pumps & electrical boards for outside facilities damaged due to tsunami.	• No problem with access road that had been reinforced. • Heavy fuel oil tank and crane were drifted by tsunami, and blocked transportation.
Fukushima Dai-ni	• 4 cases of water leakage by sloshing (2 cases at unit 1, 2 cases at unit 2). • Unit 3: Overflow leakage of surge tank (Reactor building). 1 case. • Unit 4: Leak in turbine building. • 1 case of oil leak from electric transformer. • **Fatal accident of the tower crane operator** during anti-seismic construction at main exhaust stack. • 1 case of water leakage due to on-site bunker sloshing. • Unit 4: Crack of mother line of support leg’s connection duct in the main exhaust duct for ventilation & air conditioning system.	• No problem with access road.
Onagawa	• Unit 1: Collapse of heavy fuel tank (tsunami). **Fire from regular M/C** (Regulatory accident reports: 4 cases). • Light damage to main facilities: **61** cases • Light damage to non-major facilities that did not affect the core safety (565 cases): Falling of foreign material into SFP, and tumbling of drum cans with miscellaneous radioactive solid waste, etc.	• With 3 access roads to the plant, there was 1 place that causes a bottleneck, and **landslide occurred** there. • Took **4 days to recover with heavy machineries.** • Due to **a lack of food for 4 days, food was brought in by helicopter** (researched by plant operator).
Tokai Dai-ni	• Automatic stoppage of DGSW (SC), stream overflow in 125V battery room (Regulatory accident reports: 2 cases). • 139 cases of light damage (**sloshing of spent fuel pool**, etc)	• No problem with access road.

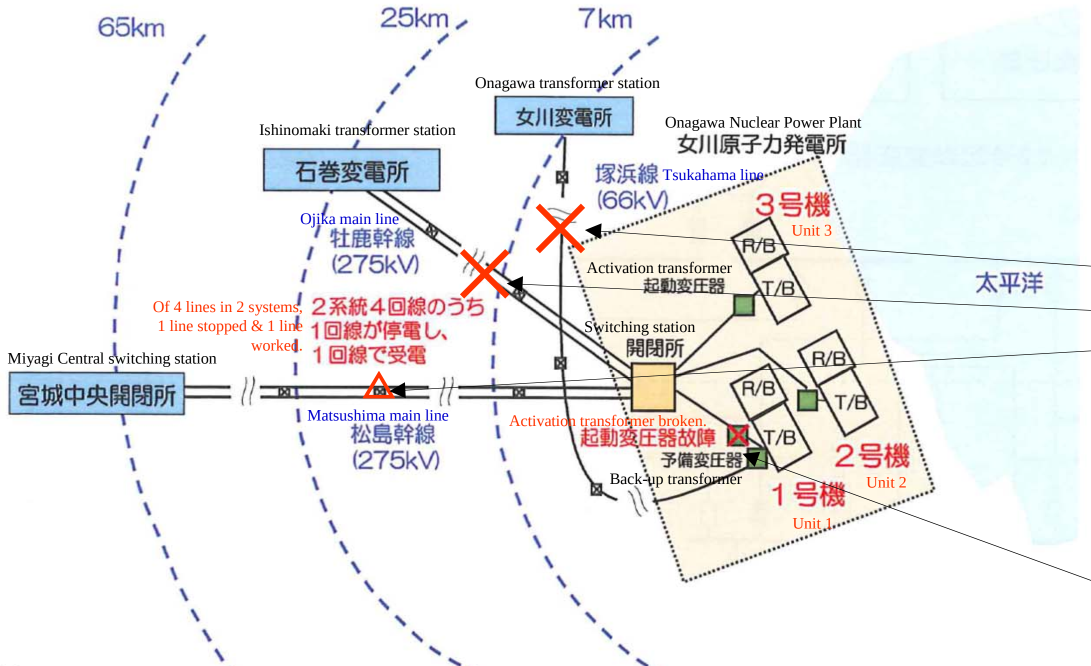
Loss of power: External power was so vulnerable to earthquakes that all but two lines, each at Dai-ni and Onagawa, were lost. Even one power source had made a life-or-death difference in accident progression between Fukushima Dai-ichi and others, whether it was external or emergency.

- **External power source is vulnerable to earthquake.**
  - Not only Dai-ichi, but other plants had lost almost all external power.
- **Even one emergency DG made a huge difference.**
  - Dai-ichi had lost all external and emergency power except for one DG at Unit 6, and lost core cooling function.
  - Other plants had achieved cold shutdown as at least one of either external or emergency power survived.
- **Emergency DG at Dai-ichi is especially vulnerable.**
  - At Dai-ichi emergency DG for Units 1-4 are located on the sea side (of TB building), and their cooling systems were placed outside on the coast.
  - Because of the location, all functions were lost due to tsunami.

	Fukushima Dai-ichi	Fukushima Dai-ni	Onagawa	Tokai Dai-ni	**Status of Dai-ni, Onagawa, & Tokai Dai-ni**
External Power	**All lost.** **(of 6 lines)**	**1 line active.** (of 4 lines)	**1 line active.** (of 5 lines)	**All lost.** (of 3 lines)	AC power (or emergency DG) was active. => Core cooling was possible.
Emergency DG	**Unit 1-5: all lost.** Unit 6: OK (1 unit. Air cooling). **Lost (2 units**. Water cooling).	Unit 1: **all lost**. Unit 2: **all lost**. Unit 3: 2/3 OK. Unit 4: 1/3 OK.	Unit 1: all OK. Unit 2: 1/3 OK. Unit 3: all OK.	2/3 OK.	
(Location)	Turbine Building (Sea side)	Reactor Building (Mountain side)	Reactor Building (Mountain side)	Reactor Building (Mountain side)	Emergency DG was located in the reactor building.
Seawater Pump System	**All submerged.**	Partially submerged.	Partially submerged.	Partially submerged.	Some seawater pumps survived.
(Location)	Outside of the building.	In the building.	In the building (partially outside).	Outside of the building.	No big difference. (Tsunami height at Dai-ichi was huge.)
Equipments procured for power supply	**Power supply vehicle.** **(Couldn't use due to Tsunami & explosions)**	Power supply vehicles (partially used).	As external power or emergency DG survived, power supply vehicles were not necessary.		

Looking at an overview of power loss at other plants, they were not particularly safer than Dai-ichi, and faced the same risk of the extreme accident as Dai-ichi.

Damage to external power: 4 out of 5 external power lines were lost due to the damage to switching and transformer substations by the earthquake. On-site star-up transformer was also damaged.



出典： Overview of major facilities, Tohoku Electric Power Company (HP)
東北電力 概要 主要設備(東北電力HP)
http://www.tohoku-epco.co.jp/comp/gaiyo/gaiyo_data/setubi.html
地震発生による原子力発電所の状況について(第1報)（平成23年 3月11日 東北電力女川発電所）
http://www.tohoku-epco.co.jp/emergency/8/1182594_1800.html
Status of nuclear power plant after earthquake (1st report) (March, 11, 2011 Tohoku Onagawa Nuclear Power Plant)

Transmission from transformer stations
=> 4 out of 5 lines lost due to earthquake

- Ishinomaki transformer station, Onagawa transformer station, & Miyagi Central switching station had system accidents due to strong earthquake.
  (= accident of system protection line by the transmission accident of Tohoku Electric Power Company)
- Tsukahama main line (66kV1): Stopped.
- Oshika main line (275kV) (2 lines): Both Stopped.
- Matsushima main line (275kV) (2 lines): Unit 1 stopped. Unit 2 survived.

On-site incoming facility => Activation transformer at Unit 1 malfunctioned.

- On-site incoming facility: Activation transformer of Unit 1 tripped, and unable to receive power. (= Due to short circuit earth fault caused by earthquake).
- The activation transformer was recovered on March 12th. The plant had switched to receive the regular external power (275kV1).

Chronology of Onagawa Nuclear Power Plant Unit 1 (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6-)**
(M9.0. 4th in recorded history)

- 14:46 Due to the vertical earthquake acceleration, **the reactor automatically shut down.**

14:47 All control rods were fully inserted. Automatic shutdown of main turbine.
Reactor water level was low (L-3).
Emergency DG (A)(B) automatically activated (non-loaded operation).
FPC pump (A) automatically stopped.
Water circulation pump (B), condenser pump (B), & reactor water supply pump (A) were all automatically stopped.

14:55 Transformer for activation was damaged and stopped (due to excess relay current).
Emergency DG (A), (B) begun.
Water circulation pump (A), condensing pump (C), nuclear reactor water supply pump (B), turbine-driven auxiliary seawater cooling pump (A,C) were all automatically stopped (power outage).

Electrical board caught fire due to earthquake.

External power lost.

Emergency DG activated

- **14:57 Fire alarm generated**

14:59 RCIC manually activated.
15:00~01 RHR pump (A) (C) manually activated. => Cooling of S/C begun.
15:02 All MSIV closed manually (as water condenser was unusable).

- **15：05 Sub criticality of reactor confirmed.**

15:05~12 RHR pump (B) (D) manually activated. => Cooling of S/C begun.

15:29 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 13m)

No problem with seawater pump system for cooling.

Core de-pressurization.

Maintained core water level.

Cold shutdown with emergency LP pump.

17:10 Core de-pressurization begun by SRV

18:29 RCIC pump automatically stopped (core water level high (L-8)).
19:30~ FPC pump A manually activated (for SFP cooling).
20:20 CRD pump A manually activated (for water supply to reactor).
21:56 RHR pump A manually stopped (to prepare for shutdown cooling (SHC)).
23:46 RHR pump A manually activated (SHC mode).

3/12 **0:58 Cold shutdown achieved**

Implications

- **As external power was lost due to earthquake, emergency DG started to generate power.**
  - The nuclear reactor behaved (scrammed) after earthquake in accordance with the design. No major problems found.
  - Due to loss of regular power, all pumps for water supply & condenser system were stopped. Following the AM manual, they activated RCIC and secured the water supply to the core.
  - Emergency DG was activated by the low voltage generated when the external power supply was switched from regular line to back-up line within the plant.
  - It is assumed that a fire alarm was on by the arc discharge, due to the short circuit & earth fault occurred when regular power supply system was damaged by the earthquake.
  - As the over-current relay of activation transformer was activated by the fire, the transformer was tripped. This trip activated the emergency DG.
  - As the condenser pump was lost, they closed MSIV and de-pressurized the core, in accordance with the AM manual.
  - FPC pump (A) was automatically stopped, because the level switch for 'skimmer surge tank' was activated by the seismic motion, or the intake pressure of SFP pump dropped when the water level in the pool went down temporarily by sloshing.

- **Core depressurization by Safety Relief Valve (SRV).**
  - They opened SRV and released the steam to S/C.
  - After RCIC pump was stopped, they supplied water to the core by CRD pump.
  - Regarding core cooling operation, it was done by RHR system in accordance with the AM manual. No problems found.
  - Having inspected the FPC pump (A) after earthquake and confirmed as normal, they re-activated the FPC and started cooling the SFP. During this stop of FPC, there was no significant rise in water temperature of the pool.

- **Cold shutdown achieved.**
  - With RHR system, cold shutdown was achieved.

Chronology of Onagawa Unit 2 (The plant was under 11th regular inspection and had been activated just before the earthquake.)

Events

Emergency shutdown of the reactor

3/11

14:00 Started to pulling out the fuel rods.

14:46 **Earthquake occurred (Level 6-)**
(M9.0. 4th in recorded history)

● **14:46 Nuclear reactor automatically shut down due to the horizontal acceleration of seismic motion.**

14:47 All control rods were inserted.
Emergency DG (A) (B)(H) automatically activated.
FPC pump (B) automatically stopped.

14:49 Reactor mode switch was changed from 'activated' to 'stopped'. (shutdown cooling).

2 seawater pumps & 2 DG were lost due to tsunami.

15:29 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 13m)

15:34 RCW pump (B)(D) automatically stopped (as the pump submerged).
15:35 Emergency DG (B) automatically stopped (as RCW pump stopped).
15:41 HPCW pump automatically stopped (as the pump submerged).
15:35 Emergency DG (H) automatically stopped (as HPCW pump stopped).
20:29 FPC pump (A) manually activated (to cool SFP).

Maintained shutdown cooling mode with 1 sea water pump & 1 DG.

3/12

4:49 Reset the nuclear reactor scram.
12:12 RHR pump (A) manually activated (SHC mode)
=> shutdown cooling maintained.

Implications

● **As the earthquake occurred when the reactor was being activated, it was already in shutdown cooling condition.**

- The nuclear reactor behaved (scrammed) after earthquake in accordance with the design. No major problems found.
- As the reactor was under sub-critical condition with water temperature below100℃ at the time of earthquake, 'shutdown cooling' status was brought about by mode switching.
- As the generator signaled for 'magnetic loss' due to the seismic motion, emergency DG(A) (B) (H) were automatically activated and became standby condition without power generation.
- FPC pump was automatically stopped, because the level switch for 'skimmer surge tank' was activated by the seismic motion, or the intake pressure of SFP pump dropped when the water level in the pool went down temporarily by sloshing.

● **Due to submergence from tsunami, RCW pump (B) was stopped.**

- The sea water flowed into the reactor building, through the penetration of the water gauge for automatic stop of circulation pump in the seawater pump room. Due to this flooding, RCW (B,D) pump and HPCW pump were disabled. As the coolant water was lost due to this stoppage, emergency DG (B) (H) were automatically halted.
- As RCW(A) system was sound, emergency DG (A) continued to operate and the reactor cooling function was secured. The cooling function of SFP was also secured by FPC pump (A).

Chronology of Onagawa Unit 3 (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6-)**
(M9.0. 4th in recorded history)

● **14:46 Nuclear reactor automatically stopped due to vertical acceleration of seismic motion.**

14:47 All control rods were inserted. Main turbines automatically stopped. FPC pump (B) automatically stopped.

● **14:57 Core sub criticality confirmed.**

15:22 Turbine building closed cooling water system (TSW) pump (A,C) automatically stopped (as pump submerged).

15:23 Water circulation pump (A, B) automatically stopped. FPC pump (A) manually activated.

15:25 MD-RFP (A,B), HPCP (A,B) manually stopped (as all TSW stopped).

15:26 Closed MSIV manually (as condenser being unusable). RCIC manually activated (to supply water to reactor).

15:28 RSW pump (D) manually activated. => Cooling of S/C.

Turbine-driven cooling system lost by Tsunami.

Started RCIC cooling.

15:29 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 13m)

15:30 RCW pump (B) manually activated. => Cooling of S/C. RHR(B) manually activated => Cooling of S/C.

15:36 Vacuum break of condenser (as condenser being unusable).

15:43 RSW pump (C) manually activated. => Cooling of S/C.

15:44 RHR(A) manually activated. => Cooling of S/C.

15:45 RCW pump (A) manually activated => Cooling of S/C.

Core de-pressurization.

Maintained core water level.

Cold shutdown with emergency LP pump.

16:40~ Started core depressurization by SRV

16:40 RCIC pump stopped (core water level (L-8)).

16:57 RCIC manually activated (water supply to the core).

21:44 RHR pump A manually stopped (to prepare for SHC (flushing)).

21:45 RCIC manually stopped.

21:54 Water injection to the core by MUWC.

23:51 RHR pump (A) manually started (SHC mode).

3/12 **1:17 Cold shutdown achieved.**

Implications

● **Nuclear reactor automatically shutdown due to earthquake.**

- The nuclear reactor behaved (scrammed) after earthquake in accordance with the design. No major problems found.
- Both regular power & all emergency DG were secured.
- FPC pump was automatically stopped, because the level switch for ‘skimmer surge tank’ was activated by the seismic motion, or the intake pressure of SFP pump dropped when the water level in the pool went down temporarily by sloshing.

● **As seawater pump for turbine cooling was lost by Tsunami, coolant water was supplied by RCIC.**

- As the signal for extremely low water level in the seawater pump room was generated, water circulation pump stopped. Furthermore, seawater flooded into the seawater pump room of heat exchanger building, causing TSW pump to stop.
- As the coolant water supply was gone, they manually activated RCIC and continued to supply water to the core.

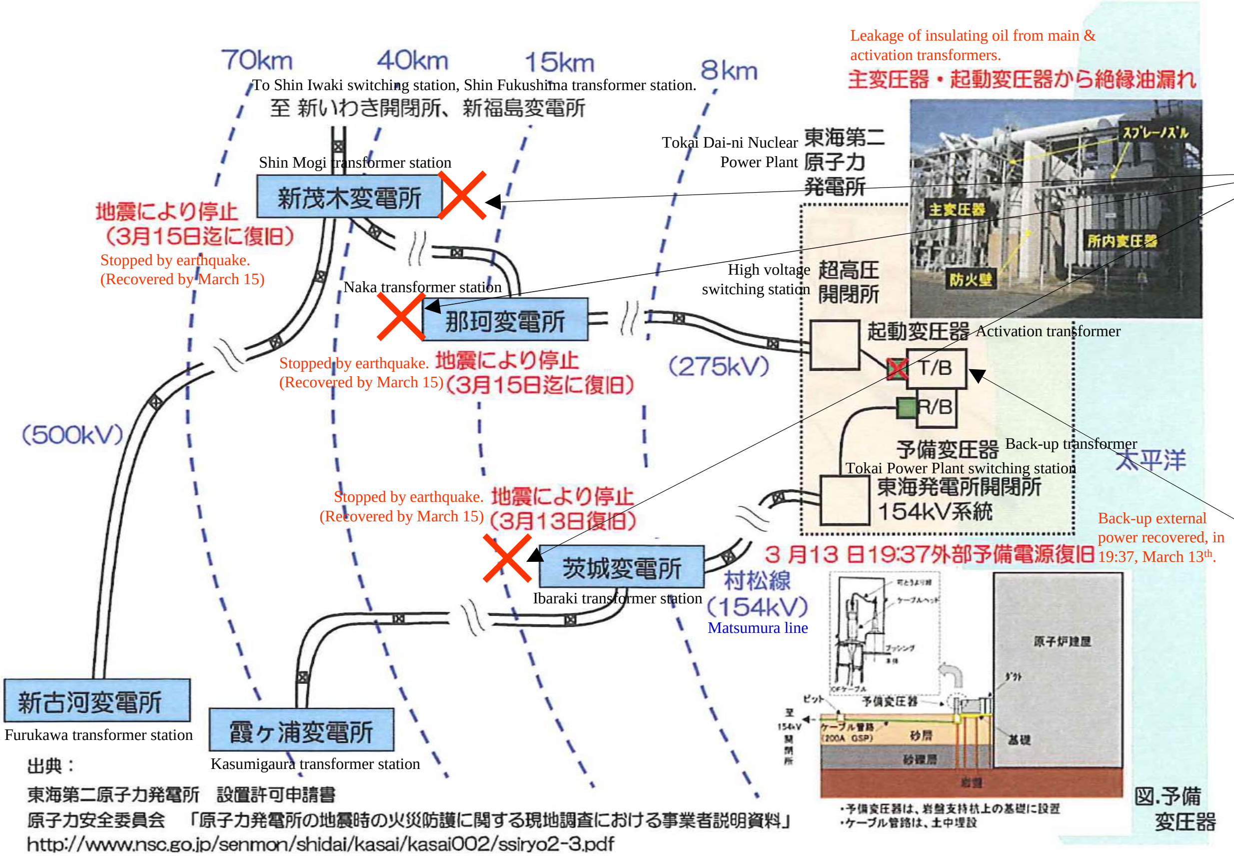
● **Core depressurization by safety relief valve.**

- As condenser became unusable due to stoppage of water circulator pump, following the AM manual, they closed all MSIV and depressurized the core by SRV.
- After RCIC pump was stopped, they supplied water to the core, using make-up water system (MUWC).
- They activated residual heat removal (RHR) system manually, and started cooling with SHC mode.

● **Cold shutdown achieved.**

- With RHR system operation, cold shutdown was achieved.

Damage to external power: As Naka and Ibaraki transformer stations stopped by strong seismic motion, all the external power was lost. Insulating oil was leaked from transformer in the plant.



Leakage of insulating oil from main & activation transformers.

主変圧器・起動変圧器から絶縁油漏れ

地震により停止
（3月15日迄に復旧）
Stopped by earthquake.
(Recovered by March 15)

Stopped by earthquake. 地震により停止
(Recovered by March 15)（3月15日迄に復旧）

Stopped by earthquake. 地震により停止
(Recovered by March 15)（3月13日復旧）

３月13 日19:37外部予備電源復旧

Back-up external power recovered, in 19:37, March 13th.

出典：
東海第二原子力発電所　設置許可申請書
原子力安全委員会　「原子力発電所の地震時の火災防護に関する現地調査における事業者説明資料」
http://www.nsc.go.jp/senmon/shidai/kasai/kasai002/ssiryo2-3.pdf
Tokai Dai-ni Nuclear Power Plant, application for construction permission.
Nuclear Safety Committee, ‘Report of power company on fire protection at nuclear power plant in case of earthquake’.

Transmission from transformer station
=> All stopped due to earthquake.

- As Naha and Ibaraki transformer stations were stopped due to strong seismic motion, all the transmission lines were stopped.

Incoming facilities on-site
=> Insulation oil leaked from main & activation transformer

- Of the incoming power facilities, insulating oil was leaked from main transformer and activation transformer.
- On March 13th: External backup power (154kV, 1 system, 1 line) was recovered.
- On March 18th: Switched to external regular power line (275kV, 1 system 1 line), and regular power systems recovered.

Chronology of Tokai Dai-ni (Before earthquake: regular operation)

Events

Emergency shutdown of the reactor

3/11 14:46 **Earthquake occurred (Level 6-)**
(M9.0. 4th in recorded history)

- **14:48 Nuclear reactor automatically stopped due to turbine trip (large seismic motion).**
- **All external power lost =>** Emergency DG automatically activated. => Emergency power secured.
  RCIC & HPCS automatically activated => then stopped (water level = high).

15:01 RHR pump (A) activated. => Cooling of S/C begun.

- **15:10 Core sub criticality confirmed.**

1 emergency DG lost due to tsunami

15:32 **Tsunami hit**
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 3m)

15:36 Started maintaining water level by RCIC.
16:40 RHR pump (B) activated. => Cooling of S/C begun.

- **19:01 Seawater pump for emergency DG stopped automatically.**

19:21 RHR pump (A), RHRS pump (A,C) stopped.
19:25 Emergency DG (2C) stopped. => Main emergency power line (2C) lost.

Transition to cold shutdown through core depressurization & RHR.

21:52 Started core depressurization by SRV

3/12 13:11 RCIC pump manually stopped. => Switched to HPCS for maintaining core water level.

3/13

- **19:37 Backup external power recovered. => Incoming power to emergency main line (2C) recovered.**

3/14 3:50 RHR pump A started. => Cooling of S/C begun.
23:43 RHR pump A started. => Started shutdown cooling mode (core water temperature: 117℃).

3/15 **0:40 Cold shutdown achieved.**

(core water temperature: 99.8℃. Core pressure: atmospheric pressure)
2:26 RHR pump B stopped. => Cooling of S/C stopped.
2:49 Emergency DG (2D) stopped.
4:09 HPCS pump stopped.
4:19 DG for HPCS system stopped.

Recovery of external power.

3/17

- **15:47 Regular external power recovered. => switched from backup power.**

Implications

● **All external power was lost due to earthquake.**

- The nuclear reactor behaved (scrammed) after earthquake in accordance with the design. No major problems found.
- Automatic startup of emergency DG by the scram was in accordance with the design, and the emergency power was secured.

● **1 emergency DG system was lost due to submergence of tsunami.**

- With tsunami re-evaluation on Sumatra Earthquake (March, 2007), the assumed height of tsunami was raised by 1m. Following this, the safety measure to seawater pump for emergency DG was raised to 6.11m from 4.91m.
- The tsunami did not reach the newly erected floodgate, but flooded into the gate through a ground cable tray that was being dug for fortification, then flowed into the seawater pump pit. The pit was submerged up to 2m, and 2 seawater pumps for emergency DG located below, were totally submerged, and stopped.
- Because of that, emergency DG (2C) was stopped manually. The emergency DG (2D) and DG for HPCS system was working and power was secured. However, if all 3 seawater pumps for DG were submerged, the entire power source could have been lost, as all the external power had been already lost by earthquake.
- Underground cable pit that had been submerged goes through the newly erected floodgate. Normally it is sealed and a tsunami of this height would not have flooded into the gate.

● **Core depressurization by safety relief valve (SRV).**

- They opened SRV for core depressurization, and the steam was released into the suppression chamber (S/C).
- They stopped RCIC pump manually, and transitioned to water level adjustment with HPCS.
- After that, as backup external power was recovered, the emergency main line (2C), that had been lost due to the loss of DG, started receiving power again.
- With incoming power to emergency main line 2C, the RHR system was started manually to cool the reactor.

● **Cold shutdown achieved.**

- With recovery of RHR system, cold shutdown had been achieved within a short time.

Loss of power other than external power: Compared to Dai-ichi, the loss of emergency DG, electrical panels & DC power were less serious in Onagawa, Higashi-Dori, & Tokai Dai-ni, where the submergence was small. This had become a lifeline.

Loss of electrical facilities & sea water systems after tsunami

		Onagawa (Tohoku Electric Power Co)						Tokai Dai-ni	
		Unit 1		Unit 2		Unit 3			
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG A	○	DG A	○ (non-lead standby)	DG A	○ (standby)	DG2C (※ 2)	×Sea water pump stopped (DGS)
		DG B	○	DG B (※ 2)	× Sea water pump stopped	DG B	○ (standby)	DG2D	○
				HPCS D/G (※ 2)	×Sea water pump stopped	HPCS D/G	○ (standby)	DG2H	○
M／C	Emergency	M／C6－1C	○	M／C6－2C	○	M／C6－3C	○	M／C－2C	×
		M／C6－1D	○	M／C6－2D	○	M／C6－3D	○	M／C－2D	○
				M／C6－2H	○	M／C6－3H	○	M／C－HPCS	○
	Normal	M／C6－1A	×Damaged by earthquake	M／C6－2A	○	M／C6－3A	○	M／C－2A-1	×
		M／C6－1B	×	M／C6－2B	○	M／C6－3B	○	M／C－2A-2	×
		M／C6－1S	×	M／C6－2SA-1	○	M／C6－3SA-1	○		
		M／C6－1E	×	M／C6－2SB-1	○	M／C6－3SB-1	○	M／C－2B-1	×
				M／C6－2SA-2	○	M／C6－3SA-2	○	M／C－2B-2	×
				M／C6－2SB-2	○	M／C6－3SB-2	○		
								M／C－2E	×
P／C	Emergency	P/C 4-1C	○	P/C 4-2C	○	P/C 4-3C-1	○	P/C 2C	×
		P/C 4-1D	○	P/C 4-2D	○	P/C4- 3C-2	○	P/C 2D	○
						P/C 4-3D-1	○	P/C 2A	×
	Normal	P/C 4-1A	×	P/C 4-2A	○	P/C 4-3D-2	○	P/C 2B	×
		P/C 4-1B	×	P/C 4-2B	○	P/C 4-3A-1	○	P/C 2S	×
		P/C 4-1S	×	P/C 4-2SA	○	P/C 4-3A-2	○		
				P/C 4-2SB	○	P/C 4-3B-1	○		
						P/C 4-3B-2	○		
						P/C 4-3SA-1	○		
						P/C 4-3SB-1	○		
						P/C 4-3SA-2	○		
						P/C 4-3SB-2	○		
DC power	125VDC A/B	125VDC main&transfer bus 1A	○	125VDC main&transfer bus 2A	○	125VDC main&transfer bus 3A	○	DC125V main&transfer bus 2A	○
		125VDC main&transfer bus 1B	○	125VDC main&transfer bus 2B	○	125VDC main&transfer bus 3B	○	DC125V main&transfer bus 2B	○
Sea water system	A	RHRS A	○	RSW A	○	RSW A	○	RHRS A	×
	B	RHRS B	○	RSW B	× RCW/RSW submerged	RSW B	○	RHRS B	○
				HPSW	× HPCW submerged	HPSW	○	HPCS DGS	○

🟪 : Lost functions

🟨 : Unable to activate due to electrical board and/or cooling system were lost

🟧 : Incoming power was inaccessible due to the loss of electrical supply source

Loss of cooling function: Compared to Dai-ichi, functions of water injection to the core and cooling worked normally in other plants as at least one AC/DC power and sea water cooling system functioned.

● **Loss of DC power was fatal.**

- At Dai-ichi, as DC power was submerged or depleted, they could hardly inject water to the core.
- As a result, they could not conduct AM operations (high pressure cooling, depressurization, low pressure cooling).
- If DC batteries had not been submerged, they could have recharged the batteries from AC power.

● **Damage of sea side (sea water cooling system) by tsunami.**

- At Dai-ichi, the tsunami damage on the sea side was so enormous that the functions of the sea water pumps and emergency pumps were completely lost.
- The damage at other plants was small.

	Fukushima Dai-ichi	**Fukushima Dai-ni**	**Onagawa**	**Tokai Dai-ni**	**Comment on Dai-ni, Onagawa & Tokai Dai-ni**
Water Injection to Core	Though all AC power was lost, DC power partially survived in units 2 & 3, and the high pressure cooling (RCIC) was continued for a while. It stopped when batteries run out. The system line for low pressure cooling could not be reconstructed in time.	While RCIC and high pressure spray systems were working, they could set up the system line for low pressure cooling and maintain the core water level.			Water injection to the core had functioned.
Removal of Decay Heat	With no AC power and loss of auxiliary sea water systems by Tsunami, they could not release the decay heat to the ocean.	As the residual heat removal system (RHR) partially functioned, they could cool the core and release the decay heat to the ocean.			Seawater cooling and pump systems had functioned.
Cooling Water Source	Pure water (on-site) and sea water.	Pure water (on-site)			They could supply water from the existing source.
Equipments Prepared for Water Supply	Pump vehicle, makeshift hose (Took much time to connect).	Since AC power and core cooling systems had survived, it was not necessary to procure additional pumps for water injection.			

Process to cold shutdown: Since AC power (external or emergency DG), DC power, and seawater cooling functions were active at other plants, cold shutdown was achieved. At Fukushima Dai-ichi, these were all lost simultaneously.

	Fukushima Dai-ni Unit 1	Fukushima Dai-ni Unit 2	Fukushima Dai-ni Unit 3	Fukushima Dai-ni Unit 4	Onagawa Unit 1	Onagawa Unit 2	Onagawa Unit 3	Tokai Dai-ni Unit 2
Form	Mark 2 (BWR-5)	Improved Mark 2 (BWR-5)	Improved Mark 2 (BWR-5)	Improved Mark 2 (BWR-5)	Mark 1 (BWR-4)	Improved Mark 1 (BWR-5)	Improved Mark 1 (BWR-5)	Mark 2 (BWR-5)
	In operation	In operation	In operation	In operation	In operation	Under regular inspection, but activated just before the	In operation	In operation
External AC power	○(1/4 lines)	○(1/4 lines)	○(1/4 lines)	○(1/4 lines)	○(1/5 lines)	○(1/5 lines)	○(1/5 lines)	×
DC power (A),(B)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)
Emergency DG	×	×	○(2/3 units)	○(1/3 units)	○(2/2 units)	○(1/3 units)	○(3/3 units)	○(2/3 units)
Sea water system	×	×	○(2/3 systems)	○(1/3 systems)	○(2/2 systems)	○(1/3 systems)	○(3/3 systems)	○(2/3 systems)
2011/3/11	Earthquake occurred (14:46)	Earthquake occurred (14:46)	Earthquake occurred (14:46)	Earthquake occurred (14:46)	Earthquake occurred (14:46)	Earthquake occurred (14:46)	Earthquake occurred (14:46)	Earthquake occurred (14:46)
	Scram	Scram	Scram	Scram	Scram	Scram (Shutdown cooling)	Scram	Scram
					Fire started (Arc discharge in regular electrical panel 14:57)			
							RCIC manually activated (15:26)	
					RCIC manually activated (14:59)			
	Tsunami hit (1st wave : 15:22)	Tsunami hit (1st wave : 15:22)	Tsunami hit (1st wave : 15:22)	Tsunami hit (1st wave : 15:22)	Tsunami hit (around 15:29 Tide indicator at maximum water level)	Tsunami hit (around 15:29 Tide indicator at maximum water level)	Tsunami hit (around 15:29 Tide indicator at maximum water level)	Tsunami hit (1st wave : 15:32)
	RCIC activated (15:36)	**Core depressurized (SRV operation 15:41)**	**Core depressurized (SRV operation 15:46)**	**Core depressurized (SRV operation 15:46)**	**Core depressurized (SRV operation 17:10)**			**RCIC manually activated (15:36)**
	Core depressurized (SRV operation 15:55)	**RCIC activated (15:43)**	**RCIC activated (16:06)**	**RCIC activated (15:54)**	RCIC automatically stopped (18:29)		**Core depressurized (SRV operation approx. 16:40)**	**Core depressurized (SRV operation 21:52)**
	D/W cooling system activated (17:53)	D/W cooling system activated (20:02)	D/W cooling system activated (20:12)	D/W cooling system activated (19:14)	Spent fuel pool cooling (FPC pump manually activated 19:30)	Spent fuel pool cooling (FPC pump manually activated 20:29)	RCIC manually stopped (21:45)	
			Water injection begun (MUWC system 22:53)		Water injection to nuclear reactor begun (CRD pump manually activated 20:20)		Water injection to nuclear reactor begun (MUWC 21:54)	
			RCIC manually stopped (23:11)		**RHR pump manually activated (SHC mode 23:46)**		**RHR pump activated (SHC mode 23:51)**	
2011/3/12	Water injection begun (MUWC system 0:00)		RHR manually activated (SHC cooling mode 2:39)	RCIC automatically stopped (0:16) Water injection begun (MUWC	**Cold shutdown (0:58)**	Nuclear reactor scram/reset (4:49)	**Cold shutdown (1:17)**	
	Nuclear reactor rapid depressurization begun (3:50)	Water injection begun (MUWC system 4:50)	RHR S/C spray mode begun (2:41)	S/C cooling (from MUWC to FCS7:23)		**RHR pump manually activated (SHC mode 12:12)**		
	RCIC manually stopped (4:58)	RCIC manually stopped (4:53)	**RHR manually activated (SHC mode begun 9:37)**	S/C spray (MUWC system 7:35)		**Cold shutdown maintained (12:12～)**		
	S/C cooling (MUWC from FCS line 6:20)	S/C cooling (MUWP from FCS line 6:30)	PCV pressure resistant vent line structure completed (12:13)	Water injection to nuclear reactor (switch to HPCS 11:17)				RCIC manually stopped (13:11)
	S/C cooling stopped (MUWC 7:45)	S/C cooling stopped (MUWP 7:52)	**Cold shutdown (12:15)**	PCV pressure resistant vent line structure complete(11:52)				
	PCV pressure resistant vent line structure completed (18:30)	PCV pressure resistant vent line structure completed (10:58)		Nuclear reactor water injection stopped (HPCS 13:48)				
2011/3/13	RHRS, RHRC pump activated (incoming power from makeshift cable 20:17/21:03)							Supplemental external power recovered (19:37)
2011/3/14	Emergency auxiliary cooling system activated (EECW. Incoming power from makeshift power 1:44)	Emergency auxiliary cooling system activated (EECW. Incoming power from makeshift power 3:20)						RHR pump activated (S/C pool cooling begun 3:50)
				EECW manually activated (received power from supply vehicle 11:00)				
	Water injection to nuclear reactor begun (RHR LPCI mode 10:05)	**Water injection to nuclear reactor begun (RHR LPCI mode 10:48)**		RHR S/C spray mode begun (16:02)				
	Water injection to spent fuel pool begun (FPMUW system 16:30)			**Water injection to nuclear reactor begun (RHR LPCI mode 18:58)**				
	Cold shutdown (17:00)	**Cold shutdown (18:00)**						**RHR pump activated (Shutdown cooling mode 23:43)**
2011/3/15				**Cold shutdown (7:15)**				**Cold shutdown (0:40)**
2011/3/16								
2011/3/17								Switched to normal external power (15:47)

Facts and Issues of Major Functions

- Power Supply
- High Pressure Cooling System
- Ventilation System
- Low Pressure Cooling System
- Hydrogen Explosion

Long-term power outage (DC&AC) had occurred, while design philosophy assumed "in case of Station Blackout, AC power would be quickly restored, and DC will last for at least 8 hours".

	Fukushima Dai-ichi Reactor 1	Fukushima Dai-ichi Reactor 2	Fukushima Dai-ichi Reactor 3	Fukushima Dai-ichi Reactor 4	Fukushima Dai-ichi Reactors 5&6	Fukushima Dai-ni Reactors 1 – 4	Onagawa Reactors 1 - 3	Tokai Dai-ni
External AC power	× All 6 lines were lost from the earthquake					△ Only 1/4 lines worked	△ Only 1/5 lines worked	× All 2 lines lost from the earthquake
Backup diesel generator	× Lost all from the tsunami				△ Only 1/5 was working	△ ・Reactors 1 & 2: none worked ・Reactor 3: 2/3 Reactor 4: 1/3 worked	○ ・Reactor 1 & 3: all working ・Reactor 2: 1/3 working	○ ・2/3 working
DC power supply	× Lost all from the tsunami		○ 2/2 working	× Lost all from the tsunami	○ 4/4 working	○ 8/8 working	○ 6/6 working	○ 2/2 working
Power supply vehicle	× ・Reactor 2: Planned to use the power supply vehicle but it was destroyed by explosion in Reactor 1. ・Reactors 1, 3 and 4: Response was slow due to search for usable power panels and installing of cables to the available power panels.				○ Used to power sea-line pump	○ Power partially restored by power supply vehicle	— Not required since external power supply or emergency generator was working.	
Restoration of external power	× Not restored before the hydrogen explosion				× Not restored before cold shutdown	— At least one external power source was available right after the earthquake and Tsunami.		○ 154kV backup power restored on March 13 at 19:37.

Power loss lasted longer than expected in the design

At Fukushima Dai-ichi Reactor 1, complete loss of all cooling systems, due to total power loss, had rapidly led to core-meltdown. Core damage is estimated to have started 2 to 3 hours after Tsunami.

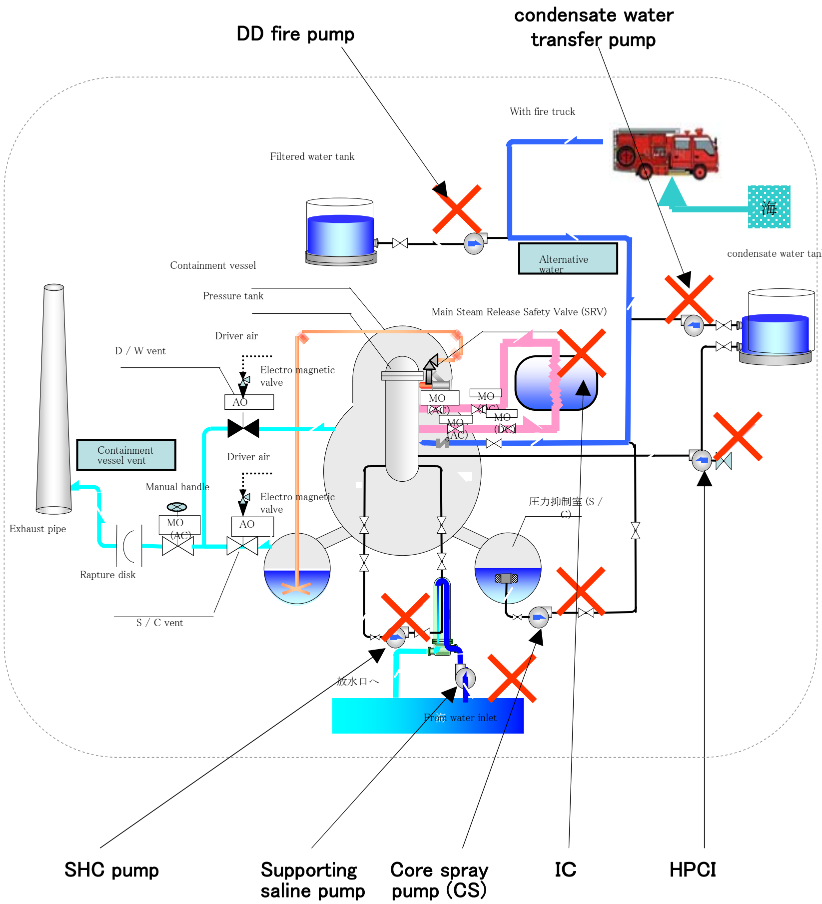
Loss of cooling system and occurrence of core meltdown

		Dai-ichi Reactor 1	Dai-ichi Reactor 2	Dai-ichi Reactor 3	Dai-ichi Reactor 4	Dai-ichi Reactor 5&6	Fukushima Dai-ni	Onagawa	Tokai Dai-ni
High Pressure Cooling	HPCI / HPCS	× Malfunction		× After DC power drained	– In cold shutdown		× Rctr 1&2: Flooded and lost. ○Rctr 3&4	× Rcr2 ○Rctr 1.3	○
	IC / RCIC	× Worked but later malfunctioned (Reactor 2: 3 days after)		× After DC power drained	– In cold shutdown		○	○ (to be verified)	
	SLC System	× Due to power loss				× Rctr 5 ○Rctr 6	○	○ (to be verified)	
	CRD System	× Due to power loss				× Rctr 5 ○Rctr6	○	○ (to be verified)	
Low Pressure Cooling	FP	× FP pump not working			× Power loss	× Rctr 5 ○Rctr 6	○	△ (to be verified)	
	MUWC / MUWP	× Power supply and motor flooded				○ Power supplied	○	○ (to be verified)	
LPCS seawater pump	CCSW / RSW / RHRS etc.	× Seawater cooling type power supply and motor flooded				△ RHR partially functioned, then restored	△ Lost except Rctr 3 (no power & motor)	○ Partially flooded	
Core damage start (Analysis)		**3 / 11 18:46**	**3 / 14 19:46**	**3 / 13 8:46**	On halt **Reactor 4 hydrogen explosion** (Backflow from Rctr 3)		Operating => cold shutdown		

Hydrogen Explosion
(or damage)

Core was damaged a few hours after the loss of cooling functions followed by exposure of fuel rods.

Fukushima Dai-ichi Reactor 1: Total loss of cooling function



- **Dai-ichi Reactor 1: All cooling functions were lost simultaneously.**
- **No other option but to supply water to the reactor with only one fire truck.**

Even with such a strong earthquake and tsunami, cold-shutdown could have been achieved if even a single emergency power supply were secured; Fukushima Dai-ichi (Rctrs 5 & 6), Tokai Dai-ni, Fukushima Dai-ni, etc.

These reactors lost almost all external power, but were able to achieve cold shutdown with the surviving (one or two) emergency generators. (Note: Frontline (RHR pump) has to be working as well)

	Fukushima Dai-ichi Reactor 1	Fukushima Dai-ichi Reactor 2	Fukushima Dai-ichi Reactor 3	Fukushima Dai-ichi Reactor 4	Fukushima Dai-ichi Reactors 5 & 6	Fukushima Dai-ni Reactors 1 - 4	Onagawa Reactors 1 - 3	Tokai Dai-ni
External AC power supply	× Lost all 6 lines from the earthquake					△ Only 1/4 lines Working	△ Only 1/5 working	× Both lines lost in earthquake
Emergency generator	× Lost all from the tsunami				△ Only 1/5 Working (flex)	△ ・Reactors 1 & 2: None working ・Rector 3: 2/3 working ・Reactor 4: 1/3 working	○ ・Reactors 1 & 3: all working ・Reactor 2: 1/3 working	○ 2/3 working
DC power supply (A type, B type)	× Lost all from the tsunami		○ 2/2 working	× Lost all from the tsunami	○ 4/4 working	○ 8/8 working	○ 6/6 working	○ 2/2 working
HPCS(IC/ RCIC, etc.)	× Malfunctioned after a while		× Stopped after DC power drained	– On halt		○	○ All working except Onagawa Reactor 2	
LPCS (MUWC/MUWP, etc.)	× Power outage				○ Shared power supply	○	○ (Needs to be verified)	
LPCS seawater pump (CCSW/RSW/RHRS, etc.)	× seawater power supply & motor flooded by tsunami					△ None working except Reactor 3: (power & motor flooded)	○ Partially flooded	○ Partially flooded

Core damage / Hydrogen explosion (or damage)

Cold shutdown achieved

(Continued…) Chronology to cold shutdown or hydrogen explosion.

Form	Fukushima Dai-ichi Unit 1 Mark 1 (BWR-3) In operation	Fukushima Dai-ichi Unit 2 Mark 1 (BWR-4) In operation	Fukushima Dai-ichi Unit 3 Mark 1 (BWR-4) In operation	Fukushima Dai-ichi Unit 4 Mark 1 (BWR-4) Stopped (Regular inspection)	Fukushima Dai-ichi Unit 5 Mark 1 (BWR-4) Stopped (Regular inspection. Fuel loaded)	Fukushima Dai-ichi Unit 6 Mark 2 (BWR-5) Stopped (Regular inspection. Fuel loaded)	Fukushima Dai-ni Unit 1 Mark 2 (BWR-5) In operation	Fukushima Dai-ni Unit 2 Improved Mark 2 (BWR-5) In operation	Fukushima Dai-ni Unit 3 Improved Mark 2 (BWR-5) In operation	Fukushima Dai-ni Unit 4 Improved Mark 2 (BWR-5) In operation	Onagawa Unit 1 Mark 1 (BWR-4) In operation	Onagawa Unit 2 Improved Mark 1 (BWR-5) Under regular inspection, but activated just before the	Onagawa Unit 3 Improved Mark 1 (BWR-5) In operation	Tokai Dai-ni Unit 2 Mark 2 (BWR-5) In operation
External AC power	×	×	×	×	×	×	○(1/4 lines)	○(1/4 lines)	○(1/4 lines)	○(1/4 lines)	○(1/5 lines)	○(1/5 lines)	○(1/5 lines)	×
DC power (A),(B)	×	×	○(2 systems)	×	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)
Emergency DG	×	×	×	×	×	○(1/3 units)	×	×	○(2/3 units)	○(1/3 units)	○(2/2 units)	○(1/3 units)	○(3/3 units)	○(2/3 units)
Sea water system	×	×	×	×	×	×	×	×	○(2/3 systems)	○(1/3 systems)	○(2/2 systems)	○(1/3 systems)	○(3/3 systems)	○(2/3 systems)
2011/3/11	Earthquake occurred (14:46) Scram IC activated (14:52) Tsunami hit (1st wave: 15:27／2nd wave: 15:35) Core damage begun (18:46). By simulation Large quantity of hydrogen generated/accumulated	Earthquake occurred (14:46) Scram RCIC activated (14:50) / stopped (15:28) Tsunami hit (1st wave: 15:27／2nd wave: 15:35) RCIC activated (15:39)	Earthquake occurred (14:46) Scram RCIC activated (15:05) / stopped (15:25) Tsunami hit (1st wave: 15:27／2nd wave: 15:35) RCIC activated (16:03)	Earthquake occurred (14:46) Tsunami hit (1st wave: 15:27／2nd wave: 15:35)	Earthquake occurred (14:46) Tsunami hit (1st wave: 15:27／2nd wave: 15:35)	Earthquake occurred (14:46) Tsunami hit (1st wave: 15:27／2nd wave: 15:35)	Earthquake occurred (14:46) Scram Tsunami hit (1st wave : 15:22) RCIC activated (15:36) Core depressurized (SRV operation 15:55) D/W cooling system activated (17:53)	Earthquake occurred (14:46) Scram Tsunami hit (1st wave : 15:22) Core depressurized (SRV operation 15:41) RCIC activated (15:43) D/W cooling system activated (20:02)	Earthquake occurred (14:46) Scram Tsunami hit (1st wave : 15:22) Core depressurized (SRV operation 15:46) RCIC activated (16:06) D/W cooling system activated (20:12) Water injection begun (MUWC system 22:53) RCIC manually stopped (23:11)	Earthquake occurred (14:46) Scram Tsunami hit (1st wave : 15:22) Core depressurized (SRV operation 15:46) RCIC activated (15:54) D/W cooling system activated (19:14)	Earthquake occurred (14:46) Scram Fire started (Arc discharge in regular electrical panel 14:57) RCIC manually activated (14:59) Tsunami hit (around 15:29 Tide indicator at maximum water level) Core depressurized (SRV operation 17:10) RCIC automatically stopped (18:29) Spent fuel pool cooling (FPC pump manually activated 19:30) Water injection to nuclear reactor begun (CRD pump manually activated 20:20) RHR pump manually activated (SHC mode 23:46)	Earthquake occurred (14:46) Scram (Shutdown cooling) Tsunami hit (around 15:29 Tide indicator at maximum water level) Spent fuel pool cooling (FPC pump manually activated 20:29)	Earthquake occurred (14:46) Scram RCIC manually activated (15:26) Tsunami hit (around 15:29 Tide indicator at maximum water level) Core depressurized (SRV operation approx. 16:40) RCIC manually stopped (21:45) Water injection to nuclear reactor begun (MUWC 21:54) RHR pump activated (SHC mode 23:51)	Earthquake occurred (14:46) Scram Tsunami hit (1st wave : 15:32) RCIC manually activated (15:36) Core depressurized (SRV operation 21:52)
2011/3/12	D/W pressure rise (to 0.84MPa 2:30) Hydrogen explosion(15:36)	Electrical supply vehicle damaged (15:36)	RCIC stopped (11:36) HPCI activated (12:35)		SRV automatically opened (core pressure 8MPa maintained 1:40) Top valve of reactor pressure vessel opened (6:06) Power supply begun from Unit 6 DG (DC recharge 8:13)	Power supply begun to Unit 5 (DC recharge 8:13)	Water injection begun (MUWC system 0:00) Nuclear reactor rapid depressurization begun (3:50) RCIC manually stopped (4:58) S/C cooling (MUWC from FCS line 6:20) S/C cooling stopped (MUWC 7:45) PCV pressure resistant vent line structure completed (18:30)	Water injection begun (MUWC system 4:50) RCIC manually stopped (4:53) S/C cooling (MUWP from FCS line 6:30) S/C cooling stopped (MUWP 7:52) PCV pressure resistant vent line structure completed (10:58)	RHR manually activated (SHC cooling mode 2:39) RHR S/C spray mode begun (2:41) RHR manually activated (SHC mode begun 9:37) PCV pressure resistant vent line structure completed (12:13) Cold shutdown (12:15)	RCIC automatically stopped (0:16) Water injection begun (MUWC S/C cooling (from MUWC to FCS7:23) S/C spray (MUWC system 7:35) Water injection to nuclear reactor (switch to HPCS 11:17) PCV pressure resistant vent line structure complete(11:52) Nuclear reactor water injection stopped (HPCS 13:48)	Cold shutdown (0:58)	Nuclear reactor scram/reset (4:49) RHR pump manually activated (SHC mode 12:12) Cold shutdown maintained (12:12〜)	Cold shutdown (1:17)	RCIC manually stopped (13:11) transition to HPCS
2011/3/13			HPCI stopped (2:42) Core exposure begun (Water level ＝TAF attained 4:15) Core damage begun (around 8:46). By simulation Large quantity of hydrogen generated/accumulated Nuclear reactor depressurized (Release safety valve @ 9:08) Fresh water injection from fire trucks begun (with boric acid 9:25) SC vent AO valve (large valve) opened (12:30)	Hydrogen back flew (From Unit 3)	Power supply begun from Unit 6 DG (MUWC system. 18:29)	Nuclear reactor water injection begun (Make Up Water Pump system. 13:20)	RHRS, RHRC pump activated (incoming power from makeshift cable 20:17/21:03)							Supplemental external power recovered (19:37)
2011/3/14		Fire trucks damaged (@11:01) Loss of cooling function was determined (RCIC stopped (@13:25)) Core depressurized (SRV opened @18:00) Fuel rods completely exposed (Water level＝TAF-3700mm 18:22) Core damage begun (@19:46). By simulation Large quantity of hydrogen generated/accumulated Sea water injection begun by fire trucks (19:54)	SC vent AO valve (small valve) opened (5:20) Sea water supply begun from storage to reverse valve pit (9:20) Self Defense Force water supply vehicles arrive, supplied fresh water from reverse valve pit (10:53) Hydrogen explosion (11:01)		Core depressurized (SRV opened 5:00) Water injection to nuclear reactor begun (MUWC 5:30) Water supply to spent fuel pool begun (MUWC 9:27)		Emergency auxiliary cooling system activated (EECW. Incoming power from makeshift power 1:44) Water injection to nuclear reactor begun (RHR LPCI mode 10:05) Water injection to spent fuel pool begun (FPMUW system 16:30) Cold shutdown (17:00)	Emergency auxiliary cooling system activated (EECW. Incoming power from makeshift power 3:20) Water injection to nuclear reactor begun (RHR LPCI mode 10:48) Cold shutdown (18:00)		EECW manually activated (received power from supply vehicle 11:00) RHR S/C spray mode begun (16:02) Water injection to nuclear reactor begun (RHR LPCI mode 18:58)				RHR pump activated (S/C pool cooling begun 3:50) RHR pump activated (Shutdown cooling mode 23:43)
2011/3/15		Pressure in containment vessel S/C indicated 0MPa (abs) (6:00-6:10)		Hydrogen explosion (6:12)						Cold shutdown (7:15)				Cold shutdown (0:40)
2011/3/16														
2011/3/17														Switched to normal external power (15:47)
2011/3/18					Passage to roof opened (3 spots 13:30)	Passage to roof opened (3 spots 17:00)								
2011/3/19					RHR makeshift sea water pump activated (emergency system 1:55) RHR manually activated (Fuel pool cooling @5:00)	RHR makeshift sea water pump activated (emergency system 21:26) RHR manually activated (Fuel pool cooling 22:14)								
2011/3/20					RHR pump activated (Shutdown-cooling mode 12:25) Cold shutdown (14:30)	RHR pump activated (Shutdown-cooling mode 18:48) Cold shutdown (19:27)								

Critical devices, such as emergency power supplies (AC) and batteries (DC), were stored in basements and completely flooded.

- **The greater the height difference between the tsunami and the altitude of the plant, the greater the damage**
  => Dai-ichi No 1-4: 5.5m, No 5, 6: 1.5m. Onagawa: 0m. Tokai Dai-ni: -2.6m
- **These power supplies placed in areas much lower than the tsunami crest were disabled.**

	Dai-ichi Rctr1	Reactor 2	Reactor 3	Reactor 4	Reactors 5 & 6	Fukushima Dai-ni	Onagawa	Tokai Dai-ni
Height of flood (Main building area)	O.P. **15.5m** (T.P. = O.P.+0.727m)				O.P.aprx**14.5m** (T.P.= O.P.+0.727 m)	O.P.aprx**14.5m** (T.P.=O.P.+0.727m)	O.P.aprx**13m** (T.P.=O.P.+0.74m)	H.P.**6.3m** (T.P.= H.P.-0.89m)
Altitude (Main building)	O.P.**10m**				O.P.**13m**	O.P.**12m**	O.P.**13.8m**	H.P.**8.9m**
Emergency generator elevation	O.P.**4.9m**(A) O.P.**2m**(B)	O.P.**1.9m**(A) O.P.**10.2m** (B) (Air cool)	O.P.**1.9m** (A/B)	O.P.**1.9m**(A) O.P.**10.2m**(B) (Air cool)	Reactor 5 O.P.**4.9m**(A)/(B) Reactor 6 O.P.**5.8m**(A)/(H) O.P.**13.2m**(B) (Air cool, survived)	O.P.**0**m (No. 1～4 A/B/H)	O.P.**0.5m**(No.1 A/B) O.P.**14m** (No. 2/3 A/B/H)	H.P.**1.6m** (A/B/H)
DC mother board elevation (A) and (B) type	**Turbine building B1** O.P.**4.9m**	**Same** O.P.**1.9m**	**Same** O.P.**6.5m**	**Same** O.P.**1.9m**	**Same** (No. 5 &6) O.P.**9.5m**	**Control bldg 2F**(No. 1 & 2) **Control bldg 1F**(No. 3 & 4) O.P.**18m**(1/no. 2A/B) O.P.**12.2m**(No3/4 A/B)	**Control bldg 1F**(No 1) **Control bldg B1F**(No 2) **OuterB1F** (No. 3) O.P.**9.5m** (no.1A/B) O.P.**7m** (no. 2A/B) O.P.**5m** (No. 3A/B)	**Outer B1F** H.P.**9.1m** (Battery location)
Emergency generator lost?	× Lost from flood	× A: Lost from flood B: Power panel lost from flood	× Lost from flood	× A: Lost from flood B: Power panel lost from flood	○ Reactor 6: 1 unit OK	○ 2 units from Reactor 3, 2 units from Reactor 4 OK	○ All units from Reactors 1 & 3, 2 in Reactor 2 OK	○ 2 units OK
DC power supply lost?	× Malfunction from flood		○	× Lost from flood	○ Working			
Note	･O.P: Onahama Port Construction Reference Plane ･T.P. Tokyo bay standard sea level						･O.P: Onagawa Reference Plane ･Accounted in -1m of slide-down by earthquake ･H.P: Hitachi Bay Construction Reference Plane	

On-shore motors and pumps for main cooling system malfunctioned due to tsunami – Of 13 emergency generators in Dai-ichi, all but one (air cooling type) malfunctioned. Water-cooling DG with cooling devices at the coastal side were especially vulnerable.

Loss of functions of emergency generators

	Fukushima Dai-ichi											
	Unit 1		Unit 2		Unit 3		Unit 4		Unit 5		Unit 6	
	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG	DG1A	×	DG2A	×	DG3A	×	DG4A	×	DG5A (※2)	×	DG6A	× (※2)
	DG1B	×	DG2B (Air cooling)	× (※1)	DG3B	×	DG4B (Air cooling)	× (※)	DG5B (※2)	×	DG6B (Air cooling)	○
											HPCS DG	× (※2)

	Fukushima Dai-ni							
	Unit 1		Unit 2		Unit 3		Unit 4	
	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG	DG1A	×	DG2A	× (※2)	DG3A	× (※2)	DG4A	× (※2)
	DG1B	×	DG2B	× (※2)	DG3B	○	DG4B	× (※2)
	DG1H	×	DG2H	× (※2)	DG3H	○	DG4H	○

	Onagawa (Tohoku Electric Power Co)					
	Unit 1		Unit 2		Unit 3	
	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG	DG A	○	DG A	○ (non-load standby)	DG A	○ (standby)
	DG B	○	DG B (※2)	× Sea water pump stopped	DG B	○ (standby)
			HPCS D/G (※2)	× Sea water pump stopped	HPCS D/G	○ (standby)

	Tokai Dai-ni	
	Electrical panel	Usability
Emergency DG	DG2C (※2)	× Sea water pump stopped (DGS)
	DG2D	○
	DG2H	○

(Legend) ○: Working ×: Malfunctioned

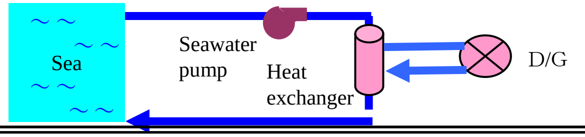
*1 Power panel malfunction from flood

*2 Malfunction from loss of cooling system

Emergency diesel generators at Fukushima Dai-ichi

Seawater cooling type emergency diesel generator (D/G 10 units)

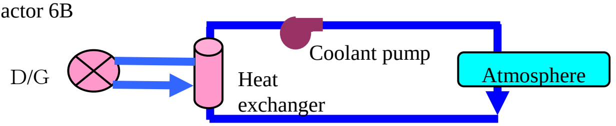
Reactor 1A･B, Reactor 2A, Reactor 3A･B, Reactor 4A, Reactor 5A&B, Reactor 6A&H



All malfunctioned from tsunami

Air cooling type D/G (3 units)

Reactor 2B, Reactor 4B, Reactor 6B

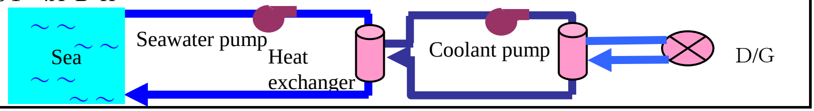


Only reactor 6 was working

Fukushima Dai-ni

Seawater cooling D/G (12 units)

Reactors 1 - 4A･B･H



Only 3 /12 working

- **Total of 24 emergency generators malfunctioned. The loss of cooling function is 1.5 times higher than loss of generator itself (= more orange than pink).**
  - Flooded generator (or power panel): 9 cases (pink)
  - Cooling system malfunction (motor, pump, etc.): 15 cases (orange)
- **This is especially so when looking at Fukushima Dai-ichi Reactors 5 & 6 and Dai-ni, which had relatively little flooding in the reactor building.**
  - Dai-ichi Reactors 5 & 6: 4/4 cooling systems on the coast lost.
  - Fukushima Dai-ni: 6/9 cooling systems on the coast lost.
- **Emergency generators for cooling system installed near the coast are vulnerable to tsunami, even with no damage to the generator unit.**
  - The only generator that survived in Fukushima Dai-ichi (Reactor 6) was an air cooling type. It had no cooling device on the coast.

Workers were unable to secure coolant for the water-cooling emergency generators.

	Dai-ichi Reactor 1	Dai-ichi Reactor 2	Dai-ichi Reactor 3	Dai-ichi Reactor 4	Dai-ichi Reactors 5 & 6	Fukushima Dai-ni	Onagawa	Tokai Dai-ni
Availability of coolant for emergency generator	✕ Lost (Seawater coolant)				○ Only one air cooling type unit was working (Reactor 6). Remaining 4 units all failed (seawater cooling type)	○ Of all 12 units, 3 units from Reactors 3 & 4 were working. Remaining 9 units failed. (8 units lost its seawater cooling system and intermediate loop. 1 unit lost intermediate loop)	○ All working for Reactors 1 & 3. 2 units lost for Reactor 2 (1 unit intermediate loop and Seawater coolant. 1 unit lost intermediate loop)	○ 2 units working. One failed. (Seawater coolant)
Recovery?	✕ Unable to recover				○ After restoring the damaged A type seawater pump for reactor 6, type A generators started operating.	○ Type B seawater cooling system for all reactors restored through maintenance checkup, motor replacement, and temporary power connection.	○ Flooded pumps and valves were restored after being inspected and repaired in a factory. DG on standby.	○ Flooded pump inspected and restored. DG on standby.

Note: Precondition is that related power panels, power bus-line and other supply routes are working.

Unable to perform ventilation from the outside – Workers spent too much time preparing the vent line and failed to execute ventilation.

Result of ventilation

	Dai-ichi Reactor 1	Dai-ichi Reactor 2	Dai-ichi Reactor 3	Dai-ichi Rctr 4	Dai-ichi Rctrs 5 & 6	Fukushima Dai-ni	Onagawa, Tokai Dai-ni
W/W vent	△ Succeeded in opening the vent valve but hydrogen explosion occurred right after.	× Vent line constructed but unable to hold the necessary pressure to open rupture disc.	△ Opened the valve once, but could not keep it open.	—	—	— Constructed vent line	—
D/W vent	—	× Constructed vent line but could not maintain it.	—			—	

○: Successful　—: Not implemented　×: Failed

- Was not able to operate the ventilation appropriately. On top of power outage, multiple obstacles such as darkness, transmission problems, parameter loss, frequent aftershocks, increasing radiation, rubble, etc., made it impossible. Manual operation of ventilation was also extremely difficult.

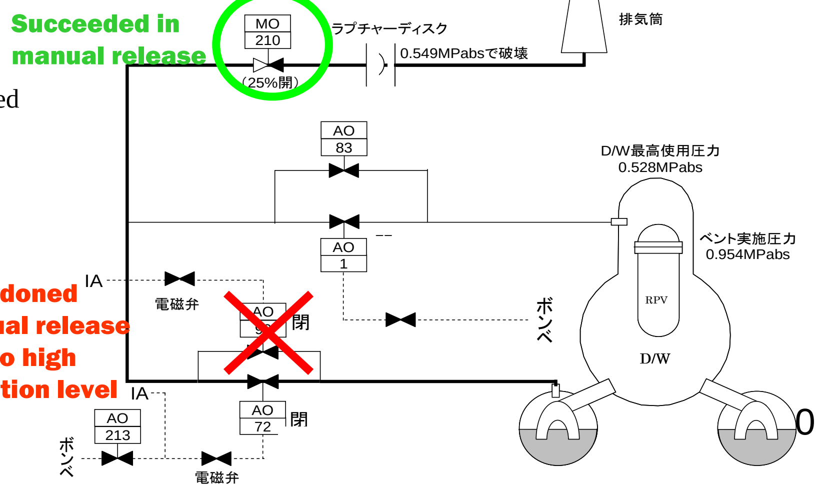
- As a result, failed to operate the ventilation at the right time.

Right after the tsunami, Reactor 1 lost all functions for coolant injection and PCV ventilation…

Equipment		status	Damage	Application	Notes(2F1)
Water injection equipment	High pressure coolant injection (HPCI)	×	No power (hydraulic pump)	—	○ Water supplied through RCIC and MUWC (emergency DG worked)
	condensate water feed (FDW)	×	Power &seawater lost	—	
	Core spray (CS)	×	power&seawater system lost	—	
	Shutdown cooling (SHC)	×	power&seawater system lost	—	
	Make-Up Water Condensate (MUWC)	×	No power, motor water	—	
		×		fire truck	
PCV vent equipment	S/C vent valve Valve no: AO-1601-72	×	Power loss/low air pressure	temp power improvised compressor Manual operation	△ Used temporary gas cylinder
	S/C vent bypass valve Valve no: AO-1601-90	×	No power/low air pressure		
	D/W vent valve Valve no: AO-1601-1	×	No power/low air pressure		
	D/W vent bypass valve Valve no: AO-1601-83	×	No power/low air		
	PCV vent valve Valve no: MO-1601-210	×	No power		

… Then tried to manually open the valve at basement but gave up as radiation level increased.

(Later succeeded by using the improvised compressor)

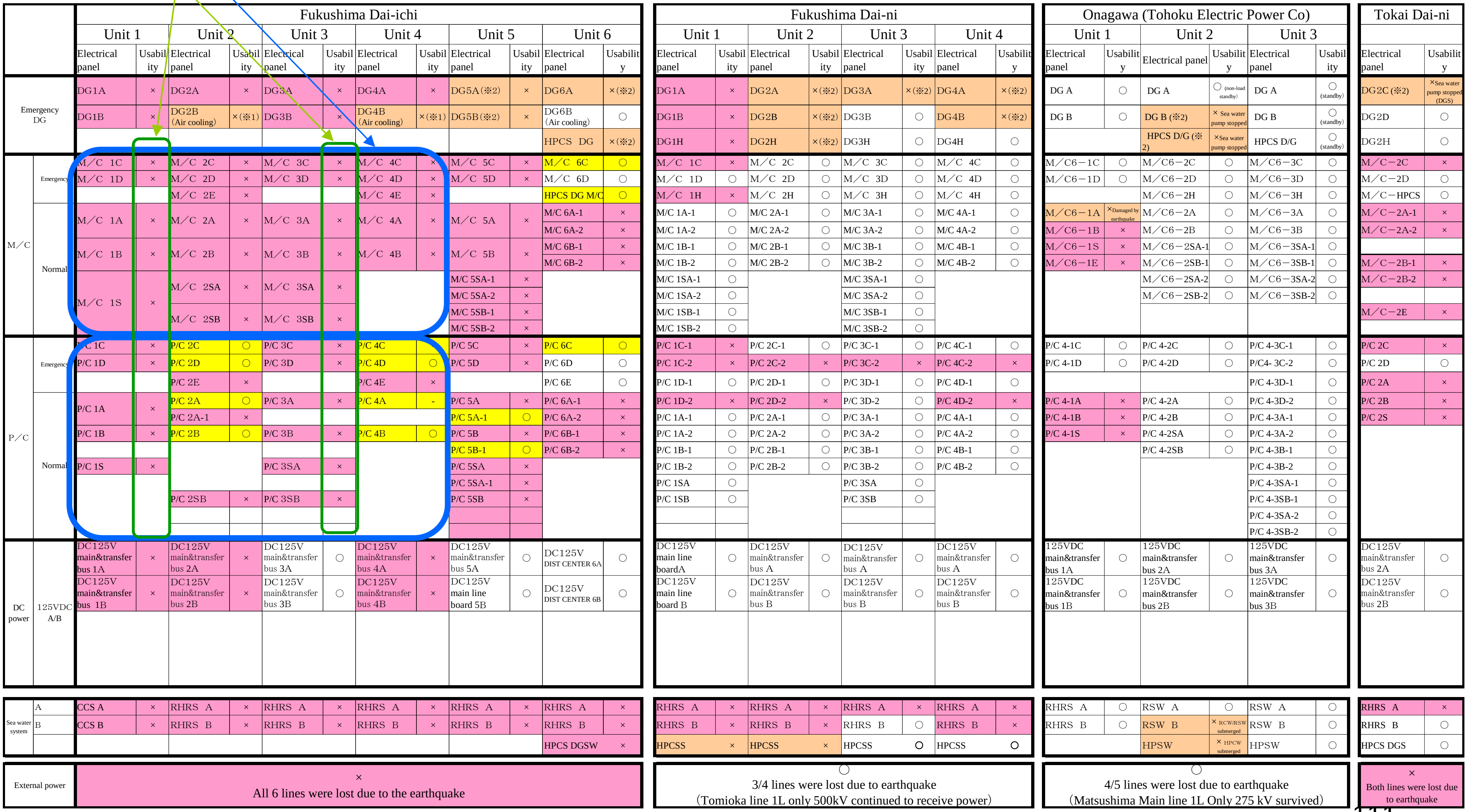


Succeeded in manual release

Abandoned manual release due to high radiation level

Dai-ichi Reactors 1 - 4, with power panels to external power flooded, failed cold shutdown.

- **Almost all of the crucial panels, such as M/C and P/C, malfunctioned in reactors 1-4 which eventually exploded.**
- **Especially, all of the power panels were lost at reactors 1 and 3.**



		Fukushima Dai-ichi											
		Unit 1		Unit 2		Unit 3		Unit 4		Unit 5		Unit 6	
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG1A	×	DG2A	×	DG3A	×	DG4A	×	DG5A(※2)	×	DG6A	×(※2)
		DG1B	×	DG2B (Air cooling)	×(※1)	DG3B	×	DG4B (Air cooling)	×(※1)	DG5B(※2)	×	DG6B (Air cooling)	○
												HPCS DG	×(※2)
M/C	Emergency	M/C 1C	×	M/C 2C	×	M/C 3C	×	M/C 4C	×	M/C 5C	×	M/C 6C	○
		M/C 1D	×	M/C 2D	×	M/C 3D	×	M/C 4D	×	M/C 5D	×	M/C 6D	○
				M/C 2E	×			M/C 4E	×			HPCS DG M/C	○
	Normal	M/C 1A	×	M/C 2A	×	M/C 3A	×	M/C 4A	×	M/C 5A	×	M/C 6A-1	×
												M/C 6A-2	×
		M/C 1B	×	M/C 2B	×	M/C 3B	×	M/C 4B	×	M/C 5B	×	M/C 6B-1	×
												M/C 6B-2	×
		M/C 1S	×	M/C 2SA	×	M/C 3SA	×			M/C 5SA-1	×		
										M/C 5SA-2	×		
				M/C 2SB	×	M/C 3SB	×			M/C 5SB-1	×		
										M/C 5SB-2	×		
P/C	Emergency	P/C 1C	×	P/C 2C	○	P/C 3C	×	P/C 4C	-	P/C 5C	×	P/C 6C	○
		P/C 1D	×	P/C 2D	○	P/C 3D	×	P/C 4D	○	P/C 5D	×	P/C 6D	○
				P/C 2E	×			P/C 4E	×			P/C 6E	○
	Normal	P/C 1A	×	P/C 2A	○	P/C 3A	×	P/C 4A	-	P/C 5A	×	P/C 6A-1	×
				P/C 2A-1	×					P/C 5A-1	○	P/C 6A-2	×
		P/C 1B	×	P/C 2B	○	P/C 3B	×	P/C 4B	○	P/C 5B	×	P/C 6B-1	×
										P/C 5B-1	○	P/C 6B-2	×
		P/C 1S	×			P/C 3SA	×			P/C 5SA	×		
										P/C 5SA-1	×		
				P/C 2SB	×	P/C 3SB	×			P/C 5SB	×		
DC power	125VDC A/B	DC125V main&transfer bus 1A	×	DC125V main&transfer bus 2A	×	DC125V main&transfer bus 3A	○	DC125V main&transfer bus 4A	×	DC125V main&transfer bus 5A	○	DC125V DIST CENTER 6A	○
		DC125V main&transfer bus 1B	×	DC125V main&transfer bus 2B	×	DC125V main&transfer bus 3B	○	DC125V main&transfer bus 4B	×	DC125V main line board 5B	○	DC125V DIST CENTER 6B	○
Sea water system	A	CCS A	×	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×
	B	CCS B	×	RHRS B	×	RHRS B	×	RHRS B	×	RHRS B	×	RHRS B	×
												HPCS DGSW	×
External power		× All 6 lines were lost due to the earthquake											

		Fukushima Dai-ni							
		Unit 1		Unit 2		Unit 3		Unit 4	
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG1A	×	DG2A	×(※2)	DG3A	×(※2)	DG4A	×(※2)
		DG1B	×	DG2B	×(※2)	DG3B	○	DG4B	×(※2)
		DG1H	×	DG2H	×(※2)	DG3H	○	DG4H	○
M/C	Emergency	M/C 1C	×	M/C 2C	○	M/C 3C	○	M/C 4C	○
		M/C 1D	○	M/C 2D	○	M/C 3D	○	M/C 4D	○
		M/C 1H	×	M/C 2H	○	M/C 3H	○	M/C 4H	○
	Normal	M/C 1A-1	○	M/C 2A-1	○	M/C 3A-1	○	M/C 4A-1	○
		M/C 1A-2	○	M/C 2A-2	○	M/C 3A-2	○	M/C 4A-2	○
		M/C 1B-1	○	M/C 2B-1	○	M/C 3B-1	○	M/C 4B-1	○
		M/C 1B-2	○	M/C 2B-2	○	M/C 3B-2	○	M/C 4B-2	○
		M/C 1SA-1	○			M/C 3SA-1	○		
		M/C 1SA-2	○			M/C 3SA-2	○		
		M/C 1SB-1	○			M/C 3SB-1	○		
		M/C 1SB-2	○			M/C 3SB-2	○		
P/C	Emergency	P/C 1C-1	×	P/C 2C-1	○	P/C 3C-1	○	P/C 4C-1	○
		P/C 1C-2	×	P/C 2C-2	×	P/C 3C-2	×	P/C 4C-2	×
		P/C 1D-1	○	P/C 2D-1	○	P/C 3D-1	○	P/C 4D-1	○
	Normal	P/C 1D-2	×	P/C 2D-2	×	P/C 3D-2	○	P/C 4D-2	×
		P/C 1A-1	○	P/C 2A-1	○	P/C 3A-1	○	P/C 4A-1	○
		P/C 1A-2	○	P/C 2A-2	○	P/C 3A-2	○	P/C 4A-2	○
		P/C 1B-1	○	P/C 2B-1	○	P/C 3B-1	○	P/C 4B-1	○
		P/C 1B-2	○	P/C 2B-2	○	P/C 3B-2	○	P/C 4B-2	○
		P/C 1SA	○			P/C 3SA	○		
		P/C 1SB	○			P/C 3SB	○		
DC power	125VDC A/B	DC125V main line boardA	○	DC125V main&transfer bus A	○	DC125V main&transfer bus A	○	DC125V main&transfer bus A	○
		DC125V main line board B	○	DC125V main&transfer bus B	○	DC125V main&transfer bus B	○	DC125V main&transfer bus B	○
Sea water system	A	RHRS A	×	RHRS A	×	RHRS A	×	RHRS A	×
	B	RHRS B	×	RHRS B	×	RHRS B	○	RHRS B	×
		HPCSS	×	HPCSS	×	HPCSS	○	HPCSS	○
External power		○ 3/4 lines were lost due to earthquake （Tomioka line 1L only 500kV continued to receive power）							

		Onagawa (Tohoku Electric Power Co)					
		Unit 1		Unit 2		Unit 3	
		Electrical panel	Usability	Electrical panel	Usability	Electrical panel	Usability
Emergency DG		DG A	○	DG A	○ (non-load standby)	DG A	○ (standby)
		DG B	○	DG B (※2)	× Sea water pump stopped	DG B	○ (standby)
				HPCS D/G (※2)	×Sea water pump stopped	HPCS D/G	○ (standby)
M/C	Emergency	M／C6−1C	○	M／C6−2C	○	M／C6−3C	○
		M／C6−1D	○	M／C6−2D	○	M／C6−3D	○
				M／C6−2H	○	M／C6−3H	○
	Normal	M／C6−1A	×Damaged by earthquake	M／C6−2A	○	M／C6−3A	○
		M／C6−1B	×	M／C6−2B	○	M／C6−3B	○
		M／C6−1S	×	M／C6−2SA-1	○	M／C6−3SA-1	○
		M／C6−1E	×	M／C6−2SB-1	○	M／C6−3SB-1	○
				M／C6−2SA-2	○	M／C6−3SA-2	○
				M／C6−2SB-2	○	M／C6−3SB-2	○
P/C	Emergency	P/C 4-1C	○	P/C 4-2C	○	P/C 4-3C-1	○
		P/C 4-1D	○	P/C 4-2D	○	P/C4- 3C-2	○
						P/C 4-3D-1	○
	Normal	P/C 4-1A	×	P/C 4-2A	○	P/C 4-3D-2	○
		P/C 4-1B	×	P/C 4-2B	○	P/C 4-3A-1	○
		P/C 4-1S	×	P/C 4-2SA	○	P/C 4-3A-2	○
				P/C 4-2SB	○	P/C 4-3B-1	○
						P/C 4-3B-2	○
						P/C 4-3SA-1	○
						P/C 4-3SB-1	○
						P/C 4-3SA-2	○
						P/C 4-3SB-2	○
DC power	125VDC A/B	125VDC main&transfer bus 1A	○	125VDC main&transfer bus 2A	○	125VDC main&transfer bus 3A	○
		125VDC main&transfer bus 1B	○	125VDC main&transfer bus 2B	○	125VDC main&transfer bus 3B	○
Sea water system	A	RHRS A	○	RSW A	○	RSW A	○
	B	RHRS B	○	RSW B	× RCW/RSW submerged	RSW B	○
				HPSW	× HPCW submerged	HPSW	○
External power		○ 4/5 lines were lost due to earthquake （Matsushima Main line 1L Only 275 kV survived）					

		Tokai Dai-ni	
		Electrical panel	Usability
Emergency DG		DG2C (※2)	×Sea water pump stopped (DGS)
		DG2D	○
		DG2H	○
M/C	Emergency	M／C−2C	×
		M／C−2D	○
		M／C−HPCS	○
	Normal	M／C−2A-1	×
		M／C−2A-2	×
		M／C−2B-1	×
		M／C−2B-2	×
		M／C−2E	×
P/C	Emergency	P/C 2C	×
		P/C 2D	○
		P/C 2A	×
	Normal	P/C 2B	×
		P/C 2S	×
DC power	125VDC A/B	DC125V main&transfer bus 2A	○
		DC125V main&transfer bus 2B	○
Sea water system	A	RHRS A	×
	B	RHRS B	○
		HPCS DGS	○
External power		× Both lines were lost due to earthquake	

🟥 : Lost functions
🟧 : Unable to activate due to electrical board and/or cooling system were lost
🟨 : Incoming power was inaccessible due to the loss of electrical supply source

Information on DC power of system-H was omitted.

Loss of functions below were based on the estimation by the project;
・ Onagawa's M/C, P/C, and Tokai Dai-ni's P/C electrical panels

With almost no working panels for the power supply vehicles to connect, it was very difficult to supply power.

Power supply vehicle arrangements

- Power supply vehicle arrived right after the tsunami (High voltage vehicle)
  - March 11 approx. 22:00 First group arrives with one unit.
  - March 12 approx. 01:20 4 units arrive (total 5 units)
  - March 12 approx. 03:00 7 units arrive (total 12 units)

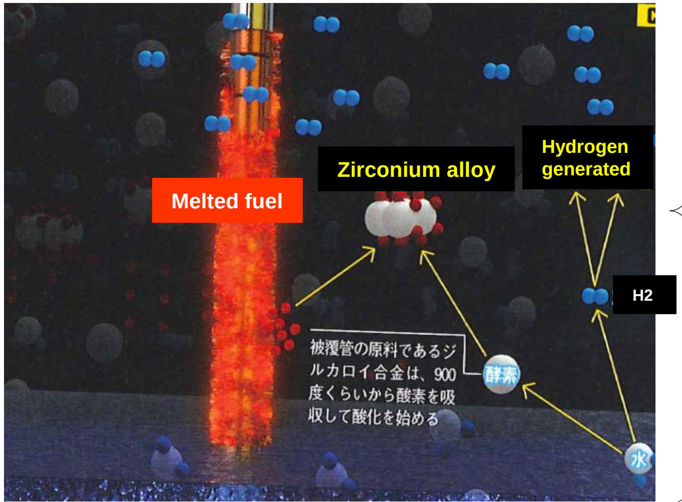
- Same as above (Low voltage vehicle)
  - March 11 approx. 23:30 2 units from Self Defense Force
  - March 12 approx. 07:00 3 more units arrive

Difficulty with connection

- Few power supply vehicles were rounded up by dawn of March 12.
- However, there was trouble connecting them as very few power panels (M/C, P/C) were working due to tsunami as well as time was consumed in identifying working ones.
- Furthermore, factors such as rubble, aftershocks, transmission problems, insufficient heavy equipment, hindered the set-up of lines to connect vehicles.
- All the preparations made for restoring power in Fukushima Dai-ichi Reactor 2 had to start from scratch when Reactor 1 exploded.

In reactor 1 with no coolant functionality, core meltdown caused the cladding tube around the fuel rods to oxidize and built up a massive amount of hydrogen.

Mechanism of hydrogen generation



図出典： 徹底解剖　東日本大震災 (双葉社)

- ● Without power and cooling, the core's temperature and pressure surged. This lowered the water level in the core and eventually caused the fuel rods to be exposed above the coolant water.
- ● As the temperature in the core increased, the cladding tube around the fuel rods (zirconium alloy) started melting and oxidizing at approximately 900℃, which raised core temperature further.
- ● The chemical reaction between the molten cladding tubes (zirconium) and oxygen in the steam in the pressure vessel produced a massive amount of hydrogen (zirconium-water reaction).
- ● According to TEPCO's simulation, in Reactors 1, 2 and 3, with the water level down and the fuel rods exposed, **core damage (melting of fuel) possibly started in about 2 hours after the exposure of the fuel rods**.

Simulated time to core damage

(From the timing of earthquake)	Fukushima Dai-ichi Reactor 1 (If water level is below the fuel)	Reactor 2 (If data of water level is correct)	Reactor 2 (If water level is below the fuel)	Reactor 3 (If data of water level is correct)	Reactor 3 (If water level is below the fuel)
Core exposure started:	Approx. 3 hrs ・March 11 17:46	Approx. 75 hrs ・March 14 17:46	Approx. 75 hrs ・ March 14 17:46	Approx. 40 hrs ・ March 13 06:46	Approx. 40 hrs ・March 13 06:46
Core damage started:	Approx. 4 hrs **・March 11 18:46**	Approx. 77 hrs **・ March 14 19:46**	Approx. 77 hrs **・March 14 19:46**	Approx. 42 hrs **・March 13 08:46**	Approx. 42 hrs **・ March 13 08:46**
Damage to containment vessel occurred:	Approx. 15 hrs **・March 12 05:46**	No damage	Approx. 109 hrs **・March 16 03:46**	No damage	Approx. 66 hrs **・ March 14 08:46**

Note)　Source　May 23, 2011 Tokyo Electric Power Company Corp. "“Analysis and effect evaluation of the records on operations and accidents at Fukushima Dai-ichi Nuclear Power Plant in Tohoku Region Pacific Coast Earthquake"

・ Date of analysis: May 16, 2011

・ Method：Used the gathered information on condition of the equipment and plant operation when the earthquake first occurred as input for simulation information, and analyzed.

・ Software：Accident Analysis Code (MAAP＝Modular Accident Analysis Program)

Extremely Confidential

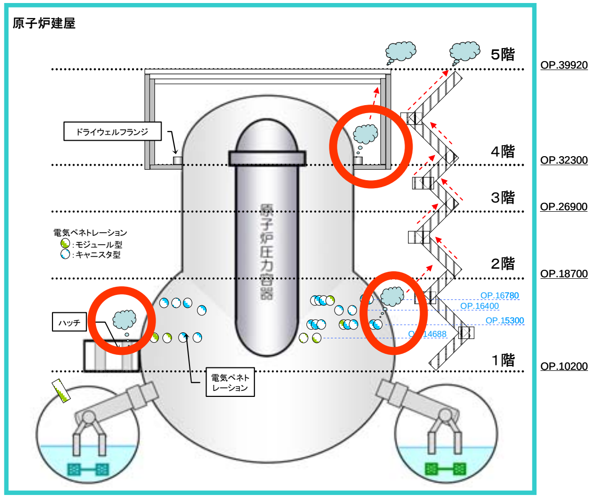
The reactor building had no system to "detect" or "release(*)" hydrogen, resulting in a massive explosion.

※)Emergency gas treatment system did not function because of the power outage

Reactor No.1 (East side)

Hydrogen built up in the 5th floor

- Leak path-1 (Reactors 1&3): It is estimated the hydrogen leaked into the reactor building through gaps in the connections and piping (hatch, drywell flange, electric penetration).

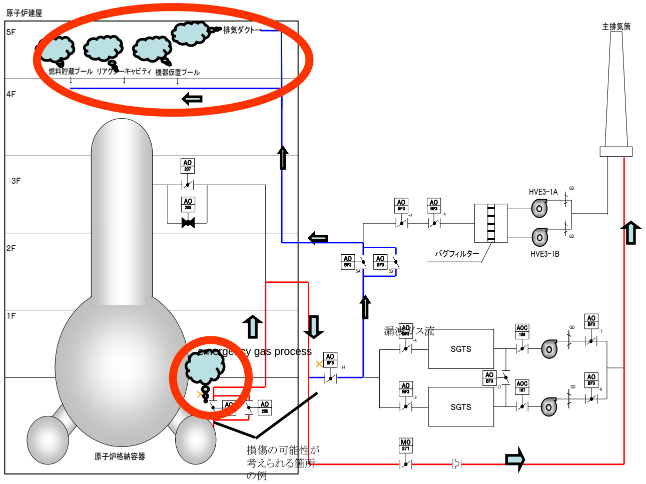


< Leak path from containment vessel (estimated) >

Reactor No. 3 (East side)

Hydrogen built up in the 5th & partially in the 4th floor (north-east)

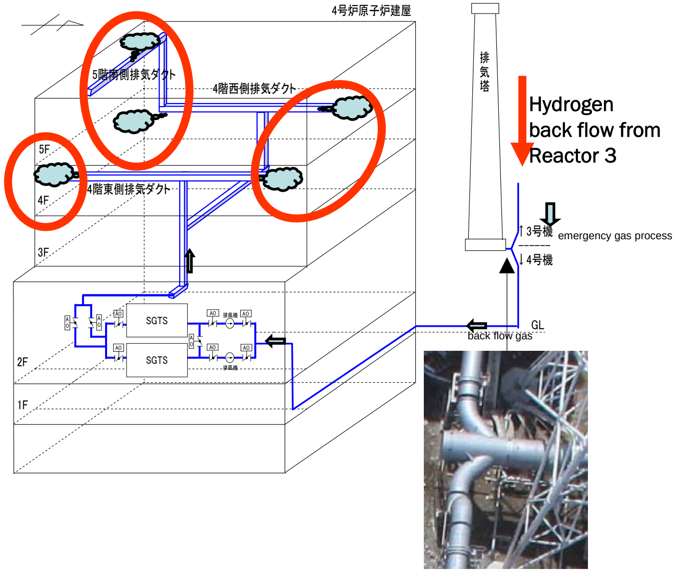
- Leak path-2 (Reactors 1&3): It is also possible that high-pressure & -temperature gas passed through vent lines and damaged the pipes and valves during the ventilation of the PCV, creating gaps for the hydrogen to leak through.



Reactor No. 4 (East side)

Hydrogen built up in the 5th & partially in the 4th, floor (east west)

- Leak path (Reactor 4) : It is estimated hydrogen produced at Reactor 3 back-flowed into reactor 4 through connecting pipes used for the emergency gas processing system.



In reactor 1 & 3, oxidation of zirconium of the fuel rods, caused by core damage, generated hydrogen, which leaked into reactor buildings from PCV, and eventually exploded. Hydrogen from reactor 3 flowed into reactor 4 through a shared vent line, accumulated and exploded.

	Fukushima Dai-ichi Unit 1	Unit 2	Unit 3	Unit 4
Why was the hydrogen generated?	● Reactions between the molten zirconium fuel rods and water (water-zircaloy reaction) caused massive hydrogen buildup within the containment vessel.			● No hydrogen buildup in Unit 4.
When did it occur?	● 4 hours after the earthquake (3/11 approx. 18:46 ※1)	● 77 hours after the earthquake (3/14 approx. 19:46 ※1)	● 42 hours after the earthquake (3/13 approx. 8:46 ※1)	● 42 hours after the earthquake (3/13 approx. 8:46 ※1)
Where did it leak from?	● Multiple possible sources • Pressure Vessel ⇒ Primary Containment Vessel (PCV): The hydrogen gas transferred to the S/C when the core was decompressed via SRV, and leaked to the D/W from the sheath of the SRV. • PCV ⇒ Reactor Building: Leaked through the D/W flange area, power penetration, hatch, air-conditioner exhaust, etc, to the upper level of the nuclear reactor building.	● Multiple possible sources • Pressure in D/W exceeded its capacity of 0.75MPa. This caused damage to areas that weren't able to cope with the pressure (i.e. bottom of the S/C vent line).	● Multiple possible sources • Same as Unit 1	● Hydrogen from Unit 3 leaked into the reactor building No.4 through the SGTS pipe.
Where did it accumulate?	● 5th floor(※2)	● Presumably in the basement area (No photographic record)	● 5th & 4th floors, and possibly 3rd floor (※2)	● 4th and 5th floors (※2)
What triggered it?	● Since hydrogen is lighter than air, it travelled and spread to the operation floor above. It exploded when it reached the combustible density 4% - 75% (unable to determine the ignition source since energy required for ignition is only 0.02mJ).	● Damage could have been caused either by the hydrogen explosion or pressure built-up in the PCV. For the former, presumed to be the S/C's narrow occluded section since the damaged area is not as wide as for Reactors 1 and 3. It is inferred that it is most likely not caused by hydrogen explosion.	● Same as Unit 1	● Same as Unit 1

※1: Start of fuel damage based on analysis. ※2: Judging from the photos.

Based on simulations by TEPCO, the pressure vessels in reactor No. 1-3 were all damaged and their PCV could have been damaged with massive H_2 leaked, if their water levels were below the fuel rods (i.e. Records of water level are not accurate).

Analysis result (Time elapsed since earthquake)	Fukushima Dai-ichi Unit 1 (Water level below fuel)	Unit 2 (Water level above fuel)	Unit 2 (Water level below fuel)	Unit 3 (Water level above fuel)	Unit 3 (Water level below fuel)
Core exposure start	approx. 3 hrs ・3/11 17:46	approx. 75 hrs ・3/14 17:46	approx. 75 hrs ・3/14 17:46	approx. 40 hrs ・3/13 06:46	approx. 40 hrs ・3/13 06:46
Core damage start	approx. 4 hrs **・3/11 18:46**	approx. 77 hrs **・3/14 19:46**	approx. 77 hrs **・3/14 19:46**	approx. 42 hrs **・3/13 08:46**	approx. 42 hrs **・3/13 08:46**
Damage to reactor pressure vessel	approx. 15 hrs **・3/12 05:46**	No damage	approx. 109 hrs **・3/16 03:46**	No damage	approx. 66 hrs **・3/14 08:46**
Analysis Precondition (Time elapsed since earthquake)					
Leak from containment Vessel's gas phase section	approx. 18hrs ・3/12 08:46 ・D/W Approx. 3cm diam.	approx. 21 hrs ・3/12 11:46 ・D/W Approx. 10cm diam.	Same as left	No record	Same as left
Same as above (to greater extent)	approx. 50 hrs ・3/13 16:46 ・D/W Approx. 7cm diam.	approx. 87 hrs 28 min ・3/15 06:14 noise around S/C ・S/C approx. 10cm diam.	Same as left	No record	Same as left
	・Theory: IC not working after DC power outage. ・Phenomenon theorized based on analysis of records.	・3/14 23:00 assumed SR valve 1 closed ・ Scenario based on analysis of records.	Same as left	・Scenario based on analysis of records.	Same as left

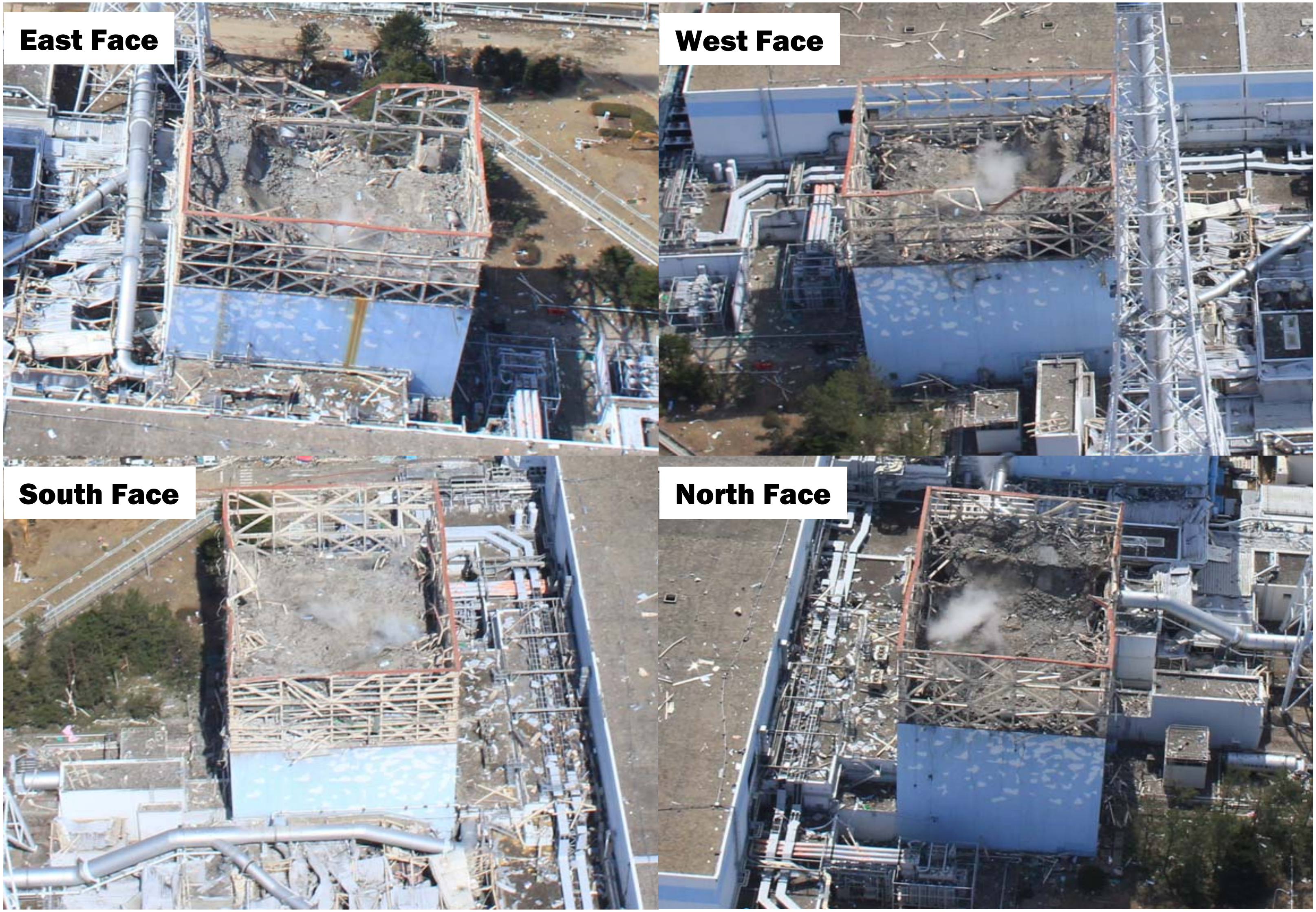
Note) Source: May 23, 2011, Tokyo Electric Power Company Corp. "Analysis of Tohoku region Pacific coast earthquake Fukushima Dai-ichi Nuclear Power Plant Operation Record and Accident Record and Effect Evaluation" (May 23 2011)

- Date of analysis: 5/16/2011
- Method: Used the gathered information on condition of the equipment and plant operation when the earthquake first occurred as input for simulation information, and analyzed.
- Software: MAAP＝Modular Accident Analysis Program

- **Core Damage of Reactors 1 - 3 started approx. 2 hrs after core exposure.**
- **Pressure vessel in reactor No.1 was already damaged before water injection (March 12th, 5:46, 2011)**

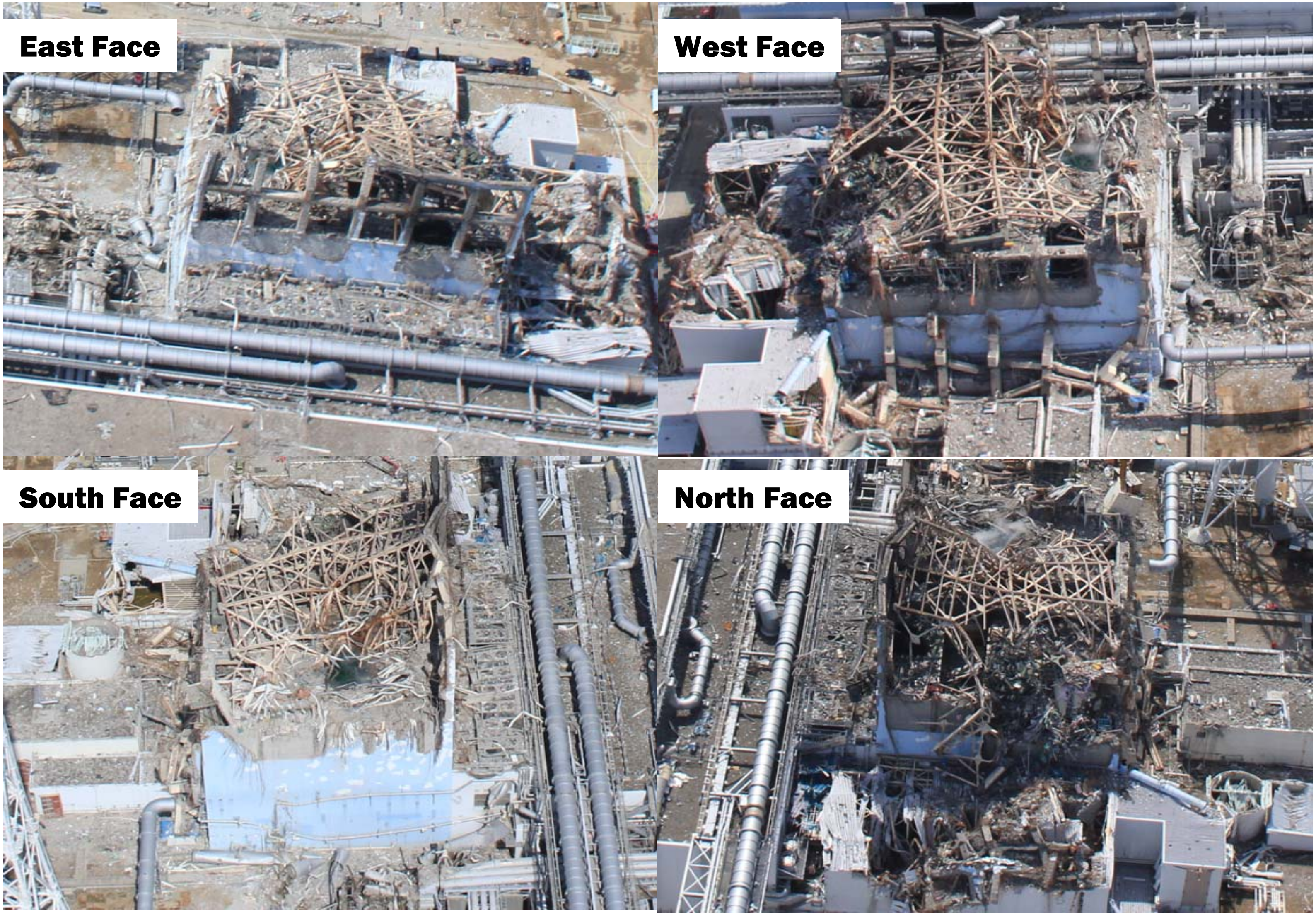
Unit 1: Only the 5th floor was badly damaged – It seems that hydrogen had accumulated primarily on the 5th floor.

Unit 1 - after explosion



Unit 3: 5th floor and north wall of the 4th floor were badly damaged – It seems that hydrogen had accumulated primarily on the 5th and possibly on the 4th floor.

Dai-ichi Unit 3 - after explosion



East Face

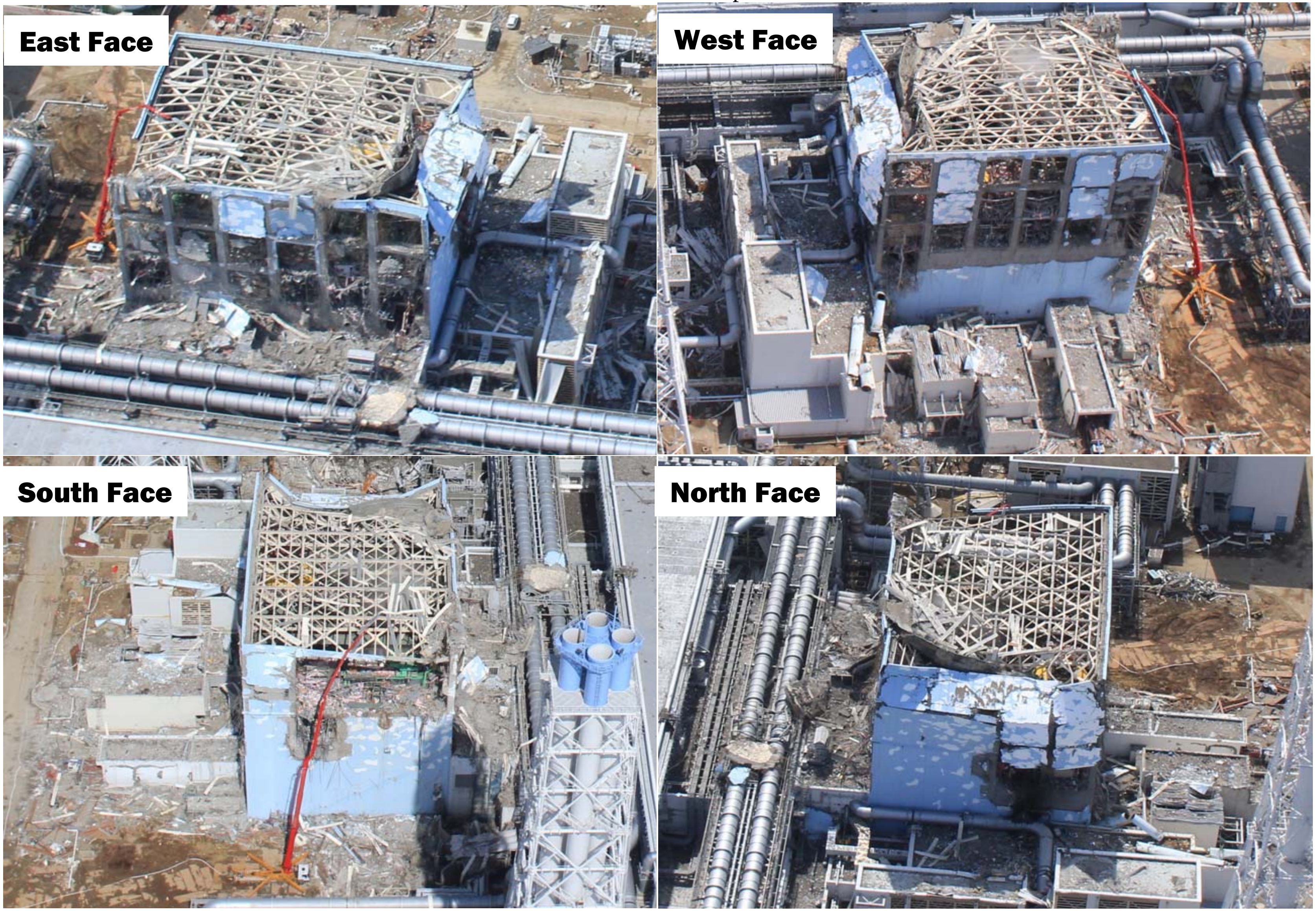
West Face

South Face

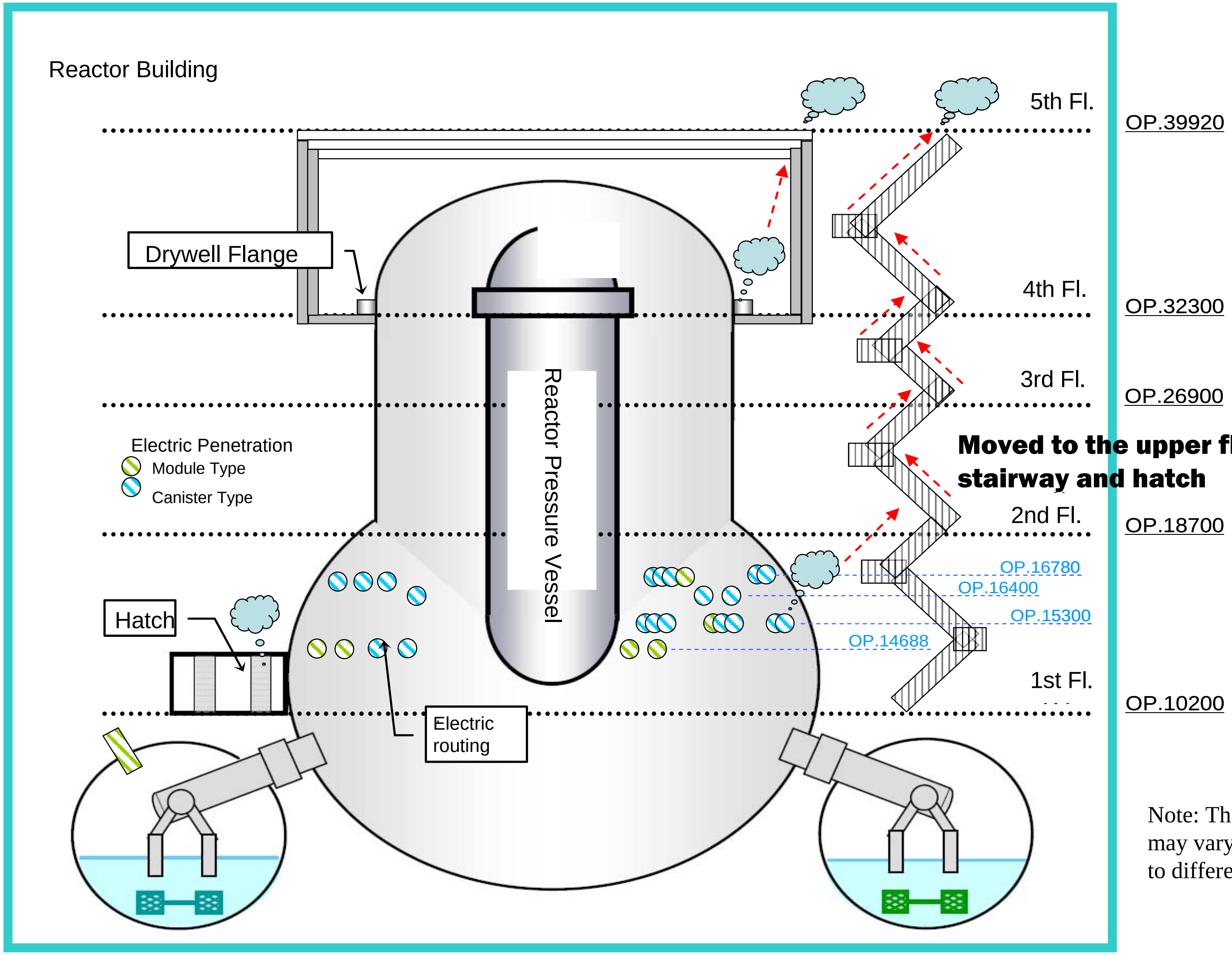
North Face

Unit 4: 5th floor, and east & west walls of 4th floor were badly damaged – It seems that hydrogen had accumulated mainly on the 5th and 4th floors.

Dai-ichi Unit 4 - after explosion



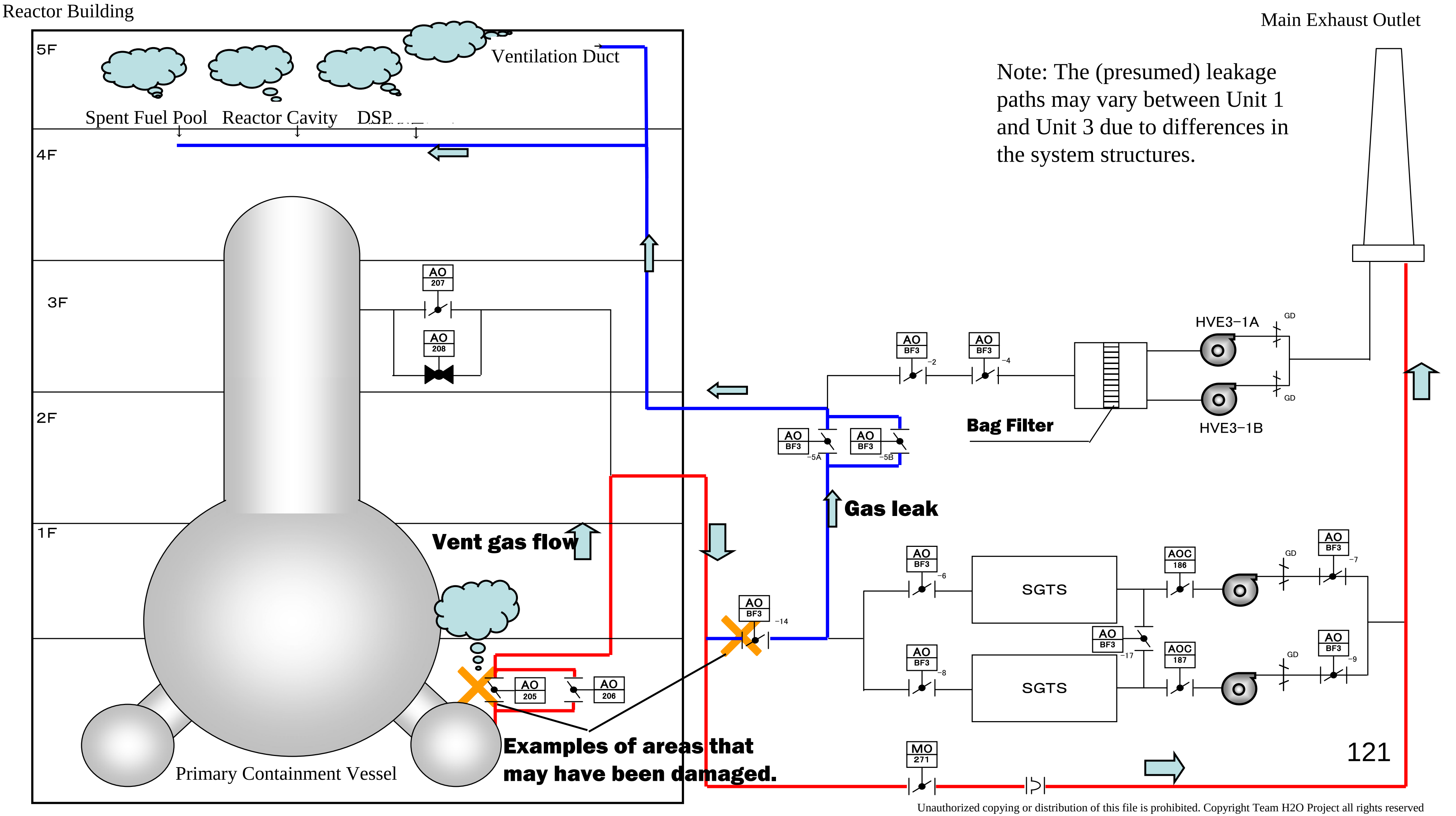
H_2 leak scenario at unit 1&3: (1) Through PCV penetration: As the seals in electric cabling routes and hatches of PCV are made of epoxy and rubber, the high temperature and pressure caused the seals to degrade and they consequently allowed H_2 to leak through.



Moved to the upper floors through stairway and hatch

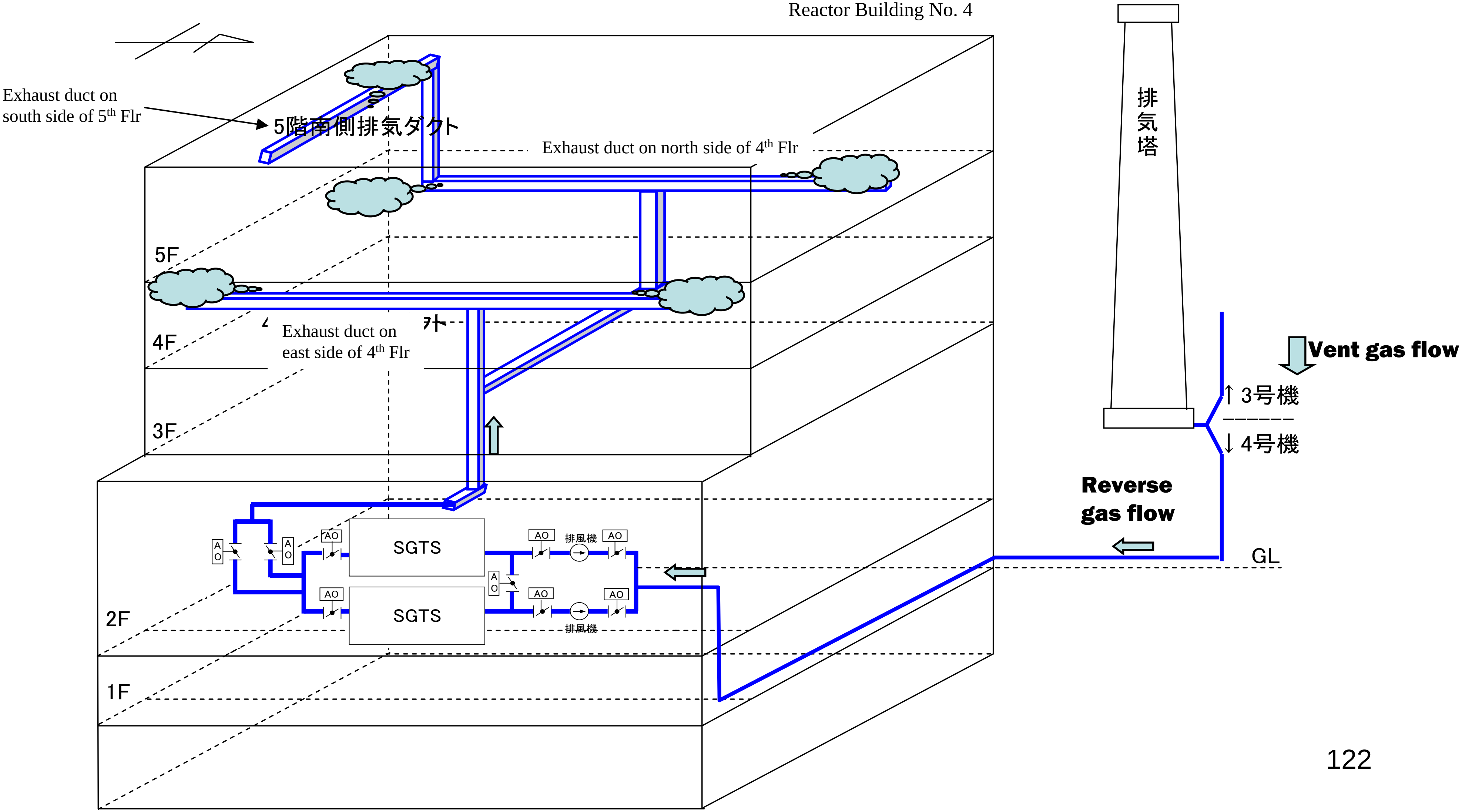
Note: The (presumed) leakage paths may vary between reactor 1 and 3 due to differences in the system structures.

H_2 leak scenario at unit 1&3: (2) Through the vent exhaust system: There is a possibility that high-temperature/-pressure gas flowed through the exhaust duct when the S/C was vented. The gas damaged the duct and valves, and created spaces for hydrogen to leak.

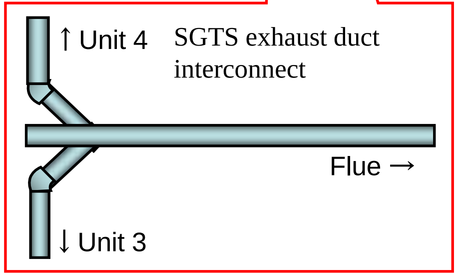


Note: The (presumed) leakage paths may vary between Unit 1 and Unit 3 due to differences in the system structures.

H_2 leak scenario at unit 4: Reverse flow from unit 3: The emergency SGTS* exhaust duct of Unit 4 is connected to Unit 3 right before the flue. Gases (including hydrogen) from Unit 3 may have flowed through into Unit 4. (*: Stand-by Gas Treatment System)



(Reference) Unit 3 & 4 SGTS exhaust duct



Lessons Learned and Countermeasures

- What lessons can be learned from the facts?
- What measures to be taken in order to prevent recurrence?

Lessons Learned and Countermeasures

- Lessons Learned -

Earthquake and Tsunami

Cause

- **Earthquake**
- **External power outage**
- **Communication function problem**
- **Liquefaction of road & infrastructure, and scattered debris from the quake and tsunami.**
- **Time and day of the disaster**

Event / Issue	Measures / Lessons
Auto stop (scram) of core reactor activated according to design. Recovery operations performed on DG auto-activation due to external power failure. Operator responded as planned .	**Nuclear reactor earthquake response was according to design.**
After the auto scram was triggered by earthquake, some DGs were activated by mistake in plants that didn't experience external power outage (because of the loss of generator's field magnet?). DG is an important emergency power source, so we need to consider whether the activation was appropriate.	**Investigate the cause of activation.** **Add DG auto-activation interlock on earthquake scram.**
No major damage to the facilities from the earthquake. Detailed examination on the earthquake disaster will require some time, so whether lessons learned from Kashiwazaki were effectively applied has yet to be verified.	**Check lessons learned from Kashiwazaki-Kariwa Nuclear Power Plant at Chuetsu offshore earthquake.**
The earthquake caused problems with communications. There were major issues in sharing information, giving instructions or commands, and making decisions. Whether the emergency satellite phone, and fire department and local government hotline were functioning and utilized have yet to be verified.	**Secure and reinforce means of communication in case of disasters such as earthquakes.**
Recovery process delayed due to difficult access along roads and facilities caused by road liquefaction from earthquake and debris from the tsunami.	**Reinforce main road to prevent liquefaction, and secure multiple access routes.**
The seismic motions recorded in Fukushima and Onagawa were as predicted. Aside from the seismic motion in some areas of Onagawa where the actual quake was stronger, the readings were on par with the prediction. This indicates that the design for seismic motion is reliable.	**Design against earthquake was appropriate.**
The earthquake happened during the day on a weekday, but we need to verify whether workers would have been able assemble at the power plant according to the manual if it occurred at night and on a holiday.	**Consider response procedures for disasters occurring on a holiday and at night.**

Earthquake and Tsunami - 2

Cause	Event / Issue	Measures / Lessons
Anti-tsunami design underestimated	Tsunami impact larger than the prediction made by the Japan Society of Civil Engineers (JSCE) 2002 (Fukushima Dai-ichi = 5.7m, Dai-ni = 5.2m). The tsunami (Dai-ichi = max 15.5m, Dai-ni = max 7.0m) greatly affected the safety of the plant. Furthermore, it's not clear whether the accuracy of the tsunami estimate data had been seriously reviewed in the past 7 years.	**Is the prediction from JSCE really adequate?** **Consider to estimate tsunami risk voluntarily and periodically.**
Seawater pump flooded from tsunami	The height of the tsunami that impacted the Onagawa Power Plant and Tokai Dai-ni Power Plant was on par with that estimated by the Japan Society of Civil Engineers (2002 estimate). However, some areas of the plant were not sealed properly, so seawater entered the facility. The emergency seawater pump malfunctioned due to flooding, causing the emergency DG to malfunction.	**Tsunami countermeasures for seawater pumps. (Reinforce pressure resistance and water seal.)**
Tsunami risk assessment system based on "height"	Tsunami impact destroyed the power plant's structures and equipment, scattering debris across its path. The debris became an obstacle during the recovery process. When deliberating measures against tsunami the discussion shouldn't be limited to the height of the tsunami, but should also include its power.	**Revise risk assessment to include consideration of the power of the tsunami.**
Gasoline tank swept away by tsunami	In Fukushima Dai-ichi and the Onagawa power plant, the tsunami swept the heavy oil tanks onto the road, blocking access to the plants. This affected the speed of the recovery process and heavy oil was also released to the sea.	**Bolt down the gasoline tanks.**
Debris created from the tsunami.	The debris scattered by the tsunami greatly affected the mobility of supply transport. There needs to be a countermeasure to enable swift actions in securing the safety of the plant.	**Secure heavy machinery and operators for clearing debris.**
Seawater coolant pump vulnerable against tsunami	Although the facilities in Fukushima Dai-ichi and Dai-ni were built in an area higher than the estimated tsunami height, the seawater pumps were not . The pumps were damaged by the tsunami and malfunctioned.	**Store mobile power supplies and seawater pumps.**

Earthquake and Tsunami - 3

Cause	Event / Issue	Measures / Lessons
Major flooding (seawater) of turbine building from the tsunami	Buildings connected to the turbine and nuclear reactor buildings were flooded badly, and equipment in the basement and ground floor were damaged and stopped functioning. The plant's cooling system was greatly affected due to flood damage of the emergency DG, DC and AC power panels, etc.	**Reconsider the location of Diesel generators, DC power panels, and AC power panels. Stock mobile power supply vehicles.**
The tsunami hit when turbine building's supply transport entrance was open.	During regular inspections, the turbine building's large entrance is used for delivery of supplies. The entrance was left open during and after the earthquake, allowing seawater from the tsunami to enter to the building. The flood resulted in the loss of the DC power supplies.	**Revise operations of wide entrances since they are vulnerable to flooding. Conduct training.**
Seismic-isolation tower's emergency power lost from the tsunami.	There was no power in the Fukushima Dai-ni emergency response room following the tsunami impact. Limitations in the emergency response room's infrastructure may have an affect on the speed of the plant's recovery process.	**Reinforce the Seismic-isolation tower against tsunami. Secure emergency power supply.**
Seawater pumps malfunctioned due to damage from tsunami.	In Fukushima Dai-ichi, almost all seawater pumps malfunctioned from the tsunami. There wasn't much damage to the pumps themselves, but most suffered damage to the motor insulation.	**Keep washing equipment for motor coil within the site and stock spare parts.**
Insufficient AM and training for simultaneous SBO occurrences of all plants.	The tsunami impact instantly compromised the entire power plant. The AM was not designed for response to an instant devastating blow to the entire plant. Furthermore, measures against disasters with low probability of occurrence may not have been seriously taken into account because of the application of the PSA method. To learn from this, it's important to not just make hard and soft preparations in responding to instant damage to the entire plant, but to enhance plant-wide training as well.	**Reinforce hard and soft preparations for plant-wide SBO. Reinforce Training.**

Power outage (Fukushima Dai-ichi) - 1

Cause	Event / Issue	Measures / Lessons
▪ **DC power supply flooded from the tsunami**	• AC and DC power supplies in the turbine building’s first floor and basement were lost from the tsunami. It is important to improve the facility's air seal, water seal, and pressure resistance to protect the power supplies.	▪ **Improve air protection, water protection, and pressure resistance of power facilities**
▪ **Flood entered through the air inlet**	• Emergency DG malfunctioned due to seawater entering the air inlet.	▪ **Apply water proof solution for air inlet**
▪ **Instant loss of DC power supply from flooding**	• DC power is the most important source in the plant. It powers the high pressure cooling devices and the main control room’s measuring equipment and lights. In Fukushima Dai-ichi, the DC battery room was located in the basement of the turbine building, so it was lost instantly in the flood. With no power, the high pressure cooling system didn’t function. When the pressure in the reactor was reduced, attempts to cool the nuclear core with the alternative low pressure cooling system had been made but failed and resulted in core meltdown, and eventually to the hydrogen explosion (Fukushima Dai-ichi Unit 1).	▪ **Secure alternative DC power supply. It's important to have diversity**
▪ **Complete external power outage**	• Fukushima Dai-ichi Reactors 1 – 6 lost external power from the earthquake. Plants that didn’t experience external power loss and those that were able to recover at least one emergency power supply achieved cold shutdown. Securing external power supply directly leads to prevention of fuel damage.	▪ **Improve earthquake resistance of external power supply** ▪ **Increase the number of external power supply routes (multiplex)** ▪ **Link external power on each plant (multiplex)**
▪ **Emergency power supplies located at altitude lower than tsunami crest** ▪ **Power supplies relied on seawater cooling system.**	• In Fukushima Dai-ichi, only one emergency DG of reactor 6 was functioning. It is located in the northern part of the plant which is at a higher altitude (O.P.13m) than Reactors 1 - 4. The height of the flood wave only reached up to 1m there. In addition, the Reactor 6 emergency DG uses air instead of seawater for its cooling system, so it wasn't affected by the flood.	▪ **Consider placing emergency DGs in higher places.** ▪ **Secure emergency power supplies for the various cooling systems with different power types.**

Power outage (Fukushima Dai-ichi) - 2

Cause	Event / Issue	Measures / Lessons
▪ **Not anticipated in AM (slow recovery of AC power at SBO)**	• Only short period station blackout was anticipated in the AM countermeasures. However, in Fukushima Dai-ichi, the power outage lasted up to a few days. This sort of situation was not covered in the recovery procedure manual.	▪ **Revise the procedures to respond to long term loss of all AC power**
▪ **Concurrent AC and DC power outage** ▪ **Instant loss of all DC power from flooding. Unable to charge 'submerged' batteries from DC power supply.**	• The countermeasures in the AM all assume definite recovery from station blackout so there isn't any countermeasure against loss of all AC and DC power at once. The plant was designed to be able to supply 8 hours of DC power in case of power outage, but it did not work. In Fukushima Dai-ichi Unit 3, where DC power was retained, the DC power lasted more than a day (1.5 – 3 days) by cutting off unnecessary power consumption, but they failed to set up the low pressure cooling system for backup during this period. When the batteries were depleted the plant lost its high pressure cooling system, and instrumentation in the main control room stop functioning.	▪ **Secure alternative AC power supply** ▪ **Secure alternative DC power supply** ▪ **Create manual for swift installation**
▪ **Dai-ichi Reactors 5 & 6 shared power, but unable to supply power to Reactors 1 - 4**	• The DG in Fukushima Dai-ichi Unit 6 still worked and they were able to connect power to Unit 5. This together with the use of the power supply vehicle allowed cold shutdown in Dai-ichi Reactors 5 & 6. There was no power line connecting from Units 5 & 6 to Units 1 - 4.	▪ **Improve power supply line within the site (per voltage class)**
▪ **Delay to supply and insufficient number of power supply vehicles**	• After the tsunami, some plants were able to partially restore power with the power supply vehicle. Utilization of power supply vehicles was effective.	▪ **Increase number and variety of power supply vehicles, revise designations, define connection areas and procedures, and reinforce training.**
▪ **Complete darkness in the main control room due to DC power outage** ▪ **Instant loss of parameter monitoring and control functions**	• The greatest fear and cause of despair for operators is the loss of the parameter monitoring function. In a severe accident such as this one, operators need to be calm and utilize their knowledge and skills acquired through training to stabilize the plant and bring it to cold shutdown. In order to achieve this, it is crucial to maintain instrumentation and control switches (and power for it).	▪ **Increase number and variety of alternative DC power supplies for maintaining monitoring functions.**

Power Outage (Fukushima Dai-ichi, Dai-ni, Higashi Dori, Onagawa, Tokai Dai-ni) - 1

Cause	Event / Issue	Measures / Lessons
Loss of power from earthquake and after shocks	External power: On 3/11, Fukushima Dai-ichi, Tokai Dai-ni, and Higashi Dori experienced external power outage. On 4/7 external power in Higashi Dori was cut-off again (emergency DG automatically activated in both cases). For defense-in-depth, it's important to have power transmission equipment that doesn't rely on emergency DG, especially in Higashi Dori where external power outage occurred twice in 1 month. The vulnerability of the power transmission system was evident. Earthquake caused the power outage in both cases, so it's recommended that the power transmission network be expanded, and earthquake resistance improved on switching stations and substations .	**Expand power supply network** **Reinforce earthquake resistance of power substation facilities and switching station**
Failure of the emergency DG, seawater coolant pumps, and cooling system caused by the tsunami and flooding.	Emergency DG Power: Emergency DGs stopped working either from flooding in the DG or in the seawater pump facility in Fukushima Dai-ichi, Dai-ni, Onagawa, and Tokai Dai-ni.	**Identify how the floodwaters entered the Emergency DG room and implement countermeasures** **Flood prevention and reinforcement of water protection of coolant pump** **Secure spare parts for emergency DG**
No anticipation or procedure for handling instant DC power outage and alternative power backup.	DC power: DC power supply was lost due to flooding in Fukushima Dai-ichi. Loss of DC power greatly effected the field environment. Measuring instruments and operation of high pressure cooling systems stopped working. This lead to the critical accident. This event has made us reaffirm that DC power supply is the most important equipment.	**Reconsider location of DC power** **Flood defense measures** **Upgrade battery capacity** **Secure alternative DC power, DC power supply vehicles, and means of battery charging**
Loss of power path such as M/C and P/C due to flooding.	The tsunami flooding damaged the power paths such as M/C and P/C in Fukushima Dai-ichi and Dai-ni. In other plants M/C and P/C stopped functioning from partial loss of power. In both cases, crucial responses such as cooling and venting of the reactor were affected .	**Consider relocating power panel to higher area** **Prepare power supply vehicles, cables, connection terminal systems, and connection route** **Equip specific procedures and reinforce training**

Power Outage (Fukushima Dai-ichi, Dai-ni, Higashi Dori, Onagawa, Tokai Dai-ni) - 2

Cause	Event / Issue	Measures / Lessons
・Insufficient number of power supply vehicles. **・Delay in arrival of additional vehicles.** **・Insufficient backup batteries, temporary orders, compact generators, etc.**	• Power supply vehicles: If necessary load for power supply vehicles had been predetermined, sufficient amount of units secured, and vehicles arrived quickly, the result could have turned out better, especially in Fukushima Dai-ichi.	**・Increase number of permanent power supply vehicles (multiplex) (DC, AC, mix)** **・Prepare emergency kit for power blackout (batteries, lights, compact generators, fuel, cables, etc.)** **・Create manuals for aforementioned items, and conduct training.**
・Not prepared to restore power, high pressure cooling system, and depressurization functions under severe and adverse environment. Insufficient AM countermeasures.	• Emergency DG, all AC power, DC power, and emergency seawater pumps ceased to function instantly from the tsunami flooding in Fukushima Dai-ichi. Restoration process was conducted in an overwhelmingly adverse environment. It was extremely difficult to maintain the high pressure cooling system and to switch to low pressure cooling (preparations, etc.). This chain of events is one of the main causes of the hydrogen explosion that occurred in the plant.	**・Reinforce training simulating worst case scenario. (Conduct continuous training repeating the following: set target restoration time, record actual completion time, and evaluate results.)**

Loss of Seawater Cooling Function (Fukushima Dai-ichi)

Cause	Event / Issue	Measures / Lessons
· Secure emergency DG **· Power sharing function** **· Reconstruct seawater cooling system that doesn't consume time**	• The tsunami didn't reach the Fukushima Dai-ichi Unit 6 air-cooled emergency DG. Power was shared between Reactors 5 and 6, and supplied to the RHR pumps. By preparing a temporary seawater pump and power supply vehicle, they were able to reconstruct the seawater cooling system and achieve cold shutdown. Learning from this experience, connection route should be defined (i.e. in the manual), and training conducted periodically to enable prompt response to such situations.	**· Reaffirmed the importance of emergency DG and the power sharing capabilities** **· Conduct periodic training simulating similar events**
· Vulnerability of emergency DG (water cool) cooling function (seawater pump, motor, etc.).	• In Fukushima Dai-ichi Reactors 1 – 6, all seawater pumps stopped functioning due to the flooding by the tsunami resulting to loss of seawater cooling system (ultimate heat sink). Although the emergency DG was also flooded and malfunctioned, even if it did survive the tsunami, the DG would still have stopped with the malfunction of the cooling equipment (seawater pumps, motors, etc.). When emergency DG stops, a chain reaction causes the ECCS pump to stop working as well.	**· Secure seawater cooling system, backup water pump, power supply, fuel, etc.** **· Prepare air-cooled DG line (not dependent of seawater)** **· Consider using motor with strong water protection**
· Loss of seawater cooling function	• Fukushima Dai-ichi 1 – 3 was not able to achieve cold shutdown due to loss of seawater cooling function.	**· Same as above.**

Comparison with other Power Plants

Cause	Event / Issue	Measures / Lessons
・ **Retained external power** ・ **Retained main control room function** ・ **Secured time for recovery with the high pressure cooling system.** ・ **No delay in the restoration and operation of seawater cooling system.**	• Plants that were able to secure external power supply achieved cold shutdown. — Fukushima Dai-ni was able to secure 1 external power system. — They lost DG and seawater cooling system from the tsunami but with the external power they were able to maintain main control room functions. With DC power, they were able to maintain high pressure cooling by using the RCIC and the SR valve. — This bought them time to restore the emergency seawater pumps and power the necessary pumps.	・ **Reaffirmed the importance of external power.** ・ **Reaffirmed the effectiveness of AM when external power and DC power are available.**
・ **Same as above.**	• In the Onagawa power plant, Reactors 2 & 3 were able to secure 1 external power system which allowed them to maintain the seawater cooling system and succeed in implementing standard cold shutdown. — Unit 1 lost external power, and DG was activated. — Achieved cold shutdown by maintaining seawater cooling function. • Cold shutdown can be achieved by maintaining power and securing seawater pump functions.	・ **Same as above.** ・ **Importance of seawater cooling function.** ・ **Secure alternative equipment when main equipment is damaged.** ・ **Affirmed the importance of recovery process training.**
・ **Same as above.**	• Partial flooding of seawater pumps caused emergency DG to stop in Onagawa Unit 2, and Tokai Dai-ni. (2 DG units in Onagawa Unit 2, and 1 unit in Tokai Dai-ni were lost.) — There's no denying that the situation could have been the same as with Fukushima Dai-ichi 1 – 3 if all external power and DG had gone out at the same time.	・ **Plants that achieved cold shutdown shouldn't blindly celebrate their successful recovery. They should acknowledge the potential risks they faced and review the necessary countermeasures and training.**

High Pressure Cooling System - 1

Cause	Event / Issue	Measures / Lessons
Loss of all DC power **Unable to read sensors** **Failed main control tower function**	1F Unit 1: Parameter data: The facility lost DC power right after the earthquake and tsunami. Without power, measurement instruments weren't functioning so it was impossible to acquire important parameters such as the core water level. As a result, operators weren't able to determine the actual situation and make appropriate decisions. They had already started making the wrong decisions in handling the high pressure cooling system.	**Countermeasures for main control room power outage.** **Flood prevention to DC power supply (location, water seal, battery water protection)** **Secure backup batteries (battery, DC power supply vehicle)**
Loss of all AC/DC power **Failed IC valve operation**	1F Unit 1: IC cooling and depressurization: Similarly, without AC/DC power, operators were unable to adjust the valves of the high pressure cooling system (IC). As a result, operating the high pressure cooling system was almost impossible. It can be inferred that water injection and depressurization failed. Our theory is that the core's water level was decreasing while temperature and pressure kept rising and damage is estimated to have started 3 hours after the tsunami.	**Restore AC & DC power within 2 hours?** **In addition (to AC), allow direct valve adjustment?** **Consider valve adjustment mechanism that doesn't rely on electricity (manual & auto).**
Loss of all AC/DC power **Failed HPCI valve operation**	1F Unit 1: HPCI water injection and depressurization: Similarly, without AC/DC power, operators were unable to adjust the valves of the HPCI system and failed to perform water injection.	**Same as above.**
Incompleteness of multiplex defense in the AM **Delay in depressurization and preparation for low pressure cooling**	1F Unit 1: AM ineffective due to unavailable measurement data and high pressure cooling system: With the complete AC/DC power outage, the plant didn't have enough time to prepare for transition from high pressure to low pressure cooling according to the AM (+ α expertise of site personnel) because everyone was busy securing AC power (power supply vehicle), securing DC power (car batteries), vent line setup (manual), low pressure coolant injection setup (fire truck, hose, water supply for fire extinguishing), etc.	**Design AM that anticipates instant and concurrent loss of entire AC and DC power (unable to recharge batteries due to flooding).**
Activation of RCIC	Effectiveness of the RCIC: Unit 1 lost its IC system and wasn't able to maintain high pressure cooling. But in Unit 2, RCIC was activated and continued working. It is believed that the RCIC kept the pressure in the S/C within the estimated limit of 0Ka (abs) for 3 – 4 days after the tsunami, before the containment vessel was eventually damaged.	**Reaffirmed effectiveness and importance of maintaining high pressure cooling system.** **Important to provide procedures and training for preparing and setting up low pressure cooling system while the high pressure cooling system is working.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

High Pressure Cooling System - 2

Cause	Event / Issue	Measures / Lessons
Fukushima Unit 1 hydrogen explosion	1F Unit 2: Set up of high pressure cooling system incomplete – repeated interruption and damage to the water injection line from hydrogen explosion (3/12): Response unit completed the preparation for backup water injection to the core, and connected the power supply vehicle to a working P/C, but the cables and the power supply vehicle were destroyed when Unit 1 exploded on 3/12 and everything had to be set up from scratch again.	**Review the risks involved in operating multiple plants** **Absolute prevention of hydrogen explosion**
Same as above. (Unit 3)	1F Unit2: Same as above (3/14): The response unit was able set up a seawater injection line using fire trucks and hoses, but the hydrogen explosion in Unit 3 on 3/14 destroyed the fire trucks and hoses and everything had to be set up from scratch again.	**Same as above.**
Frequent aftershocks	1F Unit 2: Effect of aftershocks: In parallel with previous items, repeated aftershocks interrupted the setup of injection line, and as a result the response unit was not able to execute in time.	**Redesign AM and training anticipating overwhelmingly poor environment**
Incomplete coverage in the AM	1F Unit 2: Incomplete coverage in the AM: As a result of the events above, they failed to make any effective actions to maintain high pressure cooling except for the RCIC which survived through tsunami.	**Same as above (including instant loss of power, cooling function, and seawater circulation system, as well as frequent aftershocks)**
Maintain DC power **Failed to secure alternative power source during this period**	1F Unit 3: Importance of DC power and Effectiveness of RCIC: DC power (DC125V Main bus board 3A and 3B) survived the earthquake and tsunami, and it was used to power the high pressure system (RCIC or HPCI). However, the plant wasn't able to secure backup power, and DC power was depleted up after 35 hours from activation of RCIC. At this point, HPCI was already halted. Consequently, the plant failed to decrease the reactor's pressure and recover the water level. (We were able to verify that the batteries were depleted so our theory is that this is the reason the system stopped.)	**Reaffirmed importance of DC power and RCIC** **Secure additional power sources; reinforce and conduct training**
Use of car batteries **Activation of HPCI**	1F Unit 3: Effectiveness of HPCI: The batteries depleted on 3/12, at 11:36, causing the RCIC to stop. HPCI was activated on the same day at 12:35. During this period of time the core pressure dropped from 7.53MPa to 0.58MPa, but went back up to 7.4MPa on 3/13, 2:42, when the batteries for HPCI were depleted (cause of HPCI halt is believed to be depleted batteries since the batteries were found and confirmed).	**Same as above.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

High Pressure Cooling System - 3

Cause	Event / Issue	Measures / Lessons
AM incomplete (Secure extra DC power and backup power) **Same as above. (Devise countermeasures to events when DC power is lost from flooding and batteries can't be charged.)**	1F Unit 3: AM incomplete (Secure extra DC power supply or backup power supply): 1F Unit 3 was the only reactor among Reactors 1 - 4 that retained its DC power supply. However, looking at the chronology, there is no evidence of additional backup power source being secured before the DC power supply was consumed (though used car batteries from employees' cars and other sources after HPCI stopped). Furthermore, there is no trace of reserve DC power batteries stored in the reactor building or in the seismic isolation tower. Storing of reserved batteries for emergency, such as in this case, may not have been specified in the AM (= it seems that they have no other measures than to restore the AC power within 8 hours (battery life) and then to recharge DC batteries when the AC power is restored). As a result, high pressure cooling systems such as the RCIC and HPCI had to stop prematurely.	**Reserve extra DC batteries (multiplex - since batteries can no longer be charged if flooded)**
AM incomplete (No defense-in-depth for DC power?)	1F Unit 3: AM incomplete (defense-in-depth for DC power): This is related to the previous item. It seems that AM provides only one solution for high pressure system (RCIC/HPCI) power recovery. It only seems to "restore AC power within 8 hours (the life span of the DC batteries) and recharge the batteries with the AC power." This leads to the conclusion that the facility has weaknesses in its defense-in-depth for DC power.	**Same as above.** **Update AM and training to include responding to instant loss of all DC power supplies from flooding (batteries can't be recharged).**
Restoration process under unexpected field condition (not covered by AM)	1F Unit 3: AM ineffective (core reactor scram & loss of AC power): Of all units of 1F, it is believed that only the event in Unit 3 was within the scope of the AM manual (earthquake, AC power outage, core reactor scram, DC power utilization (8hrs)). However, Unit 3 was not able to achieve cold shutdown. Although they were able to prevent damage to the core for 36 hrs by powering the high pressure cooling systems (RCIC and HPIC) with the DC power supply, they were not able to "restore AC power, depressurize the reactor core, and make the transition to low pressure cooling" as indicated in the AM.	**Same as above.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Ventilation System (Depressurization with SR valve operation) - 1

Cause	Event / Issue	Measures / Lessons
Loss of all AC & DC power **SR valve malfunction**	1F Unit 1: SRV non-functional due to loss of DC power: The SRV (safety release valve) which is used by the high pressure cooling system stopped functioning due to loss of all AC and DC power from the earthquake and tsunami. In Unit 1, the SRV didn't work at all. Because of this, workers decided to reduce core pressure by using IC. However, partially due to the adverse environment the IC didn't function as designed. At the end, site workers failed in reducing the core pressure, and it continued to build. (Regarding the decrease in the nuclear reactor pressure, SR valve may have been stuck, and steam may have leaked from the SRV flange section gasket due to the rise in pressure vessel temperature. This may have reduced the pressure in the nuclear reactor, but at this point these are just conjecture.)	**Multiplex DC power (extra batteries, and allow charging from battery vehicles and AC power supply vehicle)** **Improve water protection of DC power supplies (batteries) (safer storage location or water seal of the batteries themselves)** **Store spare batteries, and optimize installation time.** **Increase number of response unit members and conduct training to achieve the above.** **What about using a mechanism that doesn't rely on DC power to operate the SRV?**
Same as above.	1F Unit 2: SRV non-functional due to loss of DC power: Same as above. (=> P/C (2A, 2B, 2C, 2D) were working, but like in Unit 1 the entire battery room, where the DC batteries were stored, was flooded. Without power the SRV didn't function.) When the RCIC stopped, they decided to depressurize the nuclear core reactor to perform lower pressure water injection, so workers used spare batteries to power the SRV to perform the depressurization operation.	
Same as above. **Delay in securing spare batteries** **Delay in setting up water injection line for fire truck?**	1F Unit 3: Delay of depressurization (SRV) due to lack of batteries.: With DC power (3A, 3B) available, plant workers followed the manual and cut unnecessary power consumption to buy more time for RCIC/HPCI to work. The batteries provided power for approximately 35 hours until the HPCI was tripped. After the HPCI stopped working, workers attempted to depressurize the reactor to inject water via fire truck hose, but weren't able to operate the SRV because there was no power. So they collected the car batteries from the employees' cars, and at 3/13, 9:08, they were finally able to operate the SRV and depressurize the reactor (HPCI stopped at 2:42, 3/13; pressure relieved 6 hours after). Later at 9:25 the fire trucks arrived and started the alternative water injection (one truck from 1F 5 & 6, and one more from 2F).	**Same as above.** **Upgrade regular DC power supplies (extended battery life)** **Reduce the time spent for setting up water injection line for fire trucks.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Ventilation System (Depressurization with SR valve operation) - 2

Cause	Event / Issue	Measures / Lessons
· Secured external power **· Secured DC power** **· RCIC was functioning** **· Set up line for low pressure cooling**	• 2F Unit 2: Successful case in pressure vessel depressurization with the SRV: 2F Unit 2 lost its emergency DG from the flooding of tsunami, and its ultimate heat sink. However, the facility was able to receive external power, and the power panels and DC power supplies were working. They were able to maintain the water level of the nuclear reactor with RCIC, which bought time for setting up the line for the Make-up Water Condensate system (MUWC). After setting up MUWC, operators adjusted the SRV, depressurizing the reactor as planned. After that, they performed low pressure coolant injection and achieved cold shutdown => Importance of external and DC power.	**· Reconfirmed the importance of the following:** **— External and DC power** **— RCIC (with power)** **— Low pressure cooling system (with power)**
· Failed to secure power **· Failed in high pressure cooling (from lack of power)** **· Failed to depressurize (SRV)**	• 1F Units 1-3: Limitation of AM (Especially with risks in failing high pressure cooling): Nuclear reactor depressurization operation was performed on Units 1-3 after the high pressure cooling stopped working. They weren't able to set up the transition to low pressure cooling while the high pressure cooling system was running. It is believed that the delay was partially caused by the unprecedented adverse field condition.	**· Same as above.** **· Revise AM (integrate unexpected incidents learned from this event)** **· Same as above (Provide judgment base for determining plausibility of cold shutdown with the standard operating procedure. Also provide timeframe as to when to start setting up the low pressure system.)** **· In addition to the previous items, provide alternative action guidelines (the guideline should aim to prevent the worst case scenario instead of aiming for perfection. For example, prevention of hydrogen explosion, venting reactor building, seawater injection, rapidest depressurization using IC, etc)** **· Maintain worker's ability to respond to emergency situations with regular training.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Ventilation System (PCV vent) - 1

Cause	Event / Issue	Measures / Lessons
AC & DC power outage **Complete darkness inside the building** **Increasing dosage rate in the building with the progression of core reactor damage** **Frequent aftershocks (required temporary evacuation)** **Lack of pressure from air compressor** **Delay in arranging and transport of equipment such as air compressors and adaptors.** **Delay in venting containment vessel**	1F Unit 1: <u>Delay in PCV operation</u>: On 3/12 (00:06), orders were given out to prepare for vent operation, when workers realized that D/W pressure may have exceeded 600k Pa abs. However, the actual vent operation was performed at 14:30 on that day. The operation started at 09:04 but took approx. five and a half hours to complete. The reasons are: – No power to the valve (no AC & DC power) – Complete darkness inside the building due to blackout (except for main control room) – Increasing dosage rates paralleled with the progression of core reactor damage (especially at basement 1) – Orders to stop field work due to frequent aftershocks – Work halted until evacuation of neighboring residents completed. Insufficient means of communication for progress updates. – Lacking means of communication between main control room and field workers inspecting the vents – Failed in vent release due to lack of pressure from air compressor – Time consumed by arranging for temporary air compressor, delivering adapters, and transporting. Although they were able to vent the containment vessel and confirm the drop in pressure, the reactor building exploded approximately an hour after.	**Secure power (DC, AC, and backup power supplies)** **Confirm availability of emergency lights (installed in reactor building, and portable lights for field work)** **Secure emergency communication methods** **Secure extra compressors and adaptors** **Change the ventilation system. Ventilation should be performed even in the event of SBO (a system that allows ventilation operation remotely with reserved power (manual release as a last resort))**
RD operation pressure	1F Unit 2: <u>S/C vent failure due to high operation pressure of Rupture Disk (RD)</u>: In the initial attempt to vent the S/C, the workers had to overcome an obstacle in which the circuit board for energizing the solenoid valve was dislodged by the explosion in Unit 3. On the same day around 21:00, workers had completed constructing all vent lines except for the RD, but even with the D/W pressure exceeding its max capacity of 427 Pa gage (530k Pa abs), the pressure in S/C was not enough to move the RD. At 23:35, they decided that the operation was a failure and had no choice but to switch to D/W venting.	**Review RD operation pressure.** **Confirm reason for setting high pressure configuration to open the disk.** (The operation pressure was set to a little under 2 times the designed pressure value. This was done with the hopes of preventing the release of radioactive materials. But this action may have contributed to hydrogen density exceeding 4% when hydrogen (generated due to fuel damage) leaked out from the containment vessel.) **Consider replacing RDs with valve-operated ventilation system.**
Same as above.	1F Unit 2: <u>D/W vent failure</u>: On 3/15 (apprx. 00:02) after failing the vent operation in the previous issue, the attempt to open the D/W vent commenced. The preparation of the vent line was completed on 3/15, at 0:02. Although the D/W pressure shifted with the average of 750k Pa abs, after a few minutes the vent was confirmed to be shut. Around 6:00 - 6:10 the same day, it is estimated that severe damage to the PCV had occurred, judging from the record that the S/C pressure was 0K Pa. Ventilation failed.	

Ventilation System (PCV vent) - 2

Cause	Event / Issue	Measures / Lessons
▪ **Insufficient pressure from air compressor** ▪ **Faulty solenoid valve** ▪ **Delay in vent line setup**	• 1F Unit 2: Delay in vent line setup due to lack of pressure from air compressor and faulty solenoid valve: After the Unit 3 explosion on March 14 (11:01), workers attempted to open the S/C vent valve (large AO valve) but failed. The pressure from the air compressor wasn’t enough. It is postulated that the AO valve couldn’t be opened in processes with the same line up due to a faulty solenoid valve.	▪ **Consider a vent system that doesn't use air pressure (prepare temporary compressor, field environment management, line construction that allows connection; change to a valve that allows manual operation).**
▪ **Complete darkness** ▪ **Hot and humid work environment** ▪ **Difficulty in vent line setup**	• 1F Unit 3: Slow W/W vent set up progress due to the dark, hot and humid work environment: On March 12, at approximately 4:50 (RCIC still running) after energizing the S/C vent solenoid valve with the main control room’s compact generator, the shift workers went to the torus room to confirm if the valve was open. However, they found that the room was in complete darkness, and temperature and humidity was high because of steam coming out from the SR vent valve of S/C. The work environment was tough and they were making very slow progress. Also on March 13 around 11:00-12:00, workers once again entered the torus room in an attempt to lock the S/C vent valve (AO valve), but weren’t able to complete the task due to increased temperature and vibration from the SR valve.	▪ **Review and reconsider position of the valve**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Ventilation System (PCV vent) - 3

Cause	Event / Issue	Measures / Lessons
Delay in air cylinder replacement	1F Unit 3: Delay due to air cylinder replacement: On March 12, at approx. 5:23, workers attempted to open the S/C vent (AO vent) but failed. Second attempt, after replacing the air cylinder, was successful.	**Secure extra air cylinder for operating vent valve.** **Include replacing of air cylinder in the training.**
Reduced pressure of air cylinder due to leak	1F Unit 3: Problem keeping the vent valve open due to a defect in the air cylinder: On March 13, after vent was successfully performed, the S/C vent valve (AO large vent) was closed again at approx. 11:17 due to a leak in the air cylinder.	**Reinforce the joints and connections of the air cylinder (ensure reliability of air supply line by improving its safety, or secure backups (multiplex)).**
Insufficient air pressure supplied to the large valve **Energizing of solenoid valve unstable**	1F Unit 3: Difficulty maintaining air pressure for operating the large valve and energizing the air supply line's solenoid valve: Although Unit 3 succeeded in venting, workers were having difficulty keeping the vent open (or failed). The postulated reason is a problem with the air pressure used to operate the large valve, and a problem the with air supply line's solenoid valve (unable to energize consistently). This seemed to have occurred 5 times after the explosion.	**Review the vent mechanism and improve its ability to maintain open state (strengthen air supply line, or secure backups (multiplex)).**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Low Pressure Cooling Function - 1

Cause

- **Difficulties and delays in supplying water via fire trucks**
- **Trouble with the diesel-driven fire pump**
- **Damage to fire hydrant from earthquake and tsunami, and filtered water was gushing out**
- **Time consumed searching for alternative water source**
- **Not enough fire trucks**
- **Fire truck mobility issues due to adverse environment**
- **Delay in setting up water injection line from fire truck**
- **Insufficient water injection capacity of fire trucks**

Event / Issue

- 1F Unit 1: <u>Difficulties in supplying water from fire truck, and delay in commencing</u>: As early as March 11, 17:12, instructions to consider water injection from the fire line and fire trucks were given. However, the diesel-generated fire pump was having trouble, so the decision was made to inject water directly from the fire line, instead of using the fire truck (March 12, 1:48). From the previous item, setting up water injection line from fire truck (loading water to fire truck, transport the truck to reactor building, connecting the truck with water protection system line) was time consuming. The injection process started at 5:46 (3/12).
The main reasons are as follow:

  - Trouble with the diesel-driven fire pump
  - Damage to fire hydrant from earthquake and tsunami - filtered water was gushing out (valve closed manually to stop water outflow)
  - Time consumed searching for alternative water source (after surveying the site, they discovered that fire protection tank can be used)
  - Not enough fire trucks (of the 3 trucks, 1 was damaged by the tsunami, 1 was at Units 5 & 6 and was unable to transfer due to liquefaction)
  - Trouble moving the fire trucks due to adverse environment (gasoline tank blocking the road, main gate stuck due to blackout. Workers had to destroy the lock on the gate between Units 2 and 3 to create passage)
  - Delay in setting up water injection line from fire truck (ordering for fire trucks, transport to reactor building, connecting to fire protection system line)
  - Insufficient water injection capacity of fire truck (1000 liters per payload)

On March 12, filling of water to the reactor started at 5:46 and finished at 14:53 (total of 80 tons of water). At first they were only able to fill 1000 liters at a time, but later were able to fill water continuously. Before then the fire truck had to make laps for refills. Fast-progressing events required a more efficient response.

Measures / Lessons

- **Reinforce and add more backup water sources (install large fire protection tank)**
- **Increase number of fire trucks and hoses**
- **Review posting of fire trucks**
- **Secure predetermined route for fire trucks (for smooth transport during blackouts)**
- **Secure backup power supplies and pumps; upgrade fire truck; etc.**
- **Investigate cause of the diesel-driven fire pump problem, and come up with a countermeasure.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Low Pressure Cooling Function - 2

Cause	Event / Issue	Measures / Lessons
Problem with the fire protection tank's design **Inefficient water injection**	1F Unit 1: Inefficient water injection from the fire protection tank: Laps had to be made in loading fresh water from the Unit 3 fire protection tank and transporting it to the Unit 1 fire protection tank. The fire protection tanks only have one hose connection, so workers had no choice but to remove the injection hose and interrupt the injection each time it needed to be refilled.	**Review the design of the hose connection of fire protection tank**
Delay in boric acid injection (SLC)	1F Unit 1: Delay in setting up boric acid injection (SLC): Concurrently with the water injection process (via fire truck), power restoration (via power supply vehicles) and boric acid injection (SLC), pump restoration processes were ongoing. Preparation for boric acid injection was completed on March 12 (15:36), but the plant building exploded right after it was completed (15:36). SLC pump cables and the high pressure power supply vehicle were destroyed, rendered unusable.	**Secure backup power supplies (high pressure power supply vehicle)** **Supply more cables and fire trucks**
Same as above (due to explosion)	1F Unit 1: Delay in boric acid injection (SLC): After the explosion on March 12 (19:04), seawater injection through the fire protection line by fire truck commenced. Injection of seawater mixed with boric started later at 20:45.	

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

General lessons - 1

Cause	Event / Issue	Measures / Lessons
Difficulties in executing countermeasures due to overwhelmingly unexpected events, and severe accident	General AM: Overlaying difficulties and delays in executing countermeasures: As part of accident management the low pressure water injection had been enhanced, and manuals had been distributed. The actual work field environment was adverse, and extra time was required to restore power and perform low pressure water injection. They were unable to contain the situation.	**Improve the AM training to respond to more specific situations, and continue the training on a regular basis (effects of the earthquake and tsunami like this, setting of specific target completion times of actions, confirm the time required, accrue know-how)**
Insufficient daily training of AM actions in anticipating scenarios of previous item.	AM: Anticipate accidents at night time / on holiday: The field response of this event was difficult and slow because of the adverse field environment. Debris was scattered by the earthquake and tsunami, and much of the work had to be done during the night.	**Practical training simulating power outage during night / holidays** **Improve and standardize night time visibility of valves and gauges (use of fluorescent paint, etc.)**
Risk of sharing water source and injection line for multiple purposes	Water source & water line: Risk of sharing for multiple purpose: We learned the importance of fire protection system from the incident in Kashiwazaki-Kariwa Plant when the transformer in Unit 3 caught fire during the Chuetsu offshore earthquake. As for this event, the M/C power panel in Onagawa Unit 1 caught fire. There was no fire in Fukushima Dai-ichi, which allowed them to use the power protection line and water source for lower pressure water injection. But if a fire had occurred, it can't be denied that it could have caused further problems in addition to plant water injection.	**Consider segregating water sources** **(Multiplex) Increase number of water source for the most important ones (take into account water source for fire response as well)**
Risk of placing multiple plants in the same location. **Difficulties of handling severe accidents simultaneously occurring in multiple plants. The plants were not prepared for this sort of situation.**	General AM: Risk of operating multiple plants in the same location: Nuclear Emergency Response Headquarters of Fukushima Dai-ichi Units 1 – 4 prioritized responding to Unit 1 because it wasn't able to maintain high pressure cooling with IC. Units 2 & 3 weren't given priority since RCIC high pressure cooling was working. The decision was the right one at that time. However, looking at the fuel rod damage chronology of Units 2 & 3, they would have been able to avoid the worst-case scenario if they had been able to set up the low pressure cooling system before the DC power of RCIC was depleted.	**Identify the issues with the field response system** **Identify the problems encountered due to severe accidents simultaneously occurring at multiple plants** **Reflect the previous two items in the manual and conduct training.**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

General lesson - 2

Cause	Event / Issue	Measures / Lessons
Rupture-disk pressure setting in Dai-ichi Unit 2 is too high.	Dai-ichi Unit 2: Difficulties in venting R/D (required pressure was high): Dai-ichi Unit 1 and Unit 3 succeeded in venting the containment vessel suppression chamber (S/C). However, the same ventilation in Unit 2 failed to open even with the drywell pressure exceeding maximum capacity. The S/C pressure wasn't sufficient to move the rupture disk (R/D). After that, a system to release the drywell pressure was set up, but S/C was damaged and the ventilation process was once again unsuccessful.	**Reconsider the pressure settings of the rupture disk** **Regular inspection and replacement of rupture disk**
Relation between the PCV vent and hydrogen explosion **Unclear mechanism of Hydrogen leak**	Dai-ichi Units 1 & 3: Relation between the containment vessel vent and hydrogen explosion: Hydrogen explosion occurred in 1F-Unit 1 and 3 one to two hours after successful venting of PCV. The hydrogen produced inside the reactor by molten fuel may have transferred and filled the containment vessel when the SR valve was operated, and released steam to the suppression pool. The hydrogen then probably leaked to the reactor building through the containment vessel's routing channels and vent line, or back flowed from the SGTS line connected to the exhaust stack. And finally when the hydrogen accumulated beyond the combustible limit, the explosion occurred. In this project we have taken into account the possibility that the hydrogen accumulation speeded up by the ventilation of PCV. Actual details, and cause and effect are still unclear, so we are hoping that it will be solved.	**Identify the leak path of hydrogen into the reactor building** **Devise countermeasures for hydrogen leak** **Review vent in post core meltdown (nitrogen sealing, operation pressure)** **Prevention of hydrogen accumulation in reactor building and exhaust system**
Extended external power outage **Extended DC power outage**	General: Risk of extended external and DC power outage: The loss of external power and of emergency DG, and malfunction of seawater cooling system occurred in Fukushima Dai-ichi, Dai-ni, Onagawa, and Tokai Dai-ni. Only Fukushima Dai-ichi lost its DC power as well. By securing external power, the plant was able to retain its high pressure cooling system, buying time to restore the seawater pumps and motors for the low pressure cooling system, and deploy power supply vehicles. Prolonged station blackout depleted the DC power, and meant loss of hope for restoring the plant. Without the seawater pumps the DG won't function. This increases the urgency to restore external power for the seawater pump.	**Increase number of temporary DC and AC power supplies** **Prepare connection devices for alternative power supplies** **Reinforce training**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

General lesson - 3

Cause	Event / Issue	Measures / Lessons
· May not have considered the relation between vent operation pressure and hydrogen explosion. **· May have lack of understanding of hydrogen explosion risks, and lack of countermeasures in AM.**	• Fukushima Dai-ichi (General): Relation between the mechanism of hydrogen explosion and vent operation: Compared to other electric companies, TEPCO had configured a higher value for the vent operating pressure. They thought that this will further decrease the chance of releasing radioactive materials to neighboring residences. However, this decision may have been one of the main reasons the hydrogen explosion occurred. It is postulated to have caused massive build up of hydrogen in the containment vessel. Further, regarding the hydrogen explosion there is no record of a backup plan in the response chronology of Unit 1. We assume that this accident was not expected by TEPCO.	**· Identify the mechanism of hydrogen explosion (leakage path, accumulation path, ignition cause, etc.)** **· Prevent hydrogen accumulation (detector, reactor building vent, etc)** **· Verify the relation between the vent and hydrogen explosion** **· Reflect changes to corresponding manuals**
· Loss of function as main control tower due to SBO	• Fukushima Dai-ichi (General): Effect of the incomplete main control room functions: The station blackout disabled the instrumentation and took away the indicator monitoring capability from the operators. Without this capability, it's impossible to plan the next move. Additionally, when the nuclear reactor is at high temperature, it's doubtful whether the data given by the measuring instruments powered by temporary supply is accurate. Without indications and data, operators will start to fear, which affects their ability to make proper judgments. Operators must be equipped in order to be able to make proper judgments.	**· Secure main control room lights, field environment, measuring instruments, etc. (power, lights, work clothes, dosimeters, furniture)** **· Review AM procedure and reinforce constant daily training** **· Apply remote measuring instruments**
· Hydrogen explosion **· Leak of radioactive materials from explosion**	• Fukushima Dai-ichi (General): Radiation leaked to the environment when Units 1 – 4 exploded, causing enormous damage to the local community. Today, there are many that suffer from the effects of land contamination and radiation exposure. The spread of Cesium 137 (from the explosion) has a long term effect, and is an especially big problem. The most important things are to prevent a hydrogen explosion at all cost, prevent the spread of radioactive materials, and to minimize those effect.	**· Prevent hydrogen explosion** **· Prevent leak/release of radioactive material (Consider installing filter vent)**

Note: 1F = Fukushima Dai-ichi power plant, 2F = Fukushima Dai-ni power plant

Lessons Learned and Safety Measures

─ Safety Measures ─

Safety Measure: Secure power supply - 1

Purpose

Secure power

Secure control room functions

Secure high pressure cooling system

Secure vent function

Secure low pressure cooling system

Secure ultimate heat sink

Prevent hydrogen explosion / radiation leak

Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Secure external DC power supply

- Improve water protection and pressure resistance of switching stations.
- Switching stations should be located on elevated areas, or sea-walls should be built to protect the equipment from tsunami.
- Evaluate and improve earthquake resistance of switching stations, transmission line towers and power plants. Furthermore, include earthquake resistance in the design requirements.
- Minimize frequency of external power outage by drawing multiple power lines from the substation (minimum of two separate lines), or connect external power of all plants in a network for all the plant to share power source of each plant.

(Mid to long term countermeasures)

- Regarding the power transmission from substation , switch from wires to underground cable.
- Remote control: Secure power transmission route and cables for supplying power to the reactor from the power supply vehicle with remote control function. (Or is it possible to supply without wires?)
- Improve earthquake resistance of substations and include it in the design requirements.

Secure emergency diesel generator (DG)

- Apply countermeasure to DG room's air inlet against flooding.
- Improve water tightness and pressure resistance of DG rooms.
- Store control and power cables to allow power interchange between separate DG rooms.

(Mid to long term measures)

- Place DG equipment on elevated areas (DG, power panel, etc.)
- Improve DG power interchange function: interconnect all DG to allow sharing of power to all nuclear reactors (Unit 5 & 6 were able to share power each other, but not designed so with Unit 1 to 4).
- Plant should be designed to function with minor flooding.
- The plant is vulnerable to an accident during regular inspection since DG is also stopped for its own inspection. Install an additional DG to eliminate risk.
  For air-cooling DG, place it in an elevated area together with the gas turbine. Air cooling type doesn’t require seawater pumps and seawater circulation system.
  Set up fresh water cooling DG on an elevated area to avoid damage from tsunami.

Safety Measure (Impact mitigation)

Secure external DC power supply

- None

Secure emergency DG

(Mid to long term measures)

- Automatically activate a DG if scrammed during earthquakes.

Safety Measure: Secure power supply - 2

Purpose

- **Secure power**
- Secure Control room function
- Secure high pressure cooling system
- Secure vent function
- Secure low pressure cooling system
- Secure ultimate heat sink
- Prevent hydrogen explosion / radiation leak
- Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Secure emergency Diesel Generator (DG)

(Mid to long term measures)

- Place diesel and gasoline tanks at an elevated area to avoid damage from tsunami.

Secure DC power

- Relocate equipment to indoors - into a pressure resistant and water tight building to avoid flooding by tsunami.
- Station mobile battery vehicles (DC125V, 24V, and 250V) with cables in case of loss of DC power supplies.

(Mid to long term measures)

- Relocate DC power supplies to a higher place.
- Upgrade DC power supply capacity (from 8 hrs to 24 hrs or more).

Secure AC power

- Improve water protection and pressure resistance of AC power supply equipment.
- Reinforce power supply vehicle:
  - Additional permanent units (secure necessary number of units based on the required load capacity). Review their location (i.e. elevated area)
  - Increase the type of vehicles: DC, AC, AC&DC, w/ generator, w/ DG etc.
- Set multiple power-panel access points for power supply vehicles and secure water protection.
- Increase the number of backup power supplies other than power supply vehicles.
- For quick recovery of AC power, set up power supply cables and store tools for terminal handling in accessible areas for swift response.

(Mid to long term measures)

- Sharing of AC power distribution（Cross-connect all units to allow distribution of power through M/C and P/C）.
- Utilize air transport of power supply vehicle and backup power supply after the tsunami and earthquake have subsided.（Set helipad on the roof/vicinity of the reactor building.）
- Transfer the AC power supply to a higher location.

Safety Measure (Impact mitigation)

Secure emergency DG

- **None**

Secure DC power

- None

Secure AC power

- None

Safety Measure: Secure control room function

Purpose

- Secure power
- **Secure control room function**
- Secure high pressure cooling system
- Secure vent function
- Secure low pressure cooling system
- Secure ultimate heat sink
- Prevent hydrogen explosion / radiation leak
- Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Securing the functions of the control room

● Secure livable condition for operators and monitoring function.

- Since the main control room has to function as a shelter during emergencies, protection against radiation should be improved.

(Mid to long term measures)

- To ensure vent and air conditioning system in the main control room, emergency power systems such as gas turbines should be installed.

Safety Measure (Impact mitigation)

Securing the functions of the control room

● Secure livable condition for operators and monitoring function.

- Store spare batteries in case meters and gauges stop working.
- Store sufficient numbers of protective gear, masks, dosimeters, and other supplies. Since the situation in Fukushima Dai-ichi lasted a number of days, there should be at least a couple of days worth of supplies stored.

(Mid to long term measures)

- Due to power shut down the parameters, such as the reactor’s water level and pressure, were no longer observable. Portable measuring instruments and alternative measurements should be developed .

Safety Measure: Secure high pressure cooling system

Purpose

- Secure power
- Secure control room function
- **Secure high pressure cooling system**
- Secure vent function
- Secure low pressure cooling system
- Secure ultimate heat sink
- Prevent hydrogen explosion / radiation leak
- Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Securing high pressure coolant

- ● The HPCI and RCIC are installed at the basement of the reactor building. Although the reason it stopped working was due to problems with the power, it's still necessary to maintain water seals and pressure resistance of the room to ensure the safety of the pumps and motors inside.
- ● Since the high-pressure water injection can be done by SLC, CRD, and CUW systems, it's important to secure power supplies for these systems. It is necessary to consider storing temporary power supplies to ensure power for the systems.

Safety Measure (Impact mitigation)

Securing high pressure cooling system

- ● Work progress at night was slow. There was a delay in restoring the high pressure cooling system which worsened the situation in the plant, and delayed the staging of the low-pressure cooling system. To improve efficiency of the field work, mark valves and machines with fluorescent paint for easy detection. Coating the temporary power cables with fluorescent paint will provide easy direction to their installed locations.

(Mid to long term measures)

- ● It would take too much time and cause delays in decision making if unable to access the site to confirm the state of the high pressure cooling system. It will be effective to have multiple means to observe the site. This will require power but we suggest installing ITV (for vision), sound monitors, and vibration sensors to allow remote monitoring the status of the pumps, gauges and valves.

Safety Measure: Secure vent function

Purpose

Secure power

Secure control room function

Secure high pressure cooling system

Secure vent function

Secure low pressure cooling system

Secure ultimate heat sink

Prevent hydrogen explosion / radiation leak

Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Secure containment vessel vent function

- None

Depressurization with SR valve operation

- None

Safety Measure (Impact mitigation)

Secure containment vessel vent function

- Prepare items for setting up vent line (temporary power supply, air tank) beforehand for efficiency.
- Because vent operation failed in containment vessel of Unit 2, reconsider the operation guideline on the pressure level in PCV to conduct ventilation (as well as the pressure configuration of the rupture disk).

(Mid to long term measures)

- Install a neutron monitor inside the PCV to observe the activities inside the core during meltdown.
- Multiplex the air pressure supply and vent line and classify them to the 'safety-system' class to ensure the reliability.
- Too much time was consumed in setting up the vent line. Place the valve at an accessible area and allow manual operation.
- Given that ventilation with the rupture disk in reactor No.2 was unsuccessful, consider the use of a valve for ventilation without the disk.

Depressurization with SR valve operation

- Unable to perform depressurization with SR valve due to DC power outage. Prepare batteries in the central control room.

(Mid to long term measures)

- Consider SR valve mechanism that doesn't rely solely on DC power.
- Consider multiple methods for core depressurization.

Safety Measure: Secure Low pressure cooling system

Purpose

- Secure power
- Secure control room function
- Secure high pressure cooling system
- Secure vent function
- **Secure low pressure cooling system**
- Secure ultimate heat sink
- Prevent hydrogen explosion / radiation leak
- Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Secure Low Pressure Cooling System

- Place emergency core cooling pumps, used for low pressure state, at a higher location to avoid damage from tsunami, or secure water protection and pressure resistance.
- Secure appropriate number of fire trucks and hoses, and station the units on high ground. Take into account the water source, water injection range, and water injection capacity when selecting the fire trucks.
- Set multiple water injection points for fire trucks.
- Investigate and determine the cause of trouble with the diesel-driven fire pump. Add the countermeasures to the AM.

(Mid to long term measures)

- Reinforce water source: Supply water from multiple sources such as water tank, dam, reservoir, lake, river, sea. Review whether the methods and capacity are sufficient. If the water will be used as a coolant, consider the following:
  - Whether boric acid can be added.
  - Develop circulation system that allows contaminated water in the reactor building to be used as coolant.
  - Prepare multiple routes for the coolant.

Safety Measure (Impact mitigation)

Secure Low Pressure Cooling System

- Reinforce water supply paths: Confirm other means of water supply than fire truck (i.e. air-lift, sea transport).
- As there was no means of monitoring the spent fuel pool in the field, monitoring instruments for temperature and water level (requires power) need to be installed. As a backup in case instruments do not work, prepare portable contactless thermometer and water level indicator.
- Secure reliability by multiplexing cooling system for spent fuel pool.

(Long term measures)

- Secure water source for low-pressure injection which can be used for fire fighting.

Safety Measure: Secure ultimate heat sink

Purpose

- Secure power
- Secure control room function
- Secure high pressure cooling system
- Secure vent function
- Secure low pressure cooling system
- **Secure ultimate heat sink**
- Prevent hydrogen explosion / radiation leak
- Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Secure seawater system

- Need to prepare portable water pump and temporary power supply in case the seawater pumps malfunction due to tsunami.
- The seawater pump in the building was flooded and malfunctioned. Aside from improving the water seal and pressure resistance of the building, it is also important to completely shut the building doors when there is a tsunami warning.

(Mid to long term measures)

- When adding or replacing emergency generators, secure the cooling line for the air-cooled type as a backup system (not relying on seawater coolant).
- Operate feed-and-bleed cooling with the wet well vent (secure heat sink until cold shutdown.).
- Build sea-wall or breakwater.
- Implement an alternative core cooling system (water source, power source, and water injection system).

Safety Measure (Impact mitigation)

Secure seawater cooling functions

- Store cleaning equipment for motor winding and spare parts.

(Mid to long term measures)

- Since the motors for seawater pump malfunctioned due to the tsunami, consider sealed motors (to reinforce pressure resistance and water protection).

Safety Measure: Prevent hydrogen explosion/radiation leak

Purpose

- Secure power
- Secure control room function
- Secure high pressure cooling system
- Secure vent function
- Secure low pressure cooling system
- Secure ultimate heat sink
- **Prevent hydrogen explosion / radiation leak**
- Disaster response manual / infrastructure, etc.

Safety Measure (Prevention)

Prevent hydrogen explosion

- Install hydrogen ventilation in the nuclear reactor building before it's filled with hydrogen (vent system with remote control + manual control + radioactive material filtering).
- Reinforce air tightness of PCV: Review the materials in the seals including the DW flange, electrical routing, hatches etc. Reinforce resistance against high temperatures and pressure.
- In case mass hydrogen is generated, prevent it from accumulating in a closed space.
  - Install hydrogen detectors in closed spaces. (Transmit signal with own battery or RF) .
  - Perform preventive measures such as injecting nitrogen inside of the PCV when venting.

(Mid to long term measures)

- Reconsider the shape of the upper area/ ceiling of the nuclear reactor, PCV, and reactor building so that the hydrogen does not accumulate in one narrow space (i.e. slant ceiling to redirect the gas).
- Consider reinforcing the concrete or install debris catcher to prevent debris from penetrating PCV (prevent debris-concrete reaction in pedestal).

Radiation leak prevention

(Mid to long term measures)

- Considering that hydrogen explosion spread radioactive materials, evaluate the effectiveness of the wet well vent and consider installing vent filter.

Safety Measure (Impact mitigation)

Prevent hydrogen explosion

- To prevent rupture disk from not opening, conduct regular inspections and replacement.
- In Fukushima Dai-ichi, although they were apprehensive of leak of radioactive materials in Unit 1, they did not anticipate a hydrogen explosion. Define how to handle hydrogen explosions in the AM manual and conduct training to ensure accurate response.

Safety Measure: Disaster response manual / infrastructure etc.

Purpose

- Secure power
- Secure Control room function
- Secure high pressure cooling system
- Secure vent function
- Secure low pressure cooling system
- Secure ultimate heat sink
- Prevent hydrogen explosion / radiation leak
- **Disaster response manual / infrastructure, etc.**

Management response

Update disaster response manual (AM)

- Redesign AM: How many hours should the plant's water and power sources last? How to bring in alternative resources from off sites? Implement the following:
  - Define the numerical requirements specifically as to the minimum number of hours for which coolant and power should last on-site, and add to the operation manual.
  - In the logistics and accident manuals, specify how to bring in additional power, coolant, and other supplies from off-site before the on-site power and coolant are lost.
  - Reinforcement of training: Do not let the training end with the preparation phase. It's necessary to cover the actual processes (e.g. actual connection of cable terminal) and reflect its mechanism in the training as well.
- Revise the manual of power restoration: The manual originally gives guidelines for restoring short term power loss. Revise the manual to anticipate up to a few days of power loss.
- Since earthquake and tsunami can hit all the reactors in the plant at the same time, there should be plant-wide training with night and holiday scenarios as well.

Review assessment method and organization of the earthquake and tsunami risk (Mid to long term measures)

- Revise the organization of the nuclear disaster response to handle concurrent accidents at multiple plants.
- Include risk assessment in regards to the 'power' of tsunami besides its height.
- Assess the risk of tsunami and earthquake more frequently on regular basis

Management response

Reinforce infrastructure

- Enforce assembly of operators to the power plant after an earthquake (including during the night and on holidays). Secure necessary staff for the Emergency Response Room as well (require assembly within X hours).
- Communication means among operators in a control room of each plant, accident response members in the field, on-site emergency response headquarter, and the central control room were cut off, thus affecting timely reports. This slows down the emergency response, so it's important to secure and distribute appropriate numbers of communication equipments (means of communication).
- Improve the environment of the Emergency Response Room by providing sleeping quarters and bedding.
- Improve the Anti-seismic Isolation Tower's resistance against tsunami (secure emergency power supply).
- To improve the accessibility of the plant after earthquake and tsunami:
  - Secure required numbers of heavy machineries and operators for clearing debris.
  - Bolt-down the gasoline tanks to avoid floating.

(Mid to long term measures)

  - Reinforce roads to the headquarters (including anti-liquefaction)
  - Ensure that the transport path remains after earthquakes and tsunami (Construct a path that won't crack or suffer liquefaction. No manholes).

- Reinforce roads and bridges leading to the power plant.
- Secure safety of the workers: Consider responding remotely and with fewer staff. (e.g. Set up long distance hoses beforehand, allow remote control of hoses as with a crane, etc.)

Comparison with NISA instructions (Current stress test)

- Point of view
- Technical measures

Safety Measure: Secure power (external AC power and emergency DG)

Category	Countermeasure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Secure power	Secure external AC power	Improve water protection and pressure resistance of switching stations.	○	○	
		Switching stations should be located at elevated areas, or sea-walls should be built to protect the equipment from tsunami.	○	○	
		Evaluate and improve earthquake resistance of switching stations, transmission line towers and power plants. Furthermore, include earthquake resistance in the design requirements.	○	○	
		Minimize frequency of external power outage by drawing multiple power lines from the substation (minimum of two separate lines). Or connect external power of all plants in a network.	○	○	
		Regarding the substation power transmission, switch from overhead wires to underground cable.	×	×	reinforce power transmission line (instruction docs) Needs another form (IAEA、industry）
		Remote control: Secure power transmission route and cables for remote supply of power to the nuclear reactor from the power supply vehicle with remote control. (or is it possible to supply without wires?)	×	×	
		Improve earthquake resistance of substations and include it in the official design requirements.	○	○	
	Secure emergency diesel generator (DG)	Protect air inlet of DG room from flooding.	○	○	
		Improve water protection and pressure resistance of DG rooms.	○	○	
		Store control and power cables to allow power interchange between separate DG rooms.	○	○	
		Place DG equipment at higher elevation (DG, power panel, etc.)	○	○	
		Improve sharing of DG power: Interconnect all DG to enable all the reactors to share power supply from others. (Unit 5&6 could share power supplies each other but not designed so with Units 1 to 4).	○	○	
		Plant should be designed to function with minor flooding.	○	○	
		The plant becomes vulnerable against an accident during regular inspection since the DG is stopped for their own inspection. Install an additional DG. For air-cooling DG, place it in an elevated area together with the gas turbine. Air cooling DG doesn't require seawater pumps and seawater circulation system. For fresh-water cooling DG, set it up on an elevated area to avoid damage from tsunami.	○	○	
		Place diesel and gasoline tanks on an elevated area to avoid damage from tsunami.	○	○	
		Automatically activate DG if the reactor scrammed	×	×	

Safety Measure: Secure power (DC and AC power)

Item	Counter measure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Secure power	Secure DC power	Relocate equipment indoors - into a pressure resistant and water tight building to avoid flooding by tsunami. Relocate DC power supplies to a higher location.	○	○	
		Station mobile battery vehicles (DC125V, 24V, and 250V) with cables in case of accident to DC power supplies.	○	○	
		Relocate DC power supplies to a higher elevation.	○	○	
		Upgrade the capacity of DC power supply (from 8 hrs to 24 hrs or more).	○	○	
	Secure AC power	Improve water tightness and pressure resistance of AC power equipments.	○	○	
		Power supply vehicle reinforcement ・Store additional units on site (secure necessary number of units based on the required load capacity). Review location (i.e. elevated area) ・Increase the type of power supply vehicles: DC, AC, AC & DC, w/ generator, w/DG, etc.	○	○	
		Set multiple access points of power panel for power supply vehicles and secure water seal.	○	○	
		Increase the number of backup power sources other than power supply vehicles.	○	○	
		To quickly recover AC power, set up power supply cables and store tools for terminal handling in accessible areas.	○	○	
		AC power distribution（To enable all Units to share power sources through the M/C and P/C）	○	○	
		Transport power supply vehicle and backup power source by air after the tsunami and earthquake have subsided.（Set helipad on the roof/vicinity of the reactor building.）	×	×	
		Transfer the AC power supply to a higher location.	○	○	

Safety Measure: Secure control room function and high pressure cooling system

Item	Counter measure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Secure function of control room	Secure livable condition for operators and monitoring funciton	Improve radiation protection of the main control room to avoid radiation during emergencies.	○	○	
		Store spare batteries in case meters and gauges stop working.	○	○	
		Store sufficient numbers of protective gear, masks, dosimeters, and other supplies. Since the situation in Fukushima Dai-ichi lasted a few days, there should be at least a couple of days worth of supplies.	○	○	
		To ensure vent and air conditioning system in the main control room, emergency power such as gas turbines should be installed.	○	○	
		Due to power shut down the parameters, such as the water and pressure level of the core, were no longer observable. Portable measuring instruments and alternative measurements should be developed .	○	○	
Secure high pressure cooling system	Secure high pressure cooling system	The HPCI and RCIC are installed in the basement of the reactor building. Although the reason they stopped working was due to the loss of power, it's still necessary to maintain water protection and pressure resistance of the room to secure the pumps and motors inside it.	○	○	
		Since the systems for SLC, CRD, and CUW can be used for high pressure cooling, it's important to secure power supplies for these systems including temprary power supply.	○	○	
		Work at night was slow. There was a delay in restoring high pressure cooling system which worsened the situation in the plant, and delayed the staging of low-pressure cooling system. To improve efficiency in the field work, mark valves and machines with fluorescent paint for easy detection. Coating the temporary power cables with fluorescent paint will provide easy direction to its location.	×	×	No policy to check operation state
		It would take too much time and cause delay in the decision making if unable to access the site to confirm the state of the high pressure cooling. It will be effective to have multiple means to observe the site. Install ITV (for vision), sound monitor, and vibration sensors to allow remote monitoring of the pumps, gauges, and valve.	×	×	No measures for working night time

Safety Measure: Secure Low pressure cooling system

Item	Counter measure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Secure Low Pressure Cooling System	Secure Low Pressure Cooling System	Place pumps for low-pressure emergency core cooling on a high location to avoid damage from tsunami. Secure water protection and pressure resistance.	○	○	
		Secure appropriate number of fire trucks and hoses, and station them on high ground. Consider the source, range, and capacity of water injection when selecting fire trucks.	○	○	
		Set multiple water injection points for fire trucks	○	○	
		Investigate and determine the cause of trouble with the diesel-driven fire pump. Reflect in the countermeasures.	×	×	
		Reinforce water supply paths: Confirm other delivery means of water than fire truck (i.e. air-lift, sea transport).	○	○	
		Reinforce water source: Supply water from multiple sources such as water tank, dam, reservoir, lake, river, sea. Review whether the supply methods and capacity are sufficient. If the water is used as core coolant, consider the following: ・ Whether boric acid can be added. ・ The circulation system which use contaminated water in the reactor building as coolant. ・ Prepare multiple routes for the coolant.	○ × ×	○ × ×	No reference on recyling of contaminated water. Mentioned air cooling method
		Secure water for low-pressure injection for fire fighting in addition to core coolant.	×	×	Mentioned securing of water source for cooling system (ST instructions, IAEA)
	Secure spent fuel pool system	There was no means of monitoring the spent fuel pool in the field, so monitoring instruments for temperature and water level (requires power) are necessary. As alternatives in case instruments are not working, prepare portable contactless thermometer and water level indicator.	×	○	Stated to secure cooling functions for spent fuel pool (ST instructions).
		Secure reliability by multiplexing cooling system for spent fuel pool.	×	×	Mentioned securing cooling function

Safety Measure: Secure ventilation function

Item	Counter measure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Secure vent function	Secure containment vessel vent function	Prepare items for setting up vent line (temporary power supply, air tank) beforehand for efficiency.	○	○	
		Given that PCV vent operation failed in Unit 2, reconsider the activation pressure of ventilation (= the configuration of the rupture disk to open).	×	×	Mentioned improving vent stream operation (IAEA)
		Install a neutron monitor inside the PCV to observe the activities inside the core during meltdown.	×	○	Mentioned indicators for monitoring core status (industry report)
		Multiplex and improve the equipments for vent line to stabilize air supply for the operation. Designate them as the 'safety system'.	○	○	
		Consumed too much time in setting up the vent line. Place the valve at an accessible area and redesign for manual operation.	○	○	
		Gievn that venting with rupture disk in Unit 2 was unsuccessful, consider to use a valve for vent operation.	×	×	
	Depressur-ization with SR valve operation	Unable to perform depressurization by the SR valve due to DC power outage.	○	○	
		Consider SR valve that can work by other than DC power.	×	×	
		Consider multiple methods on nuclear reactor depressurization.	×	×	

Safety Measure: Secure low pressure cooling system and ultimate heat sink

Counter measure	Item	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Secure ultimate head sink	Secure seawater system	Need to prepare portable water pump and temporary power supply in case the seawater pumps malfunction from tsunami.	○	○	
		The seawater pump in the building was flooded and malfunctioned. Aside from improving the water seal and pressure resistance of the building, it is also important to completely shut the building doors when there is a tsunami warning.	○	○	
		Store cleaning equipments for motor winding and secure spare parts.	○	○	
		When adding or replacing emergency DG, secure cooling line for air-cooling type as backup (not relying on seawater coolant).	○	○	
		Operate feed-and-bleed cooling with wet well vent (secure heat sink until cold shutdown.).	×	×	
		Build sea-wall or breakwater	○	×	
		Have an alternative core cooling system (water source, power source and water injection system)	×	×	
		Consider completely sealed motors (pressure resistance, water protection reinforced) as the seawater pump motors malfunctioned from the tsunami.	○	○	

Safety Measure: Prevent hydrogen explosion/radiation leak

Item	Counter measure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Prevent hydrogen explosion/ Radiation leak	Prevent hydrogen explosion	Install ventilation for hydrogen in the reactor building to prevent accumulation (with remote control + manual control + radioactive material filtering).	○	○	
		Reinforce air tightness of PCV: Review the materials in the seals such as D/W flange, electric cabling routes, hatches, etc. Reinforce resistance against high temperature and pressure.	×	×	No mention of PCV reinforcement
		To prevent rupture disk from failing to open, conduct regular inspection and replacement.	×	×	
		In Unit 1 of 1F, though they were apprehensive of radiation leak, they did't anticipate a hydrogen explosion. Define AM as to how to handle hydrogen explosions and conduct training to ensure accurate procedure.	○	○	
		In case mass hydrogen accumulated, prevent its accumulation in a closed space. ・Install hydrogen detectors in closed spaces (Transmit signal using own battery or RF) ・Perform preventive measures such as nitrogen seal inside the PCV when venting.	× × ×	○ × ○	Mentioned prevention of hydrogen accumulation (ST instructions)
		Consider reinforcing the concrete or install debris catcher to prevent debris penetrating the PCV (prevent debris-concrete reaction in pedestal).	×	×	
	Prevent radiation leak	With the hydrogen explosion causing spread of radioactive materials, evaluate the effectiveness of the wet well vent and consider installing vent filter.	×	○	Mentioned vent system reinforcement (IAEA)

Note: 1F = Fukushima Dai-ichi Nuclear Power plant

Safety Measure: Disaster response manual / Reinforcement of infrastructure

Item	Counte measure	Content	Match with NISA ST?	Match with report to IAEA?	Notes
Disaster response manual / reinforce-ment of infrastructure	Update disaster response manual (AM)	Redesign AM: How many hours should the plant's water and power sources last? How to bring in alternative resources from off sites? Implement the following: ・Define the numerical requirements specifically as to the minimum number of hours for which coolant and power should last on-site, and add to the operation manual. ・ In the logistics and accident manuals, specify how to bring in additional power, coolant, and other supplies from off-site before the on-site power and coolant are lost. ・Reinforcement of training: Do not let the training end with the preparation phase. It's necessary to cover the actual processes (e.g. actual connection of cable terminal) and reflect its mechanism in the training as well.	○ ○ ○	○ ○ ○	
		Revise the manual of power restoration: The manual originally gives guidelines for restoring short term power loss. Revise the manual to anticipate up to a few days of power loss.	○	○	
		Since earthquake and tsunami can hit all the reactors in the plant at the same time, there should be plant-wide training with night and holiday scenarios as well.	○	○	

Safety Measure: Disaster response manual / Reinforcement of infrastructure

Item	Counter measure	Content	Match with NISA ST?	Match with report to IAEA?	Note
Disaster response manual / reinforcement of infrastructure	Reinforce infrastructure	Enforce assembly of operators to the power plant after an earthquake (including during the night and on holidays). Secure necessary staff for the Emergency Response Room as well (require assembly within X hours).	×	○	Mentioned to work out as necessary countermeasure.
		Communication means among operators in a control room of each plant, accident response members in the field, on-site emergency response headquarter, and the central control room were cut off, thus affecting timely reports. This slows down the emergency response, so it's important to secure and distribute appropriate numbers of communication equipments (means of communication).	○	○	
		Improve the environment of the Emergency Response Room by providing sleeping quarters and bedding.	×	×	
		Improve the Anti-seismic Isolation Tower's resistance against tsunami (secure emergency power supply).	×	×	
		To improve the accessibility of the plant after earthquake and tsunami: ・Secure required numbers of heavy machineries and operators for clearing debris. ・Bolt-down the gasoline tanks to avoid floating. ・Reinforce roads to the headquarters (including anti-liquefaction) ・Ensure that the transport path remains after earthquakes and tsunami (Construct a path that won't crack or suffer liquefaction. No manholes).	○	○	
		Reinforce roads and bridges leading to the power plant.	×	×	
		Secure safety of the workers: Consider responding remotely and with fewer staff. (e.g. Set up long distance hoses beforehand, allow remote control of hoses as with a crane, etc.)	×	×	Mentioned rescue team, materials and equipment for emergency response
	Review the earthquake and tsunami assessment method and organization	Revise the organization of the nuclear disaster response to handle concurrent accidents at multiple plants.	×	○	Mentioned issues on locations with multiple reactors (IAEA)
		Include risk assessment in regards to the 'power' of tsunami besides its height.	×	×	
		Assess the risk of tsunami and earthquake more frequently on regular basis	×	×	

Accident Management (AM)

- What can be learned from the accident analysis?
- What decision-making mechanism should be established?

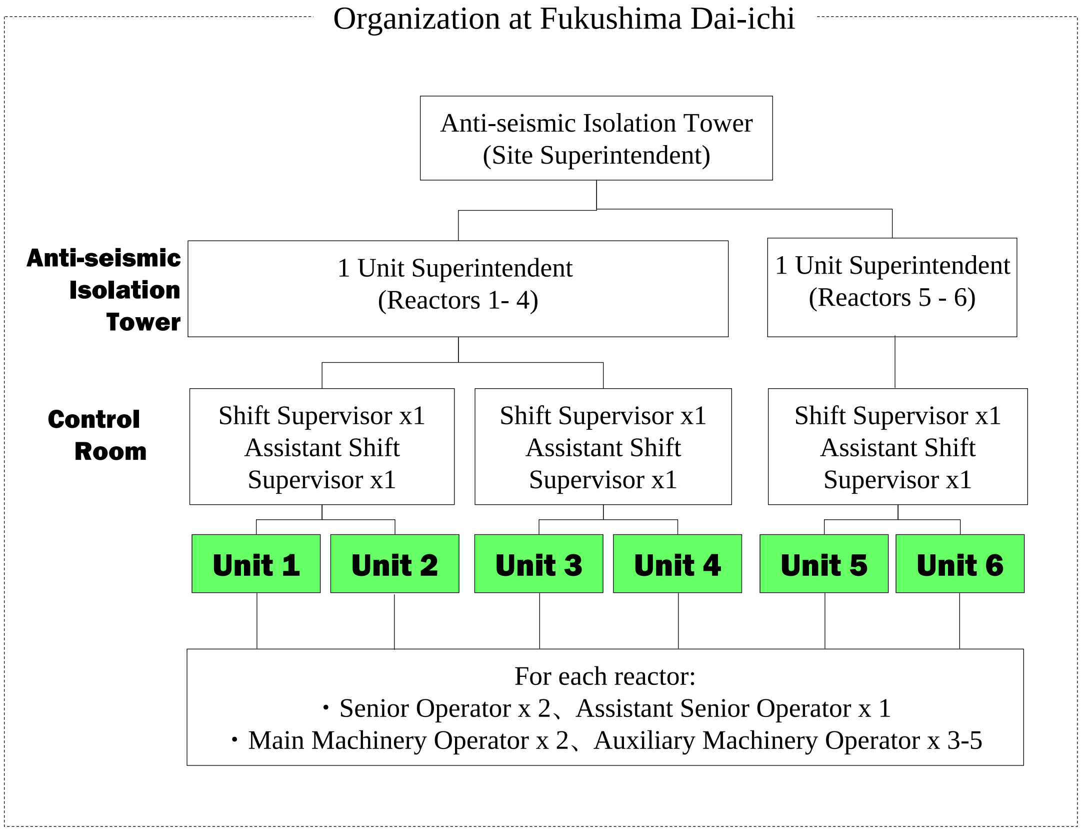
Issues – Many lessons and issues regarding system and decision making process of the Accident Management (AM)

Suspected cause	Event / Issue	Safety Measures / Lessons
● **Constant education and training on accident response procedures.**	● Field personnel under Site Superintendent and Shift Supervisors acted with emphasis on safety in consistency with the AM manual. Plant operators have undergone practical operation training in addition to the AM training. We believe that the training was effective in the response process in the site but only until the hydrogen explosion.	● **Reaffirmed importance and reinforced routine training** ● **Emphasis on execution speed of safety measures**
● **Insufficient procedures and functions for information sharing and means of communication** ● **Establish joint headquarters for emergency response**	● Initially the issue of insufficient communication between TEPCO head office and power plants, and communication between TEPCO and the national government was picked up by the press (e.g. government directly contacting Fukushima Dai-ichi). This was left un-clarified. ● This problem seemed to have resolved with the establishment of joint headquarters for emergency response between the national government and TEPCO on 3/15.	● **Improve quality, capacity, and speed of information shared** ● **Create a system to achieve the above** ● **Reaffirmed importance of a system for real-time information sharing.**
● **Insufficient measures for handling multiple plants concurrently resulted in delay of response**	● The head office at TEPCO had to respond to a total of 10 plants in Dai-ichi and Dai-ni. However, they did not anticipate concurrent accidents occurring in multiple plants. Although they had a sufficient number of employees (head office 200, Dai-ichi 400, Dai-ni 200-300) they did not have sufficient organization, response staff, and training to be effective in the response.	● **Assign and train personnel to respond to multiple severe accidents for each plant**
● **Insufficient preparation and training for supplies arrangement** ● **Swift supply delivery by the Defense Force**	● Transporting equipment from head office to the plants wasn't executed smoothly (e.g. sending from JV and Obama CC). They also were having difficulties with the required supplies (and timing) for the severe accident like this. ● Since the establishment of joint headquarters of the Government and TEPCO on 3/15, the Self Defense Force was able to transport supplies smoothly.	● **Design a structure and training for ordering equipment. Include means of communication, specification list, and delivery check for outgoing and incoming equipment.** ● **Establish manual and structure for collaboration with Self Defense Force during severe accidents.**
● **Power outage and communication problem in offsite center**	● During the day of the earthquake, the offsite center wasn't functioning due to power failure. Later they were also unable to use the TV conference system (another one at TEPCO booth was working). For this reason they had difficulties sharing information at most crucial	● **Secure emergency power supply and means of communication in offsite centers**

(continued)

Suspected cause	Event / Issue	Safety Measures / Lessons
● **Purpose of offsite center was unclear. Lack of common understanding of its purpose among stakeholders. Insufficient training.**	● The offsite center served its purpose as an information sharing center after the restoration, but it didn't seem to have served as a place for conferences and decision-making. The scale of the evacuation grew huge, making assembly of all the representatives from the national government, TEPCO, and local government difficult.	● **Redefine the structure of AM and roles, and disseminate the information to all stakeholders.** ● **Conduct practical training for all stakeholders. Secure a location for the training.**
● **Insufficient training for upper levels in TEPCO, national government and local government.**	● Although TEPCO, and the national and local governments have defined response methods and conducted training, they weren't able to execute in a timely manner during the actual emergency which eventually led to the hydrogen explosion.	● **Reinforce practical training (emphasis on improving response speed)**
● **Local response headquarters (of country, prefecture, municipalities, etc.) lacked design and training in directing and leading an evacuation.**	● Nuclear disaster local response headquarters was not always unified in directing and leading the evacuation. The roles of the national and local government (prefecture & municipalities) were defined but unclear, thus ineffective.	● **Review the structure and role distribution of local disaster response** ● **Conduct and reinforce training for mastery of subject.**
	● Disaster response headquarters (prefecture and municipality) with nuclear power plants in its jurisdiction have to respond to nuclear disasters in addition to other disasters such as fire, earthquake, and flood. There needs to be a countermeasure designed specifically for nuclear disasters. ● During a nuclear disaster it is crucial to obtain and understand current information, and promptly deliver response policies and make decisions. To achieve this, there must be a nuclear specialist in the local government (prefecture or municipality) to consult with.	● **Reorganize local structure and response plan for multilayered disasters** ● **Conduct hands-on education and training** ● **Assign and utilize nuclear specialist**

Current AM Organization (Fukushima Dai-ichi example) **: Need to verify whether the power company/ government had the ability and capacity to respond to simultaneous and severe accidents in multiple plants.**



Organization at Fukushima Dai-ichi

Anti-seismic Isolation Tower (Site Superintendent)

Anti-seismic Isolation Tower

1 Unit Superintendent (Reactors 1- 4)

1 Unit Superintendent (Reactors 5 - 6)

Control Room

Shift Supervisor x1 Assistant Shift Supervisor x1

Shift Supervisor x1 Assistant Shift Supervisor x1

Shift Supervisor x1 Assistant Shift Supervisor x1

Unit 1 **Unit 2** **Unit 3** **Unit 4** **Unit 5** **Unit 6**

For each reactor:

・Senior Operator x 2、Assistant Senior Operator x 1

・Main Machinery Operator x 2、Auxiliary Machinery Operator x 3-5

Current organization of plant operation

- Decisions by Site Superintendent: Deployment of power supply vehicles and fire trucks to the plant. Execution of vent and seawater injection. Decisions on matters not defined in the AM manual.
- Decisions by Shift Supervisor: Items defined in AM.
- Shift Supervisor license and training = Have to pass the BTC "lead operator" examination.

Issues

- Compared to the plant with single nuclear reactor, it is believed that **the risks in those with multiple reactors increase dramatically if a severe accident occurs.**
- At the same time, **pressure on the field's management, the skills required, and the response speed and accuracy in such events are much greater.**
- Looking at the chronology, it's postulated that **preparations for responding to multiple units may not have been sufficient**.

“Regarding the reoperation of the plant, what happened at Fukushima Dai-ichi, including decision making, has to be examined. Computer simulation that hasn’t taken this into account is unsubstantiated” – Governor of Niigata Pref(*). Izumida

*) re: Another nuclear power plant location.

Governor Izumida’s comment (extracted from regular briefing on Sep 14th)

● Q: What do you think about the government’s announcement regarding the IAEA’s participation in the evaluation of the stress test?

○ Governor: **It isn’t enough. What happened in the Fukushima Dai-ichi isn’t just about the mechanisms and equipment. The decision making mechanism must be evaluated as well.** We need to consider questions such as, **when should the decision to pour seawater have been made? who should have made the decision?** can someone really make such a decision knowing that he/she is disposing of a plant worth hundreds of billions of yen?

Was there really nothing that could have been done to prevent the release of a massive amount of radiation? It was pointed out in IAEA ‘s report that the prime minister was intervening too much with the site. Considering this, **there isn’t much point in conducting stress test without reviewing the decision making mechanism, like who’s responsible for what**.

If you ask me if there really is any point in computer simulations, without even verifying if there was a pipeline rupture, that is solely based on past knowledge and perception, and then having the IAEA review it, **I’d say that it may be better than doing nothing at all, but it’s really nothing more than that.**

What it means

● **Prevention measures must be made from both the technical and organizational aspects.**

● **Technical aspect: Inspect Fukushima Dai-ichi (back from design philosophy), and identify lessons learned and countermeasures.**

● **Organizational aspect: Establish an organization to implement the countermeasures, and clarify the requirement for the decision-making mechanism.**

- Redesign the decision-making mechanism to prioritize prevention of recurrence as top priority.
  (Head Office, Technical Support Center, Off-site Center, Central Control Office)
- Design the organizational structure and identify the roles for the implementation of the countermeasures (Power company, National Government, Local Government)

● **Reinforce training: Practical training necessary for countermeasures and organizations (that were established based on the lessons learned) to be effective.**

- Training program simulating the accident in Fukushima Dai-ichi.
- Plan and practice program, and improve the results.
- Case study around the world.

In addition to technical measures, accident management systems for local participation in terms of decision-making, organization, and training are required.

In order to achieve that, it is very important to incorporate the following missions in the design of Accident Management.

Safety Priority

- To protect human life and promote safety culture, create a system that prioritizes "safety of plant" and "safety of local community" above all.
- Hydrogen explosion and radiation leaks must be prevented at all cost. (Never Fukushima again.)

Real time information sharing NW

- Provide network that allows real-time and transparent information sharing during severe accidents (or risks).
- Create a system that notify the status once the accident mode is on, and that allows information sharing and discussion regarding the progress of the accident.

Local participation

- System that allows local bodies to share information and make decisions on the safety of the area.
- Enrich human resources of the local administration such as nuclear power specialists and consultants.
- Impel and reinforce training.

Transparent and swift decision making

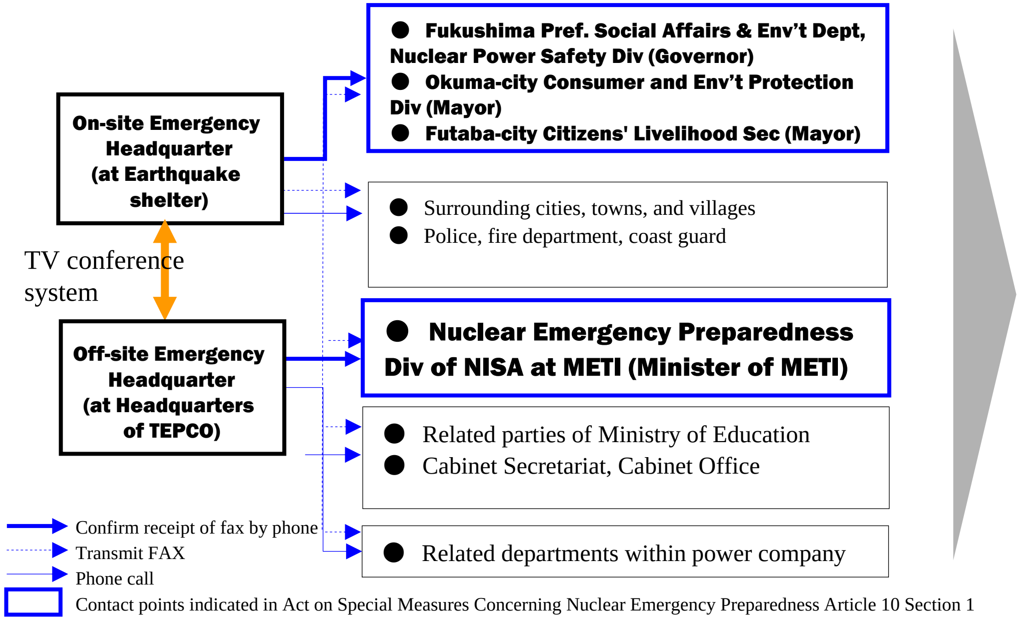
- Design an organization and authority where proper and transparent governance works.
  - Plant safety: The site (plant head or shift manager) is the chief decision maker.
  - Local safety: The local government can share information from the plant in real-time to make final decisions.
  - Decision-making process should be transparent and should not be delayed or diverted due to external influences.

Proper training to secure safety

- To guarantee the items above, AM (accident management) procedure manual and countermeasures have been defined appropriately.
- Select qualified personnel for executing the manual.
- Selected personnel will undergo necessary training.
- Periodic evaluation on these procedures, personnel, and training shall be conducted from a neutral point of view (possibly a third party)

For severe accidents that require prompt action, there needs to be a real-time network that enables all the stakeholders to share information and participate in discussion.

Current situation (Article 10 In case of accident)



On-site Emergency Headquarter (at Earthquake shelter)

TV conference system

Off-site Emergency Headquarter (at Headquarters of TEPCO)

- **Fukushima Pref. Social Affairs & Env't Dept, Nuclear Power Safety Div (Governor)**
- **Okuma-city Consumer and Env't Protection Div (Mayor)**
- **Futaba-city Citizens' Livelihood Sec (Mayor)**

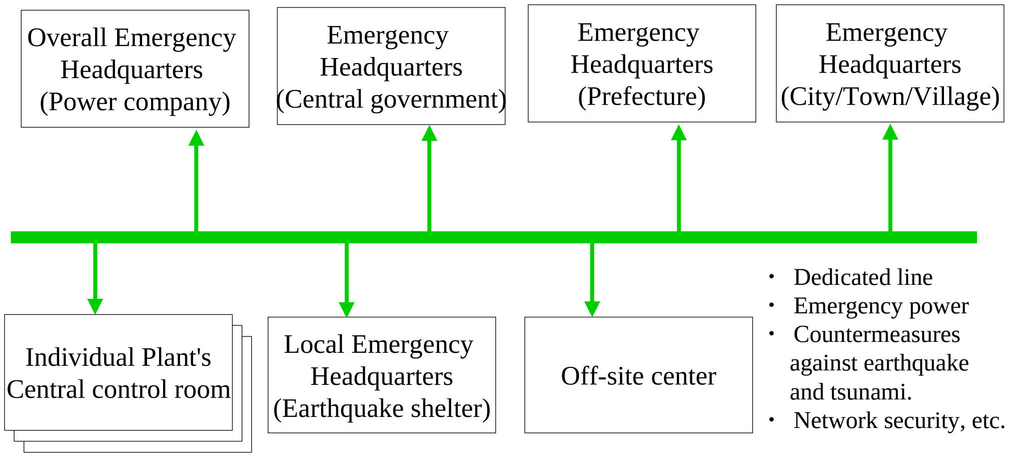
- Surrounding cities, towns, and villages
- Police, fire department, coast guard

- **Nuclear Emergency Preparedness Div of NISA at METI (Minister of METI)**

- Related parties of Ministry of Education
- Cabinet Secretariat, Cabinet Office

- Related departments within power company

Future



Overall Emergency Headquarters (Power company)

Emergency Headquarters (Central government)

Emergency Headquarters (Prefecture)

Emergency Headquarters (City/Town/Village)

Individual Plant's Central control room

Local Emergency Headquarters (Earthquake shelter)

Off-site center

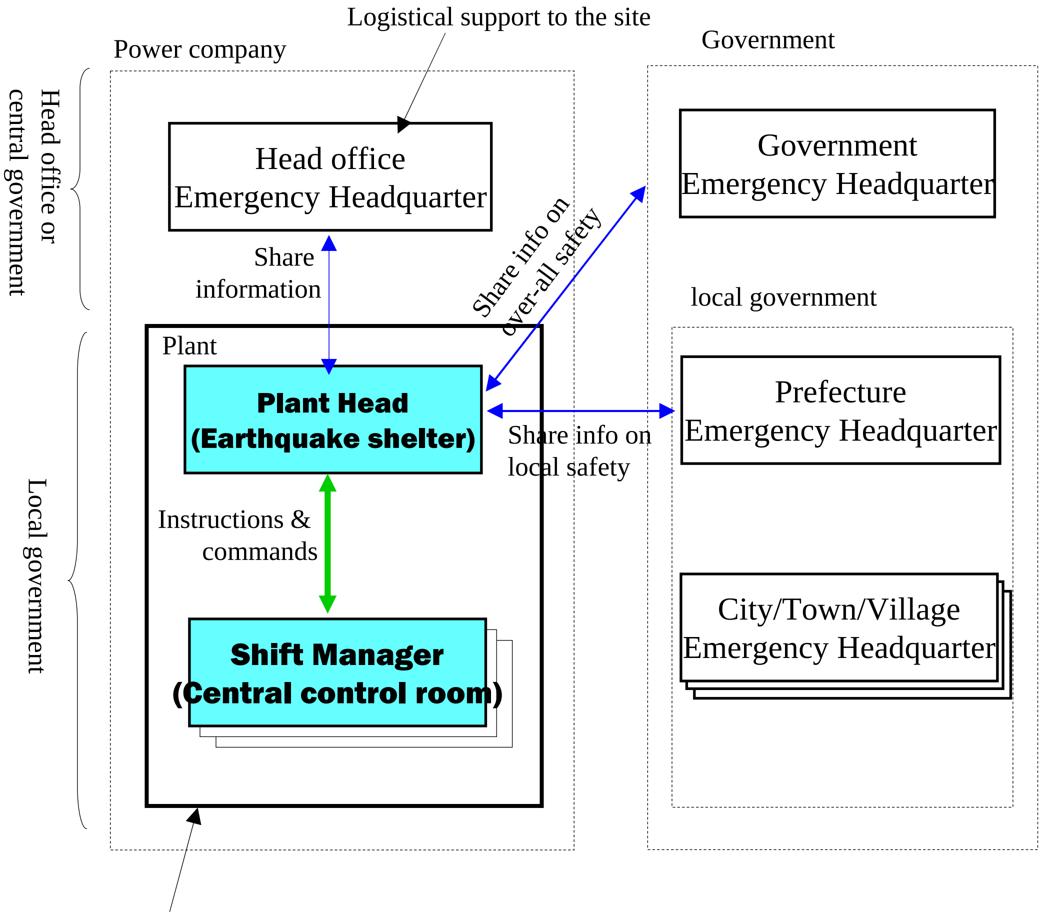
- Dedicated line
- Emergency power
- Countermeasures against earthquake and tsunami.
- Network security, etc.

- **Real-time (limited):** Real-time TV conference available between the power plan and Head Office.
- **Bi-directional (partial):** Communication other than with government bodies are mainly one-directional through phone, FAX and mail.
- **Limited information sharing:**
  - Communication difficulties during power outage and transmission problems.
  - Local government pointed out that information on the accident provided to them was insufficient (partly because they were using public lines).

- **System that enables the network to simultaneously connects related stakeholders and plants, and help real-time information sharing, meetings, and decision making.**
  - Stakeholders: Plant, power company's headquarter, government, prefecture and city/state/province of the plant.
  - Function: Share information and hold conference regarding plant status, countermeasures, local safety, evacuation, etc.
  - Let stakeholders know that AM (accident management) mode is on, and share the progress of events.
  - Help transparent and prompt decision-making with all the information shared.
  - Prevent information from leaking.

It will be too late to consult with the head office when the accident passes a critical point.

Ensure plant safety: Front line (Plant Head and Unit Manager) shall have absolute authority, and must govern the plant with accident prevention and containment as top priority – equivalent to airline's "air-traffic controller" and "pilot", or manufacturing's "CEO" and "Chief Engineer".



Logistical support to the site

Power company

Government

Head office or central government

Head office Emergency Headquarter

Government Emergency Headquarter

Share information

Share info on over-all safety

local government

Local government

Plant

Plant Head (Earthquake shelter)

Share info on local safety

Prefecture Emergency Headquarter

Instructions & commands

Shift Manager (Central control room)

City/Town/Village Emergency Headquarter

Full authority over the plant's accident response

- **Undefined accident = Plant Head**
- **Defined accident = Shift Manager on-site**

Power Company's Head Office and Plant: Separation of Safety from Business

- Power plant: **Decisions and actions with top priorities on accident prevention and safety.** On this issue, it should be **independent from management**.
- Head office: Entrust the site to "plant safety". Provides **logistical support** to the plant.

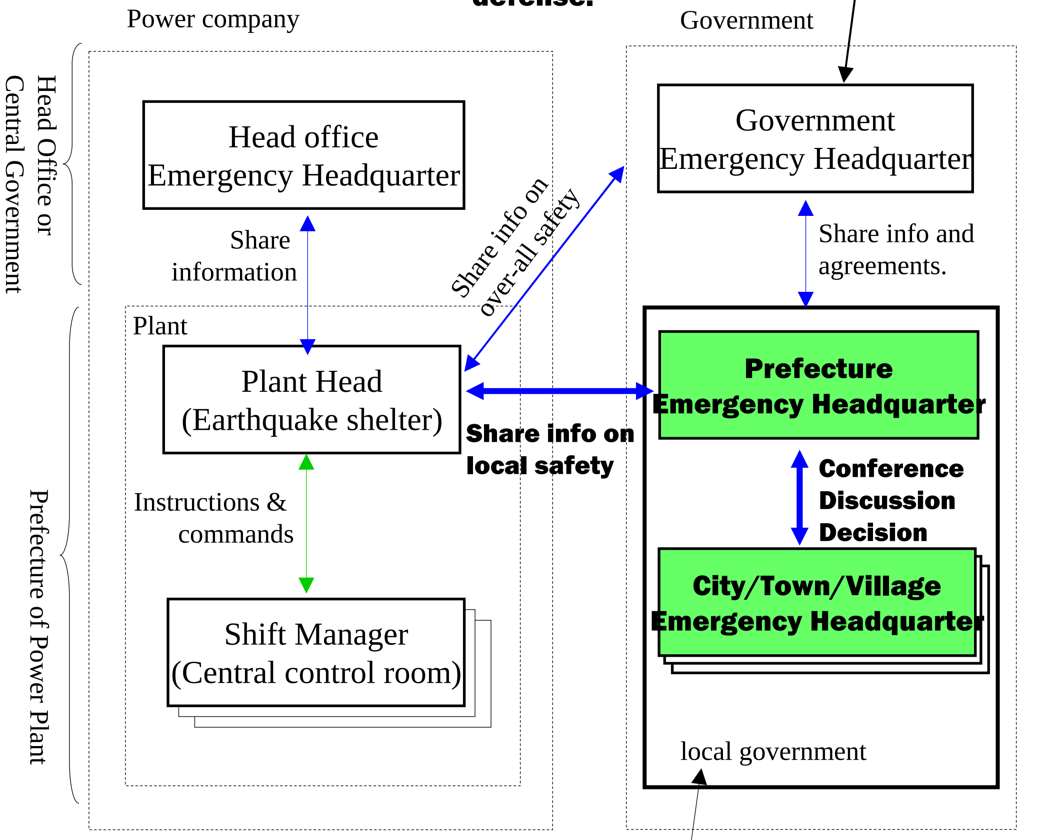
Plant Head and Shift Manager: Act as 'Traffic Controller' and 'Pilot'.

- Plant Head (= Traffic Controller):
  - Provide **instructions to the shift manager in the event not defined in the Accident Procedure** (AM Manual).
  - Has absolute authority and responsibility over the safety and accident prevention of all reactors in the plant.
- Shift Manager (= Pilot):
  - **Has absolute authority over the plant's safety** on events and operations defined in the AM manual.
  - Shares information to stakeholders when in AM mode.

In order to achieve this mission, Plant Head and Unit Managers should go through stricter qualification and trainings, and receive appropriate rewards.

We must aim for a decision-making system where the local officials can make decisions on "the safety of the citizens" as a local autonomy.

Only in extremely severe events, the central government shall instruct local governments for the interests of national defense.



Understand the situation of the accident so that decisions such as whether to evacuate can be made.

The accident from the local government's view point

- ● **Overwhelmed with incomplete and erroneous information.**
- ● **Delayed information** (status of the accident, evacuation, etc.)
- ● Contents of the **information were confusing**.
- ● It was **confusing who had authority** to make decisions (accident response, evacuation, etc.)
- ★ The local governments had **no authority to participate in decision-making**, so were positioned like "**victims**".

Ideal role of local government

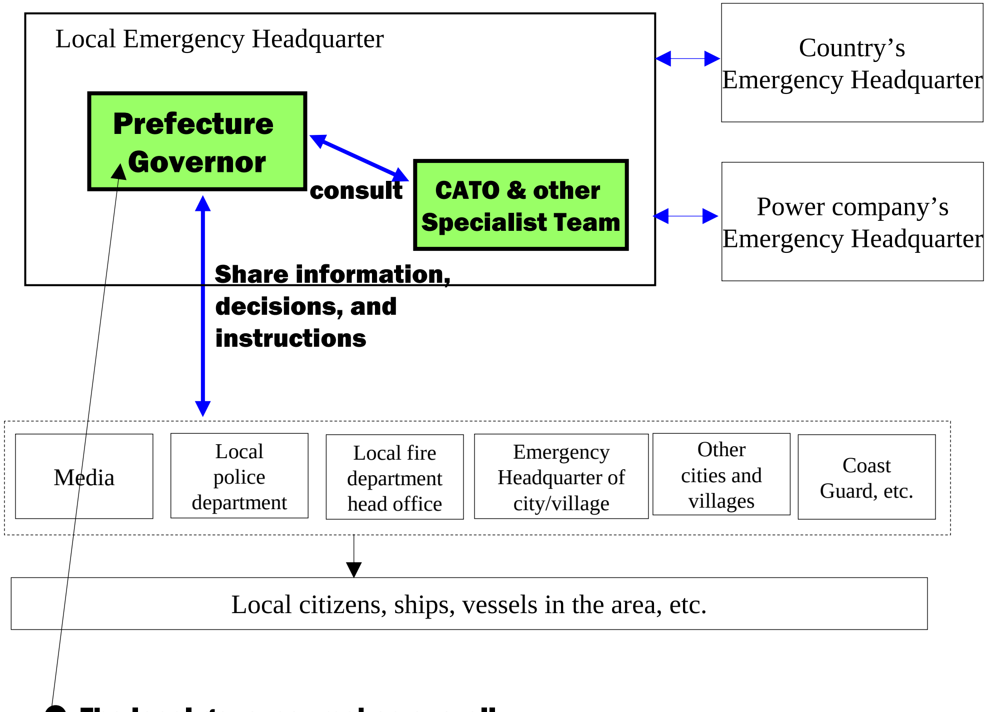
- ● **Decision-making**: On local safety and evacuation, the head of local government should have full understanding of the situation and discuss with plant's head before making any final decision.
- ● **Training**: Head of local government should receive constant training to develop good judgment skills.
- ● **Information sharing**: Information needed to make decisions shall be provided directly from the plant rather than from the central government or head office of power company.
- ● **Network**: There is a network to conduct these missions.
- ● **Decision standards:** Basis on the roles and responsibilities of the national and local government is explicitly defined.

(Three Mile Island accident in US: One of the reasons the power company was able to build a good relationship with the local government/community was because they involved the locals in the operations/trainings of the plant after the accident.)

Principle is to "Operate the plant safely with the locals".

In order to achieve that, the local government should strengthen human resources, such as by hiring a senior officer (CATO*) with expertise on nuclear technology. (* Chief Atomic Technology Officer)

Future direction (vision)



Local Emergency Headquarter

Prefecture Governor

consult

CATO & other Specialist Team

Country's Emergency Headquarter

Power company's Emergency Headquarter

Share information, decisions, and instructions

Media

Local police department

Local fire department head office

Emergency Headquarter of city/village

Other cities and villages

Coast Guard, etc.

Local citizens, ships, vessels in the area, etc.

- **The local governor makes overall judgments while consulting to CATO and others and act as a control tower.**

Mission of CATO

- **Qualifications**: **If the local governor** deems that he/she will **have difficulty in handling issues on the nuclear power plant accident, which require technical knowledge and expertise, he/she should assign a CATO**, who is responsible for the technology and safety of the nuclear power plant .
- To maintain neutrality, CATO candidates should have no previous affiliation with the power company or the government.
- This is only subject to areas with nuclear power plants.
- **Role of CATO: To have meetings and share information with the power company, government, administrative agencies, emergency headquarters. To advise to the governor.**

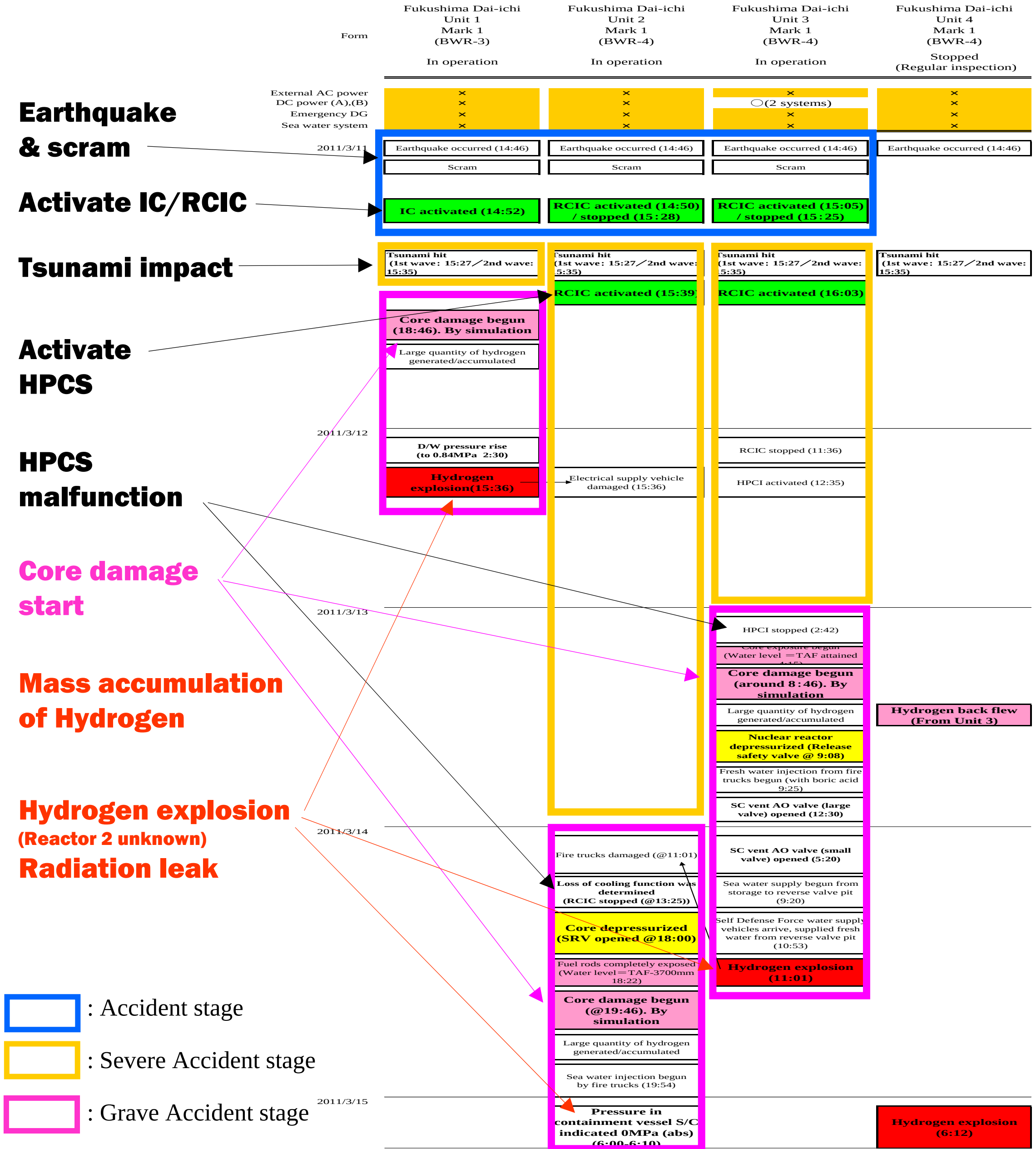
For example, Niigata Prefecture introduced a new post, "Crisis Manager", who manages risks related to the nuclear power plants. - Expenses including training should be shouldered by the central government.

From now on, we need to manage accidents in 3 categories and establish its own AM structure.

Accident Category	Examples	Information NW	Responsibility of "Plant Safety"	Responsibility of "Local Safety"	Responsibility within government
Accident	• Core reactor scram + external power outage + activation of emergency generator (DG) • Fukushima Dai-ichi Reactor 6, Tokai Dai-ni, etc.	ON	• Defined in AM = Shift Manager • Not defined in AM = Plant Head	• Plant shares information directly with local government. • Local government makes final decision to evacuate. • Central government provides logistical support and agreement.	Ministry of Environment
Severe Accident	• Reactor scram + complete power outage (DG unavailable) • Fukushima Dai-ichi Reactor 5	ON	• Same as above	• Same as above	Ministry of Environment
Grave Accident	• Complete loss of power and cooling function • Core meltdown, increasing risk of radioactive leakage • Fukushima Dai-ichi Reactors 1 - 4 • Terrorist attack	ON	• Same as above • Central government provides necessary support (e.g. Self Defense Force deployment)	• Central government has authority to make decisions • Central government, after consulting with local government, shall make overall decisions for national defense/national interest.	Office of Prime Minister

When the situation reaches extreme level, the central government will take control in order to protect national safety and interests.

For example, as to Fukushima Dai-ichi Reactors 1 – 3, wasn't there a need to judge the level and stage of accidents and determine the appropriate actions?



Earthquake & scram

Activate IC/RCIC

Tsunami impact

Activate HPCS

HPCS malfunction

Core damage start

Mass accumulation of Hydrogen

Hydrogen explosion
(Reactor 2 unknown)
Radiation leak

Form	Fukushima Dai-ichi Unit 1 Mark 1 (BWR-3) In operation	Fukushima Dai-ichi Unit 2 Mark 1 (BWR-4) In operation	Fukushima Dai-ichi Unit 3 Mark 1 (BWR-4) In operation	Fukushima Dai-ichi Unit 4 Mark 1 (BWR-4) Stopped (Regular inspection)
External AC power	×	×	×	×
DC power (A),(B)	×	×	○(2 systems)	×
Emergency DG	×	×	×	×
Sea water system	×	×	×	×

2011/3/11

- Unit 1: Earthquake occurred (14:46); Scram; IC activated (14:52); Tsunami hit (1st wave: 15:27／2nd wave: 15:35); Core damage begun (18:46). By simulation; Large quantity of hydrogen generated/accumulated
- Unit 2: Earthquake occurred (14:46); Scram; RCIC activated (14:50) / stopped (15:28); Tsunami hit (1st wave: 15:27／2nd wave: 15:35); RCIC activated (15:39)
- Unit 3: Earthquake occurred (14:46); Scram; RCIC activated (15:05) / stopped (15:25); Tsunami hit (1st wave: 15:27／2nd wave: 15:35); RCIC activated (16:03)
- Unit 4: Earthquake occurred (14:46); Tsunami hit (1st wave: 15:27／2nd wave: 15:35)

2011/3/12

- Unit 1: D/W pressure rise (to 0.84MPa 2:30); Hydrogen explosion(15:36)
- Unit 2: Electrical supply vehicle damaged (15:36)
- Unit 3: RCIC stopped (11:36); HPCI activated (12:35)

2011/3/13

- Unit 3: HPCI stopped (2:42); Core exposure begun (Water level ＝TAF attained 4:15); Core damage begun (around 8:46). By simulation; Large quantity of hydrogen generated/accumulated; Nuclear reactor depressurized (Release safety valve @ 9:08); Fresh water injection from fire trucks begun (with boric acid 9:25); SC vent AO valve (large valve) opened (12:30)
- Unit 4: Hydrogen back flew (From Unit 3)

2011/3/14

- Unit 2: Fire trucks damaged (@11:01); Loss of cooling function was determined (RCIC stopped (@13:25)); Core depressurized (SRV opened @18:00); Fuel rods completely exposed (Water level＝TAF-3700mm 18:22); Core damage begun (@19:46). By simulation; Large quantity of hydrogen generated/accumulated; Sea water injection begun by fire trucks (19:54)
- Unit 3: SC vent AO valve (small valve) opened (5:20); Sea water supply begun from storage to reverse valve pit (9:20); Self Defense Force water supply vehicles arrive, supplied fresh water from reverse valve pit (10:53); Hydrogen explosion (11:01)

2011/3/15

- Unit 2: Pressure in containment vessel S/C indicated 0MPa (abs) (6:00-6:10)
- Unit 4: Hydrogen explosion (6:12)

🟦 : Accident stage
🟨 : Severe Accident stage
🟪 : Grave Accident stage

Criteria of Severe Accident (SAM) and Grave Accident (GAM) (illustration)

● Availability of power (External power, Emergency DG, Battery, etc.)
- Should be able to comprehend the availability of all power sources so that it can be checked instantly.

● Availability of HPCS functions.
Possibility of malfunction and estimated timing.

● Status of the core reactor and risk of meltdown based on the overall availability and conditions of the power and cooling functions.

↓

★ Looking at the chronology of Fukushima Dai-ichi Reactors 1 – 3, power outage + HPCS malfunction resulted in meltdown and radioactive leakage. (+ Hydrogen explosion on Reactors 1 & 3)

★ When expected to lose power and cooling functions, the probability of GAM is very high.

Government announced level 4 on March 12, level 5 on March 18, and level 7 on April 12. However, were these really appropriate? (level, timing, frequency, and key message)

Facts and References

- **The event in Fukushima was the first to ever pass level 5 since the establishment of the International Nuclear Event Scale (INES) in 1989. There was no precedence of an ongoing event to be declared on such a scale.**
  - Chernobyl (April 26, 1986 - Level 7) and Three Mile Island (March 28, 1979 - Level 5) were scaled in years after the events.

- **On March 12 15:36, the hydrogen explosion occurred in Dai-ichi Reactor 1.** At that point it should have already met the criterion of **level 5.**
  - Level 5 = Severe damage to the nuclear reactor core or radiation protection vessels. Requires planned emergency action.

- "The **primary purpose** of the INES Scale **is to facilitate communication and understanding** …**on the safety significance of events**."
  "INES is a **tool for promptly communicating to the public** in consistent terms **the safety significance** of reported nuclear incidents…." (Extracted from official site of INES)

- **The "impact on people and environment" criterion in Levels 6 and 7 is highly subject to interpretation.**
  - **Level 7**: **more than several tens of thousands of tera-becquerels (TBq)** => **stochastic health effects over a wide area**, perhaps involving **more than one country, long-term environmental contamination**, and sheltering and evacuation is necessary.
  - **Level 6**: **thousands to tens of thousands of TBq** => **sheltering and evacuation is likely**.
  - Level 5: hundreds to thousands of TBq => Localized sheltering and/or evacuation may be likely.

- **Compared to Chernobyl, the amount of radiation in Fukushima Dai-ichi is around 10%.**
  - Chernobyl = 5.2 million TBq, Fukushima Dai-ichi = 370,000 TBq (NISA), 630,000 TBq (NSC)

Issues and Lessons

- **Was it really necessary to declare the scale 3 times while the accident was in-progress? (**issue with international response?**)**
- Learning from the experience in Fukushima, there needs to be specific guideline in how to declare the scale for progressing accidents.

- In hindsight, **the question remains whether the level 4 declared on March 12 23:00 was a technical mistake**.
- Why was level 7 declared on April 12, one month after explosion of Dai-ichi Reactors 1 to 4, not right after three explosions?

- The accident was still expanding, so **instead of just indicating the scale**, shouldn't it have focused **on providing more precise and clear-cut explanations regarding the "impact on people and environment"?**

- **The radiation level of Fukushima does fit the level 7 criterion but in terms of "impact on people and environment", which is the original purpose of the scale, the impact is much smaller than Chernobyl. It seems that level 6** (or a level between 6 and 7) is more appropriate in this case.

- Further discussions should be made to review INES criteria based on what was learned in the Fukushima Dai-ichi Accident and aim for improvement, especially the criteria for Level 6 and 7 (or modify into detailed scale).

Was the message to the public appropriate? Wasn't there a gap between what's stated and what actually happened? Doesn't it add anxiety to the local and international society?

Press Conference with the Chief Cabinet Secretary (Sources from various news articles from the web; March 12 onwards)

March 12 18:00 (Reactor 1 after the explosion)

- "Does it mean there was no damage to the nuclear reactor? Has it been confirmed?" => **I would like to answer that once we have clarified the details, including final confirmation of facts and analysis of the cause.**
- "Does the government expect the hydrogen explosion and radiation leak?" => **We are handling this matter while expecting the worst. This accident, when it occurred, was within the scope of our expectations….** Comments that give out a false sense of alarm or security must not be made.

March 13 (Regarding Reactor 1 and 3)

- 8:00: In regards to Reactor 1, we have confirmed that the filling of seawater is working well as it would with the pump. …we can **logically conclude that the core is now filled with seawater, or at the least filled to a level that covers the fuel rods.**
- 8:00: (regarding reactor 3) … **By this ventilation and water injection** with the pump, **we should be able to manage, secure and control the situation**, although there will be some level of radioactive materials in the gas it will have no effect on the health, **and will insure nuclear reactor safety.**
- 8:00: "At what time will the filling of seawater end?" => **Even if we're done pouring water into the pressure tank and core reactor, we'd also like to fill-up the containment vessel** …if we continue filling the pressure tank, it will overflow, meaning the water will be going outside, so we would like to continue filling it with water.

- 11:00: (regarding Reactor 3) ….water pump stopped functioning… It is presumed that water level on the fuel rods dropped, exposing the top of the fuel rods. Because of this, the safety valve of the pressure tank opened and the pressure in the nuclear reactor dropped. Pumping of water started at 9:08. At 9:25 we mixed boric acid to increase the safety even more.
- 11:00 "What is the status on the exposed fuel rods in Reactor 1?" => We believe that **water have been filled, so it's no longer exposed.**
- 11:00: **"Does it mean that core meltdown occurred in Reactor 1?" => There is a possibility. Although we can't confirm, since of course we can't see inside the reactor, it is very likely so** we are handling the situation **with the assumption that it did occur.**
- 11:00: **"Reactor 1 exploded soon after the ventilation. What about reactor 3?" => This time we were able to properly inject the water and to set up the vent.**
- 11:00: "Have you already prepared what to do in case Reactor 1 can't no longer be filled with seawater?" => We believe that, **although it was at the last moment, we were able to fill the reactor with seawater before the problem got any bigger. For the other reactors, we'd like to do the same and be prepared at all times.**

Issues & lessons learned

- When should public statements be made?
- Was the hydrogen explosion really anticipated?
- What was the basis for the methods used for the vent and water injection when planning and executing it?
- Didn't they anticipate severe damage of pressure vessel and water to leak to the containment vessel?
- At this point, did they prepare the way to restore power and to cool the core in reactor 3?
- Was the countermeasure to explosion in reactor 3 really prepared?

(continued - 2)

Press conference with Chief Cabinet Secretary (extracted from 3/12 onwards)

3/13 (About Unit 1 and Unit 3)

- 15:30 As for Unit 3, the water level was found to be low this morning so we have depressurized the reactor and have started with the fresh water injection. By doing so, we were able to restore the water level of the reactor so that it can be cooled. …after that, due to trouble with the fresh water pump, the water level inside the reactor significantly decreased. … we switched to seawater injection and the water level stably started ascending again. … also, as **for Unit 3 , we would like to promptly report the possibility of hydrogen explosion similar to Unit 1**. …In the event of explosion like yesterday, we can say the nuclear reactor unit, reactor pressure vessel, and the containment vessel will not be affected because the explosion occurred in the outer area, and the structure is designed to withstand such impact.
- 15:30 "**Is there any way to remove the accumulated hydrogen ?" = > The difference from yesterday is, this time the ventilation was working and letting out the gas. In the current situation it is possible that it is already vented out**.
- 15:30 "**Is Unit 3 in meltdown? => We have to be careful with our words here**. We cannot deny the possibility of partial deformation of the reactor core. We are certain that the fuel rods were exposed above the coolant for a certain period of time. However**, generally, the core was not exposed long enough to cause meltdown**. The water level has started rising again.
- 15:30 "How much has the water level descended?" => It was once exposed significantly. However, the water level has started ascending so the time of exposure was very limited.
- 5:30 "**How is the progress of removing hydrogen from the building going?" => Basically the process to remove hydrogen outside has been ongoing from the start**.

- 20:00 (regarding Unit 3) initially the water level increased when the seawater injection started but later the reactor pressure vessel's gauge did not indicate any increase. However, we are still continuing to supply seawater. … There is a high possibility that the valve in Unit 3 is defective. We are working hard to resolve the issue with the defect and lower the air pressure inside the reactor.
- 20:00 "**Is there possibility of explosion (Unit 3) like in Unit 1? =>** We think that the **condition may be better than yesterday**. Because, we know the hydrogen has leaked to outside at a point.
- 20:00 "**You said that the water level of Unit 3 is not ascending, what is the status of the exposed fuel rods?" =>** We are currently analyzing the situation **with the possibility of the core exposure of course**. We are currently **doing everything we can to quickly solve the issue of the faulty valve**.
- 20:00 "**What are the possible scenarios when the air pressure is this high?" => The present situation, we are not in immediate danger.** However, we cannot afford to prolong this situation.

Issues and Lessons

- ● **Didn't they know that the RCIC and HPCI had already stopped at this point?**
- ● **Didn't they know that since the hydrogen leaked into the building from the containment vessel, the relief safety valve has little effect to prevent a hydrogen explosion?**
- ● **Although it is a delicate topic, they ended up giving a false sense of security which resulted in opposite affect. (Especially with the local residents and overseas media, and with evacuation decision of foreign governments).**

(continued - 3)

Press conference with Chief Cabinet Secretary (extracted from 3/12 onwards)

3/14 (regarding Unit 3 and Unit 2)

- 10:55 "**You said earlier that the valve in Unit 3 was faulty. Is there any update in the status of repair from now on? =>** Currently the **pressure is low, so instead of attempting to force the valve open, it will be better to continue the cooling of reactor with water injection**… (★★Unit 3 explodes★★)…we received news now. At 11:05 there may be smoke coming out from Unit 3. We are currently confirming whether there was an explosion.
- 10:55 "Is the core meltdown continuing in Unit 1? Is the condition getting worse or is it improving?" => At this point, since the pressure is not increasing, the water is filled sufficiently and core meltdown is no longer progressing. If the pressure increases, there is that possibility…

- 11:40 **Explosion occurred a while ago at 11:01 in Unit 3**. Judging from the condition of the explosion, it is thought to be a hydrogen explosion similar to that of Unit 1… the **Plant Superintended at site has reported that his understanding is that the containment vessel is intact.**
- 11:40 "**What is the basis of stating that the containment vessel is not affected?" => Based on the data we received** (to Tokyo)**, water injection is ongoing, or within the specified range, although the values may be slightly low**. ...this is based on the report given directly by the Plant Superintendent.

- 12:40 The pressure inside the containment vessel is stable - 380 kilo Pa at 11:13 and 360 Pa at 11:55. … I think this proves that there is no problem.
- 12:40 "**Are there other plants with hydrogen accumulated in upper levels of the building?" => At this point, there is no such risk**. We are working hard to prevent such a situation from happening.
- 12:40 "You mentioned that the pressure decreased at the time of the explosion. Is it not related to the explosion?" => It means the pressure is maintained to a certain degree, and data is available to support that it is intact as reported by the Plant Superintendent. This is the current situation.
- 12:40 "**Isn't there an effective way to let out the hydrogen accumulated in the building?" =>** We have received the report that **they have deliberated on various options, but if we touch it there may be a risk of triggering an explosion**.

Issues and Lessons

- **Aren't they too fixated on the safety of the containment vessel?**
- **To what extent had the response headquarters evaluated the risk of hydrogen explosion of Unit 4 and S/C damage on Unit 2 at this point (which occurred in the next day)?**
- **As a result, hasn't this amplified the fear of the public?**

(continued - 4)

Press conference with Chief Cabinet Secretary (extracted from 3/12 onwards)

3/24 (Regarding Unit 1)

- **11:00 "About Unit 1, what is your understanding regarding damage or risk of damage to the core and reactor pressure vessel?" =>** we have received report that **there is no damage to the pressure vessel at this point.**

3/28 (Regarding damage to the pressure vessel)

- 16:00 **"The NSC commented on the cause of the water leak in Fukushima Dai-ichi and the possibility of damage to the primary containment vessel (PCV). On the other hand, TEPCO pointed out that the damage is to the reactor pressure vessel (RPV). What are the facts?" =>** We received a report that **there is water leaking from the PCV. …We have not received a report on the details of the RPV.**

- 16:00 "**If the water that had contact with the molten fuel is leaking outside the PCV, isn't it normal to think that it leaked from RPV?" => I think that explanation by someone with expertise with nuclear reactors is more accurate. Of course, since the fuel rods are inside the RPV the water that had contact with it had somehow moved** …

4/19 (Regarding Units 2 and 4 meltdown)

- **"Yesterday, NISA admitted that the fuel rod had melted, which it had been denying till then. However they denied the core meltdown. Is there any basis for this? => It is a very technical process, so please ask NISA regarding this matter. However, I have been saying that there may be a chance,** or it is likely **that a portion of the fuel rods are damaged. However judging by the monitoring reports in the field, we can say that it hasn't entirely melted and there is no big hole in the core. As for the degree of the damage to the fuel rods, and whether there is partial meltdown, that is being analyzed by specialists** in NISA and the Safety Committee. We simply receive the reports from them."

Issues and Lessons

- **They are too worried about how it will affect (or receive criticism from) the local and international society if they admitted to the "Meltdown". Wouldn't they have been able to provide a reasonable explanation only if they had first admitted to crucial incidents such as the damage to the reactor pressure vessel, damage to the primary containment vessel, and melting of the fuel rod?**
- **Consequently, they were unable to establish a reasonable and understandable frame work for disclosing messages and risks to the citizens. Thus ending up the awkward explanation.**

The government's safety guideline has been incorrect – "No need to consider long-term loss of power."

Nuclear Safety Commission's Design Guidelines
(Supervised by Cabinet Office Nuclear Safety Commission Secretariat)

Section 1: Safety Review Guideline No. 27 "In case of power loss"

- Nuclear reactors and facilities should be **able to safely stop and secure cooling function in case of a short-term loss of all AC** power.

(Explanation)

- There is **no need to consider long-period loss of AC power**, since we can **expect swift restoration of the transmission line** or **restoration of power through the emergency AC power supply** system.
- If the system structure or operational method (i.e. constant backup) of the emergency AC power-supply system is deemed highly reliable, then there is **no need to take into account any scenario of a complete AC power blackout in the design of the plant**.

Facts at Fukushima Dai-ichi

- Transmission line was not restored before hydrogen explosion.
- Emergency AC power supply system malfunctioned due to the tsunami and was not restored before the hydrogen explosion.
- Not only the AC power, but also the DC power supply were completely lost for a long period.
- Due to the complete loss of all AC and DC power for a long period, key functions such as parameter-control at the central operation room, cooling, and water-injection were all lost.

It is necessary to verify why and who is responsible for this guideline, and completely redesign the atomic energy administration, as known for its back-scratching structure.

It is imperative to provide clear safety guidelines for long-term power loss. For example, if it is over 24 hours, off-site support shall be provided, and if within 24 hours, the on-site team has to deal with it.

Length of AC power outage

24 hours

Guideline	● Prepare on-site plan and safety measures that can prevent core damage for at least 24 hours for any type of power loss.	● For power loss over 24 hours, off-site support and actions shall be made.
Main player	● Power company	● Power company and central government
Power supply	● Secure power supply on-site for at least 24 hours.	● Must accomplish off-site support within 24 hours.

- In US, boundary between on-site and off-site response is 72 hours for NRC and 24 hours for INPO.
- For example, USA has a special unit that is intensively trained to work in radiation-contaminated areas (e.g. Fort Leonard Wood Chemical Biological Radioactive Unit).
- Japan should have a similar special unit as well.

Future education and training should include 'lessons learned from Fukushima Dai-ichi'.

Important items for the education and training programs (Example)

- **Practical training under extreme conditions such as in Fukushima Dai-ichi Reactor 1**
  - Complete power outage, loss of cooling function, darkness, aftershocks, high radiation, insufficient materials, and telecommunication problems.
  - Risk of core damage and hydrogen build-up in a couple of hours from the stop of cooling system.
  - (Furthermore) Severe accident during holidays, night, bad weather, fire, and road blocks (simultaneously).
  - Emphasis on the absolute prevention of a hydrogen explosion under any circumstances.

- **Practical training to supply alternative power source and cooling system to the plant (for example) "within 2 hours" during complete power outage**
  - Prepare and store the requirements. (Define the type and quantity of power/water sources and equipments to meet the necessary time of cooling.)
  - Actual operation to carry and set up alternative systems such as power supply, coolant, water-injection, carry-on batteries on-site.
  - Organize and operate supply chains for emergency equipment (at the plant, at the head office, etc.)

- **Set specific indicators/goals/periods in each training and check its proficiency level.**
  - Example: Provide X amount of power/water supply within Y hours. Complete task A within B hours, etc.

- **Practical training not only for the power company, but together with the central and local government and related stakeholders.**

- **Share and pass down the experience and lessons learned from Fukushima Dai-ichi with all power companies in Japan and the world.**

Additional Research

Hearings with local governments

In this chapter, we summarized the results of additional research conducted after the interim report on October 28, 2011, on major issues pointed out by officials of local governments during our interviews.

Summary: We have investigated the following four issues which were frequently indicated or questioned during our interview sessions with local governments.

- Why did the accident in reactor No. 1 progress much faster than No. 2, 3 and 4 in Fukushima Dai-ichi?

  Issue 1: Is it because some of the major pipes of the reactor was ruptured by the earthquake?

  Issue 2: Is it because the primary containment vessel of reactor No. 1 is the old model ‘Mark I’?

  Issue 3: Otherwise, the emergency cooling function (Isolation Condenser: IC) should have functioned and the accident development should have been much slower.

- Issue 4: What could have been done to reactor No.1 in order to avoid the hydrogen explosion and leakage of radioactive materials?

In the following pages, key findings are discussed in regards to those issues.

Issue 1: The accident in reactor No. 1 progressed much faster than No. 2, 3 and 4, because some of the major pipes in the reactor were ruptured by the earthquake. – This hypothesis was analyzed from the following perspectives.

What kind of piping system, if ruptured, can significantly accelerate the core meltdown? Why?

- Pipes with large diameters such as the one for main steam circulation, for feeding and re-circulating the coolant
- Besides the above, nozzles of connection pipes such as the one for instrumental measurement.

If these piping systems were to rupture, how would the parameters in the reactor respond?

- If the rupture causes the leak of coolant water to the primary containment vessel (PCV), the following changes would be observed in the pressure, water level, and temperature of the reactor pressure vessel (RPV) and the PCV.
  - Pressure and water level in the reactor pressure vessel would drop rapidly.
  - Water level of the condensed water tank in the containment vessel would rise rapidly.
  - Pressure and temperature in the containment vessel would rise as well.
  - In all cases above, alarms would be triggered by the detection instruments.

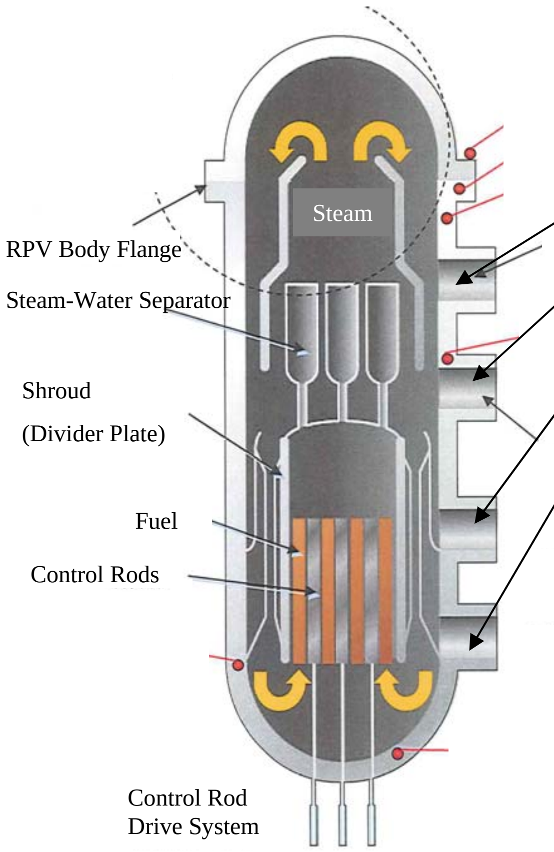
What were the actual responses of the parameters, compared to the points above?

- Water level and pressure in the reactor pressure vessel recovered from the earthquake to the tsunami.
- No significant rise in temperature and pressure in the containment vessel were observed though there were some effects from the shut down of the air-conditioning equipment.

What kind of damage would workers suffer if they were exposed to the water (steam) from the ruptured pipe?

- If the rupture occurred in the reactor building, steam of 70 Atm and 280 Celsius degree would blow out. If workers were subjected to the steam directly, they would be killed or severely injured.
- Also, the extreme volume of steam would fill the building, making the surrounding area foggy with zero visibility. Therefore, one must contact staff outside by necessity.

Issue 1: What kind of piping system, if ruptured, could accelerate core damage significantly? why?



What kind of piping system, if ruptured, could accelerate core damage significantly?

- The following pipes with large diameters would significantly accelerate core damage:
  - **Main Steam Exit Nozzle**
  - **Main Steam Feedwater Nozzle**
  - **Recirculating Water Entrance**
  - **Recirculating Water Exit**

  (Besides, pipe connectors such as the one for instrumental measurement would also be considered.)

- **If these pipes are ruptured, the following phenomena would be induced.**
  - Steam in the core would be rapidly discharged from the reactor pressure vessel.
  - Coolant water would be rapidly discharged from the reactor pressure vessel.

- **As a result, the cooling function and water injection of the core would be significantly damaged, which would accelerate the core damage.**

If rupture occurs, how do parameters in the reactor respond?

- **Water Level**
  - Water level in the reactor pressure vessel would drop rapidly.
  - Water level of the sump (tank) in containment vessel would rise rapidly and the alarm would be triggered.

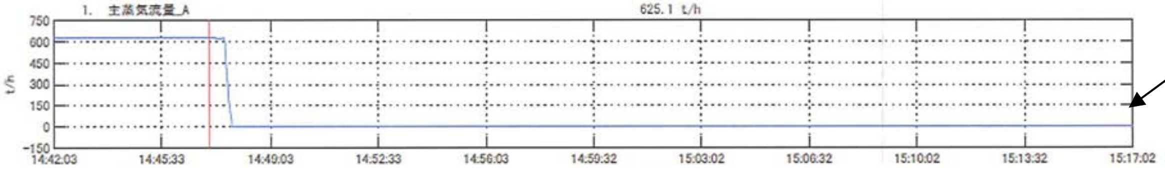
- **Pressure & Temperature**
  - Pressure in the reactor pressure vessel would drop rapidly.
  - Pressure and temperature in the containment vessel will increase rapidly and the alarm will be triggered. (Steam around 280 Celsius will be ejected.)

- **Radiation Dosage**
  - Radiation dosage within the containment vessel would increase rapidly and the alarm would be triggered. (CAMS etc.)

So, how did these parameters actually respond?

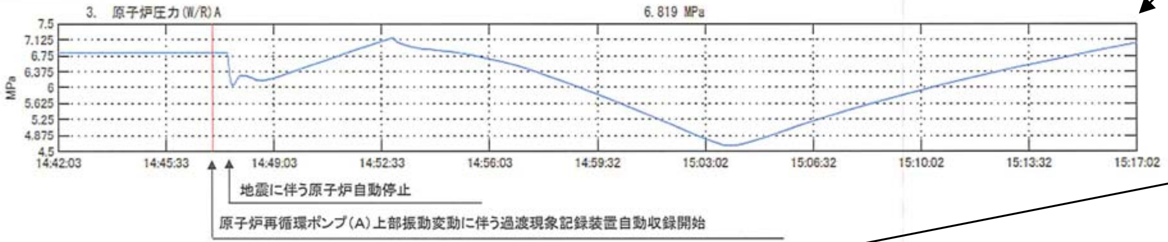
Issue 1: The parameters from the time of earthquake to tsunami indicate no significant changes in water level, temperature, and pressure. No symptoms of pipe rupture accelerating the core damage.

Volume of Main Steam Flow

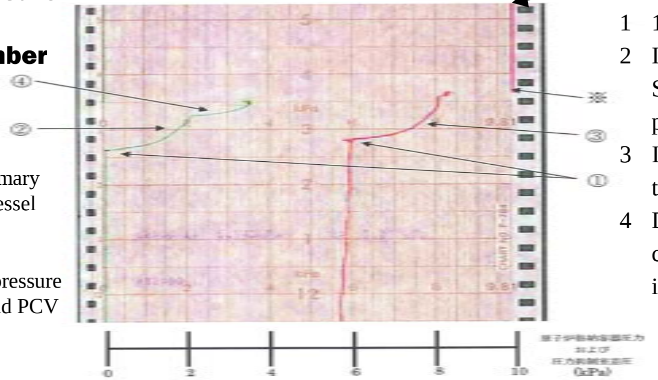


Water Level in Reactor

Pressure in Reactor



Difference in pressure between PCV and suppression chamber (SC)



🟥 Pressure in primary containment vessel (PCV)

🟩 Difference in pressure between SC and PCV

1 14:46 Scram started after earthquake.
2 Increase in pressure difference between SC and PCV, caused by the rise in pressure in PCV.
3 Increase in pressure in PCV, caused by the stop of air-conditioner in PCV.
4 Decrease in pressure in SC, caused by cooling of SC. (The difference increased further.)

- **Volume of Main Steam Flow:** Had dropped and stayed at zero level due to closure of main steam isolation valve closed right after earthquake. **(No rapid increase in flow volume)**

- **Water Level in Reactor**: Had stayed constant after instant shift caused by collapse of bubbles right after the scram. **(No rapid decrease in water level)**

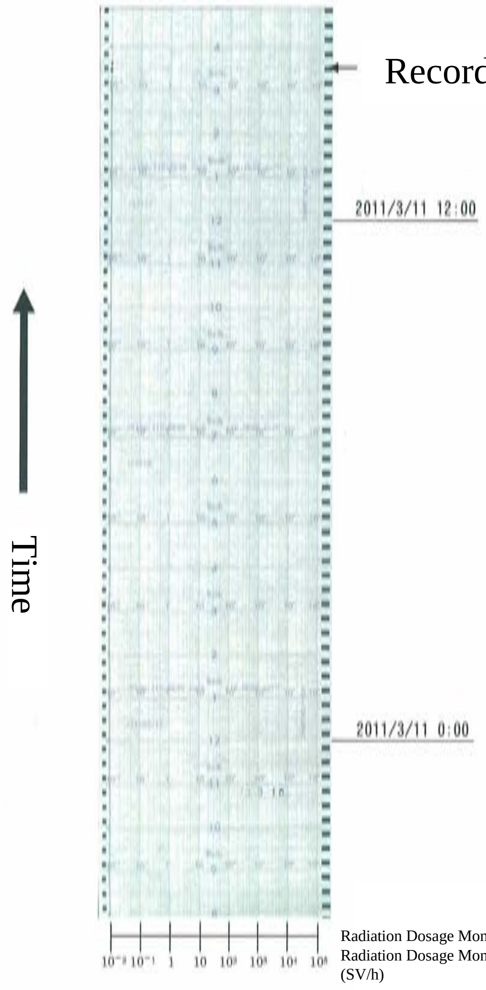
- **Pressure in Reactor:** Had increased due to closure of main steam isolation valve and decay heat, after decreasing right after the scram.
  - Around 14:52, it decreased when Isolation Condenser (IC) started cooling, then increased again with the stop of IC. **(No rapid decrease in pressure)**

- **Difference in pressure between PCV and suppression chamber (SC):** Had increased approx. 20-30 kPa during the earthquake and Tsunami.

<u>Pressure increase was slight, and is almost equivalent to the rise in temperature caused by the stop of air-conditioner.</u>

In case of guillotine break, it would increase more rapidly (more than 1atm = 101.3kPa.)

Issue 1: There was no change in radiation dosage in PCV observed by the atmosphere monitoring system between earthquake and Tsunami.



Record ended

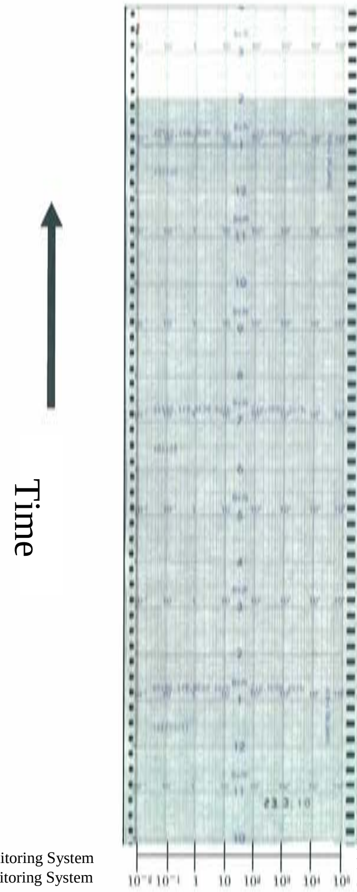
2011/3/11 12:00

2011/3/11 0:00

Radiation Dosage Monitor A in Containment Atmosphere Monitoring System
Radiation Dosage Monitor C in Containment Atmosphere Monitoring System
(SV/h)

(Red) Radiation Dosage Monitor A in Containment Atmosphere Monitoring System
(Green) Radiation Dosage Monitor C in Containment Atmosphere Monitoring System

Reactor No.1: Radiation Dosage Monitor in Containment Atmosphere Monitoring System (CH-C/A) (1/1)



Record ended

2011/3/11 12:00

2011/3/11 0:00

Radiation Dosage Monitor B in Containment Atmosphere Monitoring System
Radiation Dosage Monitor D in Containment Atmosphere Monitoring System
(SV/h)

(Red) Radiation Dosage Monitor B in Containment Atmosphere Monitoring System
(Green) Radiation Dosage Monitor D in Containment Atmosphere Monitoring System

Same as left (CH-D/B) (1/1)

Issue 1: What kind of damage would workers suffer, if they were exposed to the water (steam) from the ruptured pipe?

- If the pipes were ruptured in the reactor building, **highly radioactive steam at 70 Atm and 280 Celsius would eject** from the pipe.
- **If workers were subjected to the steam directly** from the rupture, it is highly possible that **they would be killed or be severely injured**, because the steam is extremely hot with high pressure and high radiation.
- The **sheer volume of steam** ejected from the rupture would fill the building, and **cause the surrounding area around the rupture to turn foggy with zero visibility** within a very short period of time (or instantaneously).
- In either case, one **must contact staff outside** due to the extremely dangerous situation.

- In the accident at Fukushima Dai-ichi No.1, there are no reports of fatal or severe injuries from steam at high temperature, pressure or radiation dosage.
- There are also no reports or alarms of an extreme volume of steam being generated, or on being foggy and no visibility in the affected area.

Issue 2: The accident in reactor No. 1 progressed much faster than No. 2, 3, and 4 because its primary containment vessel (PCV) is the old model 'Mark I'. – This hypothesis was analyzed from the following perspectives.

What is Mark 1? Is it the type of the whole reactor, or the type of PCV?

- It is the type of PCV.

If we assume 'Mark 1' is more vulnerable to the accident like this than Mark 2, what would be the plausible or rational reason?

- It is hard to conclude that Mark 1 is more vulnerable since its output is the same or larger than that of Mark 2, even though its spatial volume of PCV is smaller than Mark 2.
- The main reason for the acceleration of accidents in Fukushima Dai-ichi No.1 is the simultaneous loss of all power sources and the entire cooling systems. No rational data were found to conclude that the shape or volume differences in PCV were the major reason for event acceleration.

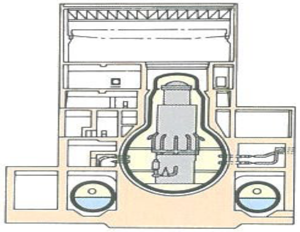
If we assume 'BWR 3' is more vulnerable to the accident like this than other models, what would be the plausible or rational reason?

- Compared to BWR3, BWR 5's high-pressure pumps for ECCS* have been changed to motor driven with an emergency DG added as power source for the pumps. The location of the DG has been shifted from the turbine building to the annex of reactor building. (ECCS = emergency core cooling system)
- In the accident in Fukushima Dai-chi, both AC power and the DG itself lost function due to flooding. There seems to be no difference between BWR 3 and BWR 5 in event progression in terms of high-pressure pumps and emergency DG.

Issue 2 Mark 1 is a type of PCV*1. There are other plants than 1F*2 reactor No. 1, which use Mark 1.

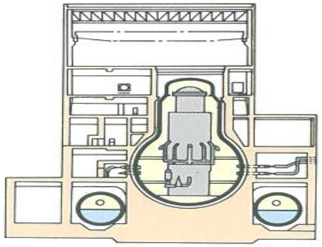
(*1: primary containment vessel. *2: Fukushima Dai-ichi Nuclear Power plant)

Fukushima Dai-ichi No.1
(Output 460,000kW)
〔1971〕



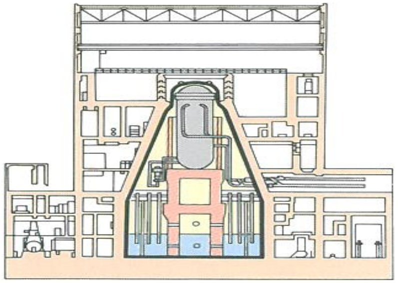
BWR-3
Mark 1
(Flask-shaped)

Fukushima Dai-ichi No.2-5
(Output 784,000kW)
〔1974～1978〕



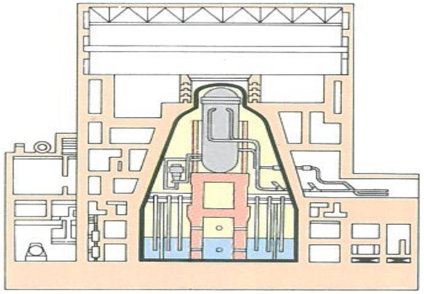
BWR-4
Mark 1
(Flask-shaped)

Fukushima Dai-ichi No.6
Fukushima Dai-ni No.1
(Output 1,100,000kW)
〔1979-1985〕



BWR-5
Mark 2
(Cone-shaped)

Fukushima Dai-ni No.2-4
(Output 1,100,000kW)
〔1984 - 1994〕



BWR-5
Mark 2 Improved
(Bell-shaped)

History of Versions for BWR Plant

	BWR-1	BWR-2	BWR-3	BWR-4	BWR-5	BWR-6
Output（MWe）	160～250	350～640	460～810	540～1100	660～1100	990～1300
Output Density (kW/l)	31.2	40.6	41.1	49.7	51.0	54.1
Cycle System	Double cycle/ Direct cycle	Direct cycle				
Core Coolant	Natural circulation/ External forced	External forced circulation	Jet pump with single nozzle			Jet pump with 5 nozzles
Fuel	7x 7 Fuel					8 x 8 Fuel
Steam-Water Separation System	Steam drum/ Internal steam-water separator	Internal steam-water separator				
ECCS	Core spray cooling		Low pressure water-feed systems		High pressure system enhanced	
PCV	**Dry well**	**Suppression chamber （Mark-I)**			**Suppression chamber （Mark-II)**	**Suppression chamber （Mark-III)**

Fukushima Dai-ichi Unit 1	Fukushima Dai-ichi Unit 2	Fukushima Dai-ichi Unit 3	Fukushima Dai-ichi Unit 4	Fukushima Dai-ichi Unit 5	Fukushima Dai-ichi Unit 6	Fukushima Dai-ni Unit 1	Fukushima Dai-ni Unit 2	Fukushima Dai-ni Unit 3	Fukushima Dai-ni Unit 4	Onagawa Unit 1	Onagawa Unit 2	Onagawa Unit 3	Tokai Dai-ni Unit 2
Mark 1 (BWR-3)	**Mark 1 (BWR-4)**	**Mark 1 (BWR-4)**	**Mark 1 (BWR-4)**	**Mark 1 (BWR-4)**	Mark 2 (BWR-5)	Mark 2 (BWR-5)	Improved Mark 2 (BWR-5)	Improved Mark 2 (BWR-5)	Improved Mark 2 (BWR-5)	**Mark 1 (BWR-4)**	**Improved Mark 1 (BWR-5)**	**Improved Mark 1 (BWR-5)**	Mark 2 (BWR-5)

Issue 2: If we assume 'Mark 1' is more vulnerable to the accident like this than Mark 2, what would be the technical or rational reason?

Possible Hypothesis	**Consideration for/against it**
● Was the accident development much faster in Reactor No. 1, **because the size and volume of Mark 1 are much smaller than the others?**	● All the PCV of Dai-ichi Reactor No.1-5 are Mark 1. There is no significant difference in the volumes per unit output. ● Though ECCS structure for BWR 3 is different from the one for later versions, none of the ECCS had effectively functioned this time.
● Was it because the Mark 1 of Reactor No.1 is **older and more aged than the rest** of the reactors?	● See following pages for more details. ● No.3, which is newer than No.1, also exploded, and No.2, older than No.3 but newer than No.1, did not explode. ・ No.1 = activated in March, 1971. No.2 = in July, 1974. No.3 = in March, 1976.
● Was it because Mark 1 is **the product of an earlier time than the others**, and its technology and functions are inferior to the later products.	● See following pages for more details. ● Fukushima Dai-ichi No.2-5, and Onagawa No.1 also have equipped Mark 1, but they had followed different event progressions. ● It is hard to conclude that all Mark 1s followed the same event progressions.

<u>The reason why the event progression at reactor 1 was much faster than others is the simultaneous and complete loss of power and cooling.</u> No rational reason was found to support that it was because of Mark 1 (or a type of plant).

Issue 2: Was the accident development much faster in Reactor No. 1, because the size and volume of Mark 1 are much smaller than the others? - There is no significant difference in the volume per unit output with the others.

- **If we look at the volume per unit output of PCV, Mark 1 and Mark 2 Improved are the highest. However, its range is among 3 – 4.4 square meters. It can not be said that Mark 1 is significantly high in output volume.**

Mark 1 (BWR3) : 4.37(㎥/MWt) (6,030㎥/1,380MWt)
Mark 1 (BWR4) : 3.11 (㎥/MWt) (7,400㎥ /2,381MWt)
Mark 2 (BWR5) : 2.97 (㎥/MWt) (9,775㎥ /3,293MWt)※
Mark 2 Improved (BWR5) : 4.37 (㎥/MWt) (14,406㎥ /3,293MWt)※
RCCV(ABWR) : 3.40 (㎥/MWt) (13,355㎥ /3,926MWt)※
(※: See Fukushima Dai-ichi Nuclear Power Plant Accident Investigation Commission Appendix 4)

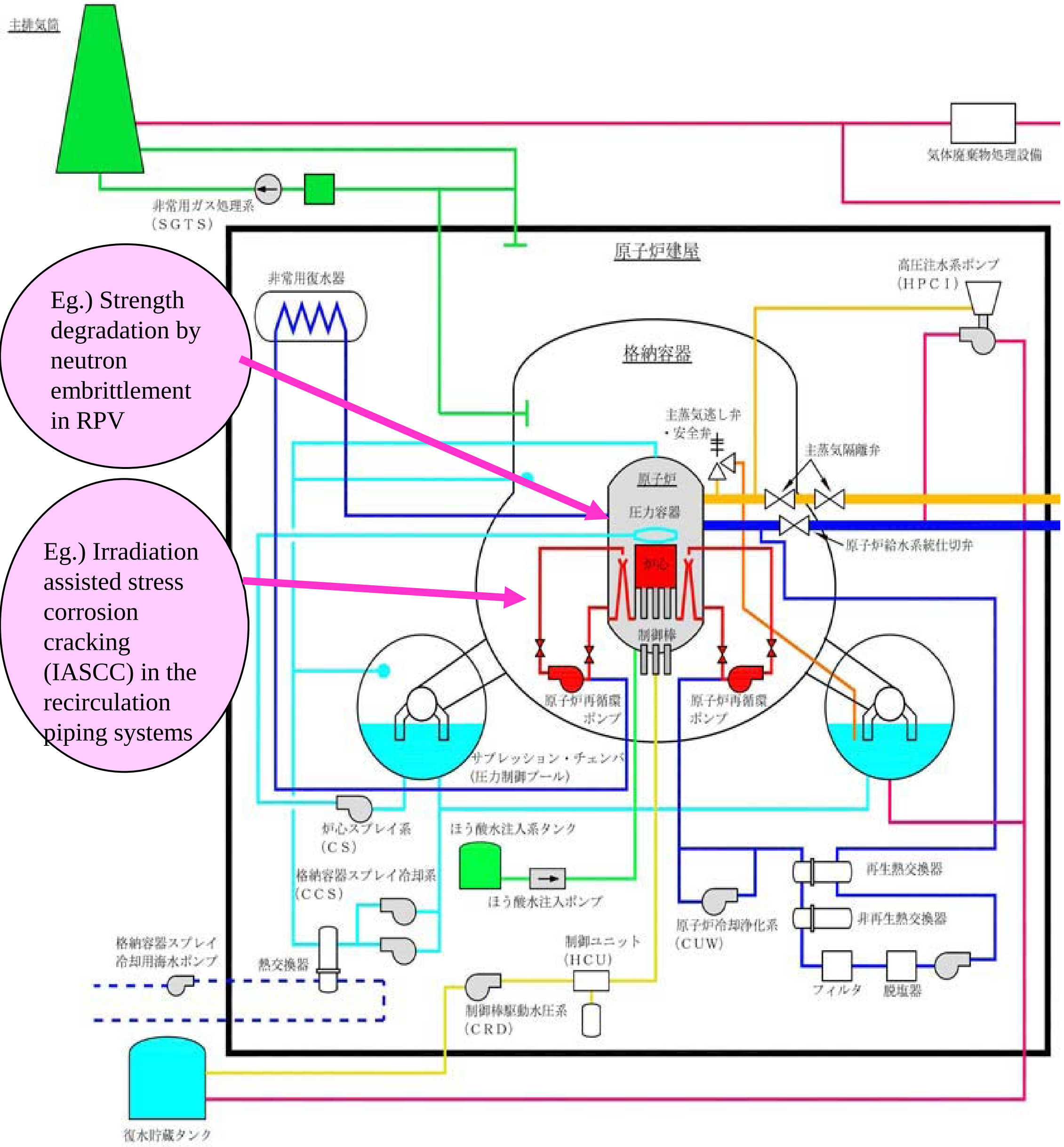
- If we examine the analytical data of accidents most similar to the one in Fukushima Dai-ichi, no results are observed to support that the time for PCV to be severely damaged (from the timing of core damage) is much shorter for Mark 1 than the other types.

Issue 2: Was it because the Mark 1 of Reactor No.1 is older and more aged than the rest of the reactors? – No data was gained to conclude aging as a major reason for faster event progression.

- The assessment of aging degradation has been conducted for plants activated over 30 years, based on the history of their operation and repairs.
  - After 30 years of operation, periodic reassessment has been mandated in less than every 10 years.
- The second assessment was conducted last year at Fukushima Dai-ichi Reactor No.1 (at the 39th year of its operation).
- If the reactor is assumed to operate for 60 years, it is assessed that most of the equipments and buildings would be maintained in a good condition in the future, by keeping current maintenance activities.
- For some of the key equipments and building structures, it was assessed that they would be maintained in a good condition by the maintenance activities with 16 maintenance items in 25 categories newly added.

Based on the accident in Dai-ichi No.1, the assessment should be conducted in RPV, structures of the reactor such as shroud, and piping systems within RPV such as the recirculation piping. However, no significant differences are observed in No.1 compared to the others.

Issue 2: (Continued) Procedure of Aging Degradation Assessment



Eg.) Strength degradation by neutron embrittlement in RPV

Eg.) Irradiation assisted stress corrosion cracking (IASCC) in the recirculation piping systems

Assessment Procedure

- **Classify major safety equipments and building structures into 16 Categories**
  - Containment (RPV, PCV), pump, heat exchanger, pump motor, pipe, valve, structures in reactor, cable, concrete and steal construction, measurement control system, power source system, etc.

- **Extract aging degradation events**
  - Equipment materials, environment of use, past accidents, etc.
- **Examples of major aging degradation events**
  - Strength degradation of RPV body in neutron-irradiated environment (neutron embrittlement)
  - Stress Corrosion Cracking (SCC) of stainless-steal equipment under high temperature and purified water environment such as core shroud , recirculation piping systems etc.
  - Material loss of inside of pipes by corrosion
  - Degradation of insulating equipments such as cables by heat, irradiation etc.
  - Strength degradation of concrete structures by heat, irradiation, etc.

- **Perspectives for aging degradation assessment**
  - Aging degradation effect to equipments
  - Effect against seismic strength
  - Appropriateness of current maintenance activities to the trends of occurrence and progression of aging degradation events
  - Extraction of additional maintenance needs to current activities.

- **Define long-term maintenance policy**
  - Action plan for next 10 years. (long-term maintenance policy)

Issue 2: (Continued) Time comparison by the Type of PCV (From Core Damage to PCV Damage) (by Analysis)

	BWR-3 Mark I	BWR-4 Mark I	BWR-5 Mark II	BWR-5 Mark II (Improved)	RCCV ABWR
Long-term loss of power source (TB)	🟨 **4.5**	**10**	🟨 **4.5**	🟨 **4.5**	**11**
Loss of power source during the small rupture of pipe & loss-of-coolant accident (LOCA) (S2B)	**17**	**16**	**12**	**12**	🟨 **9**
Failure in high/low pressure coolant injection (TQUV)	**18**	**13.5**	🟨 **7.5**	**9.5**	**33**
Failure in high pressure coolant injection and de-pressurization (TQUX)	**16**	**10**	🟨 **7**	🟨 **7**	**24.5**
Failure in coolant injection during LOCA (AE)	**10.5**	**9**	🟨 **3.5**	**4**	**16**

🟨 **Minimum Hours**

Level 2 PSA Analysis in Earthquake (BWR) in 2009, data from Japan Nuclear Energy Safety Organization in October 2010.

Issue 3: Otherwise, the emergency cooling function (Isolation Condenser: IC) should have functioned and the accident development should have been much slower. – This hypothesis was analyzed from the following perspectives.

How long was IC designed to maintain its cooling function?

- It is designed to maintain its cooling function for approximately 8 hours without any water supply in the condenser.

Had the IC been functioning after the earthquake, and Tsunami? Why?

- The IC was activated automatically by the scram after earthquake, and had been functioning normally until the Tsunami.
- The operators opened and closed the external valve (DC driven) of IC three times, following the operating procedure to keep its cooling rate at 55 Celsius/hr.
- As both the DC and AC power sources were lost simultaneously due to Tsunami, the internal valves of IC, which was designed to close in case of AC power outage (i.e. 'fail-close'), was mostly closed and the external valves (DC driven) of IC also lost its open/close function.
- As a result, it is assumed that the IC cooling system was lost after the Tsunami.

How long did the IC cool the core, according to the records?

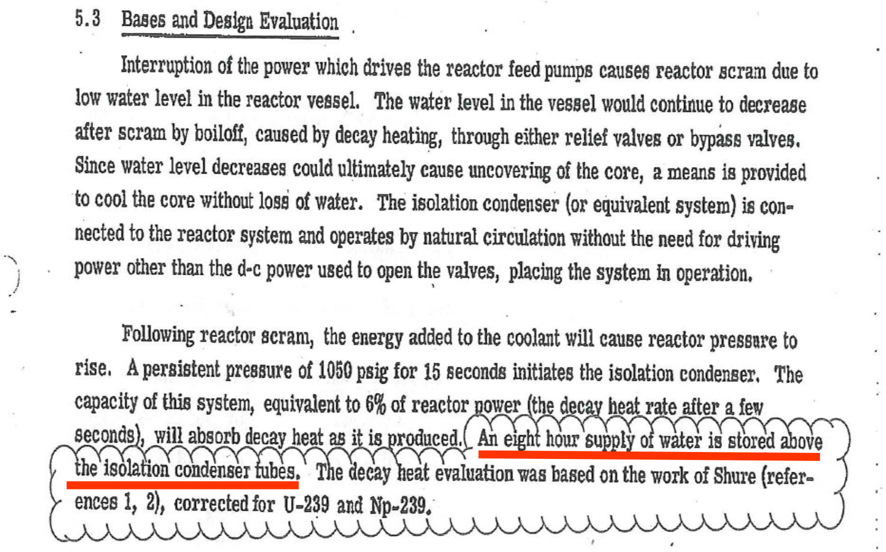
- The records of the water levels in the emergency condensers indicate that approx. 15% of the water had been evaporated in system-A, and almost no water had been evaporated in system-B.
- Deduced from the amount of there evaporation, IC cooling had functioned for only about 45 minutes from the earthquake.

Did IC stop due to inappropriate manual operations, or was it inevitable?

- Operators recognized a possibility of DC recovery at 18:18 on March 11, and <u>opened</u> the external valve and <u>closed</u> it at 18:25. Then, the operators <u>opened</u> the valve again at 21:30, and had kept it opened from then.
- However, as IC's internal valves had been "mostly closed" after the Tsunami, these open/close operations of the external valves does not seem to have had significant effects on the functionality of IC.
- Therefore, manual operations would not have made a significant difference in the accident development even though the director or operators had correctly manipulated the external valve between 18:25 to 21:30, since the internal valves had remained "mostly closed", meaning the IC was closed internally no matter what the situation of its external valves was.

Issue 3: How long was the IC designed to maintain its cooling function?

Data from GE: extracted from Design and Analysis Report



5.3 Bases and Design Evaluation

Interruption of the power which drives the reactor feed pumps causes reactor scram due to low water level in the reactor vessel. The water level in the vessel would continue to decrease after scram by boiloff, caused by decay heating, through either relief valves or bypass valves. Since water level decreases could ultimately cause uncovering of the core, a means is provided to cool the core without loss of water. The isolation condenser (or equivalent system) is connected to the reactor system and operates by natural circulation without the need for driving power other than the d-c power used to open the valves, placing the system in operation.

Following reactor scram, the energy added to the coolant will cause reactor pressure to rise. A persistent pressure of 1050 psig for 15 seconds initiates the isolation condenser. The capacity of this system, equivalent to 6% of reactor power (the decay heat rate after a few seconds), will absorb decay heat as it is produced. An eight hour supply of water is stored above the isolation condenser tubes. The decay heat evaluation was based on the work of Shure (references 1, 2), corrected for U-239 and Np-239.

Construction Permit Application of
Fukushima Dai-ichi Reactor No.1

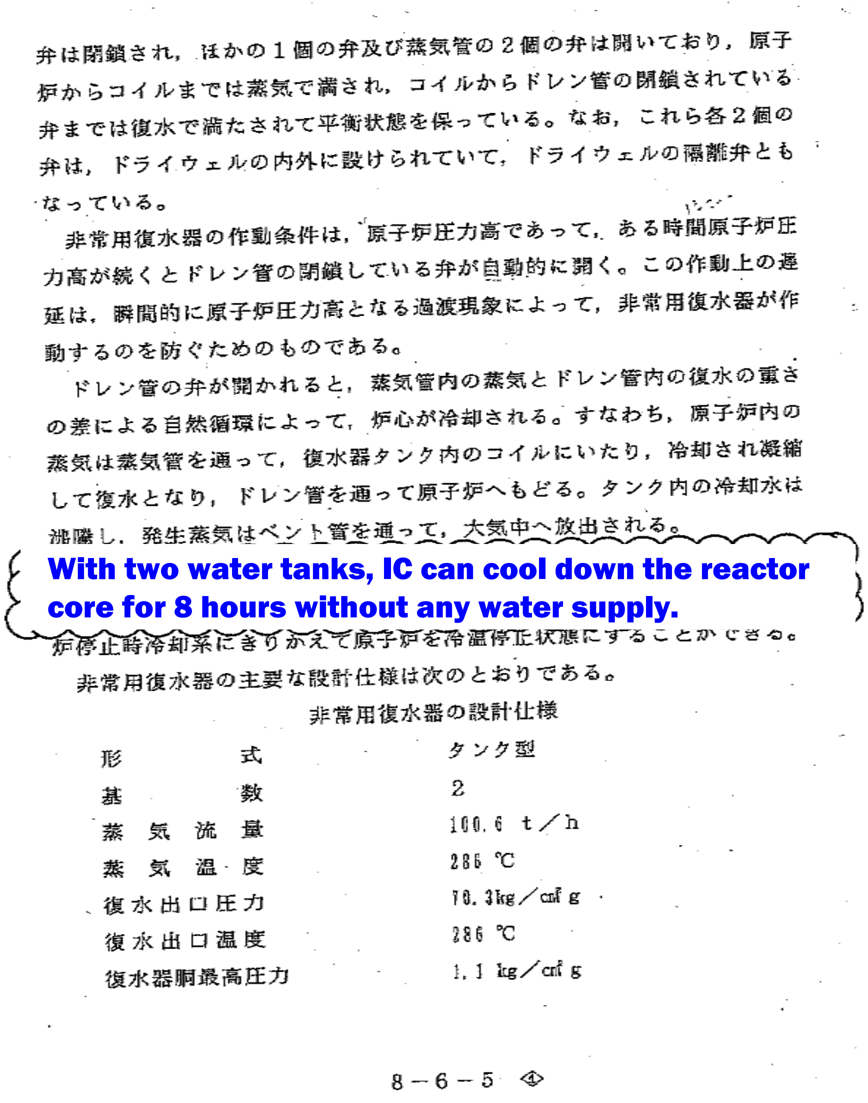
(See the next page)

- It is designed to maintain the cooling system for approximately 8 hours without any water-feed in the condenser.

"An eight hour supply of water is stored above the isolation condenser tubes"

- In actual operation, 80% of the condenser tank is filled with water but not 100%. With this water, the IC can work for approximately 8 hours.

Issue 3: (Continued) Construction Permit Application of Fukushima Dai-ichi Reactor No.1 (Extracted)



弁は閉鎖され，ほかの１個の弁及び蒸気管の２個の弁は開いており，原子炉からコイルまでは蒸気で満され，コイルからドレン管の閉鎖されている弁までは復水で満たされて平衡状態を保っている。なお，これら各２個の弁は，ドライウェルの内外に設けられていて，ドライウェルの隔離弁ともなっている。

非常用復水器の作動条件は，原子炉圧力高であって，ある時間原子炉圧力高が続くとドレン管の閉鎖している弁が自動的に開く。この作動上の遅延は，瞬間的に原子炉圧力高となる過渡現象によって，非常用復水器が作動するのを防ぐためのものである。

ドレン管の弁が開かれると，蒸気管内の蒸気とドレン管内の復水の重さの差による自然循環によって，炉心が冷却される。すなわち，原子炉内の蒸気は蒸気管を通って，復水器タンク内のコイルにいたり，冷却され凝縮して復水となり，ドレン管を通って原子炉へもどる。タンク内の冷却水は沸騰し，発生蒸気はベント管を通って，大気中へ放出される。

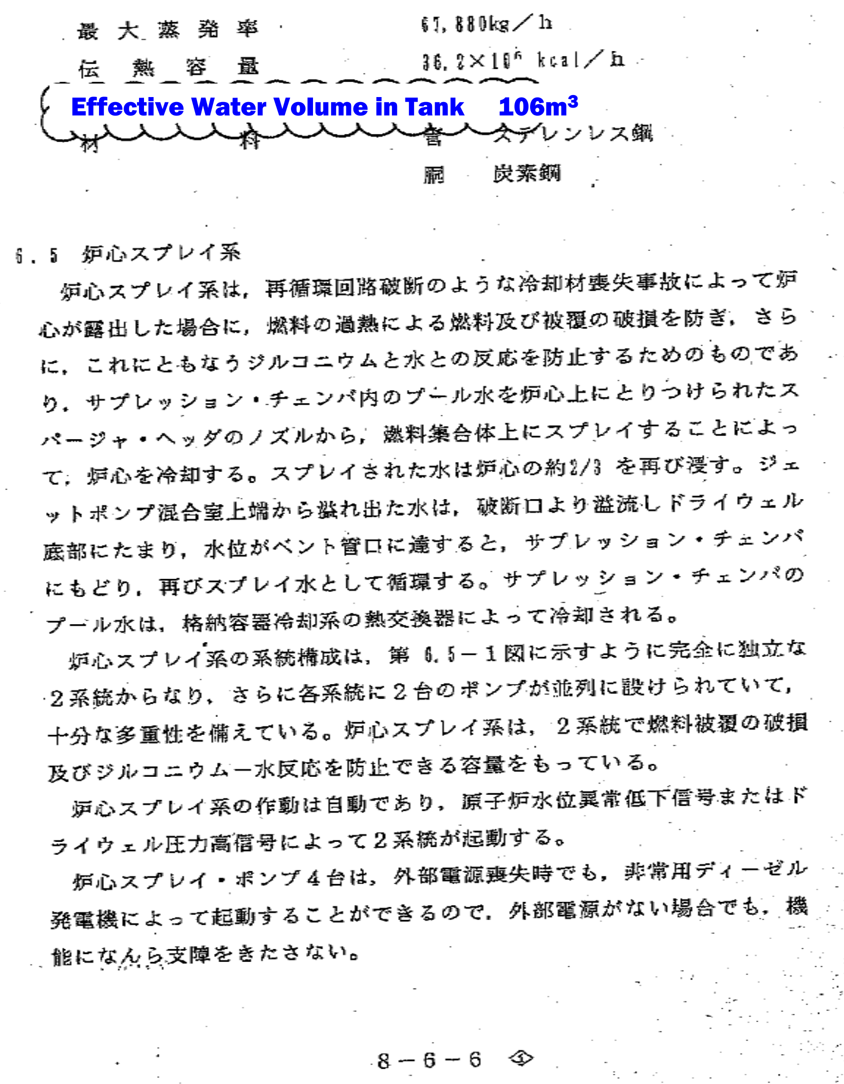
With two water tanks, IC can cool down the reactor core for 8 hours without any water supply.

炉停止時冷却系にきりかえて原子炉を冷温停止状態にすることができる。

非常用復水器の主要な設計仕様は次のとおりである。

非常用復水器の設計仕様

形　　式	タンク型
基　　数	2
蒸気流量	100.6 t／h
蒸気温度	286 ℃
復水出口圧力	70.3kg／cm² g
復水出口温度	286 ℃
復水器胴最高圧力	1.1 kg／cm² g



最大蒸発率	67,880kg／h
伝熱容量	36.2×10^6 kcal／h

Effective Water Volume in Tank　106m³

材　料	管　ステンレス鋼
	胴　炭素鋼

6．5　炉心スプレイ系

炉心スプレイ系は，再循環回路破断のような冷却材喪失事故によって炉心が露出した場合に，燃料の過熱による燃料及び被覆の破損を防ぎ，さらに，これにともなうジルコニウムと水との反応を防止するためのものであり，サプレッション・チェンバ内のプール水を炉心上にとりつけられたスパージャ・ヘッダのノズルから，燃料集合体上にスプレイすることによって，炉心を冷却する。スプレイされた水は炉心の約2/3 を再び浸す。ジェットポンプ混合室上端から溢れ出た水は，破断口より溢流しドライウェル底部にたまり，水位がベント管口に達すると，サプレッション・チェンバにもどり，再びスプレイ水として循環する。サプレッション・チェンバのプール水は，格納容器冷却系の熱交換器によって冷却される。

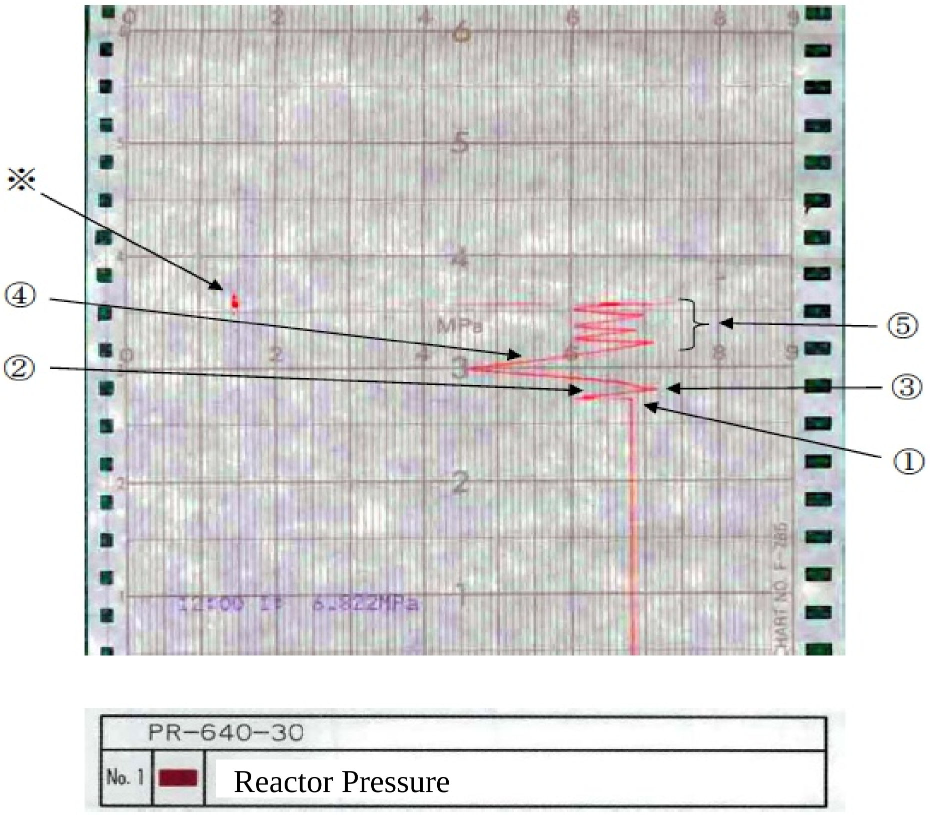
炉心スプレイ系の系統構成は，第 6.5－1図に示すように完全に独立な２系統からなり，さらに各系統に２台のポンプが並列に設けられていて，十分な多重性を備えている。炉心スプレイ系は，２系統で燃料被覆の破損及びジルコニウム－水反応を防止できる容量をもっている。

炉心スプレイ系の作動は自動であり，原子炉水位異常低下信号またはドライウェル圧力高信号によって２系統が起動する。

炉心スプレイ・ポンプ４台は，外部電源喪失時でも，非常用ディーゼル発電機によって起動することができるので，外部電源がない場合でも，機能になんら支障をきたさない。

Issue 3: Had the IC been functioning after the earthquake, and before Tsunami?
=> It had functioned normally.

Pressure of reactor No. 1



IC Operations <u>after</u> earthquake and <u>before</u> Tsunami

- **The IC was activated automatically by the scram after earthquake, and had been functioning normally before Tsunami hit.**
- **The operators opened and closed the external valve (DC driven) of IC three times, following the operating procedure to keep its cooling rate at 55 Celsius/hr.**

① 14:46 Scrammed by earthquake
② Core pressure increased by closure of main steam isolation valve
③ 14:52 IC automatically activated, and the core pressure decreased.
④ 15:03 (approx.) Valves-3A & 3B closed.
⑤ 15:10~15:30 (approx.) Adjustment of core pressure by open-close operations of valve-3A.
* 15:37 Loss of all AC power by Tsunami
(Since then, all recording had ceased due to complete power loss)

IC Operations after Tsunami

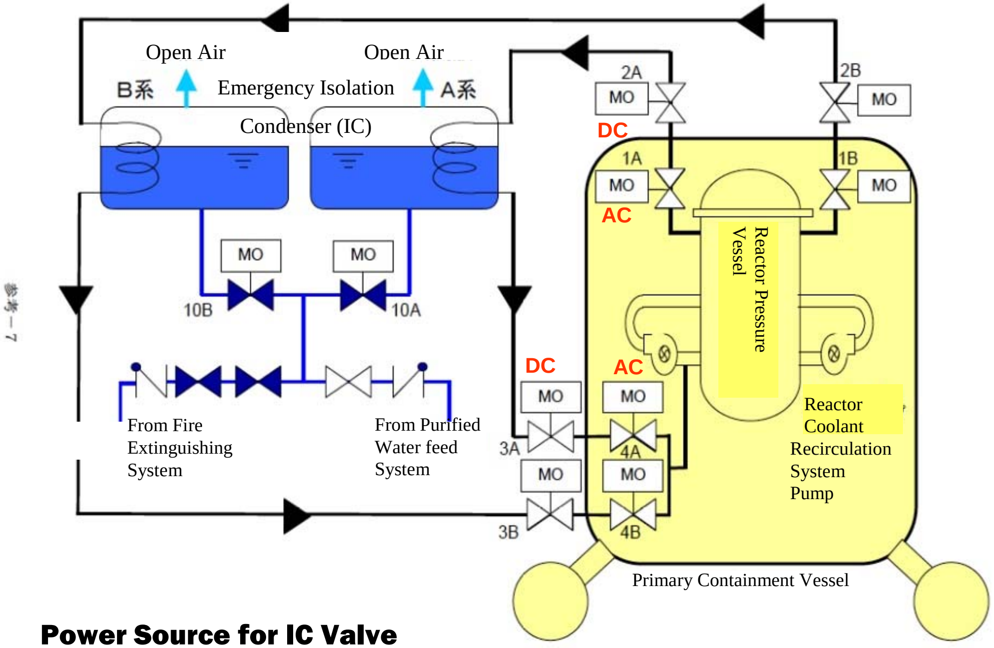
18:18 Activated (Valves-2A & 3A opened)
18:25 Deactivated (Valve-3A closed)
21:30 Activated (Valve-3A opened)
March 12, 1:48 Problems in fire pump system for cooling water supply were found.

Open/close status of IC valves (Investigated on April 1, 2011)

System-A
* Valve-1A: Opened partially
* Valve-2A: Closed ⇒ Opened (opened at 18:18)
* Valve-3A: Closed ⇔ Opened
(opened at 18:18 /closed at 18:25/opened at 21:30)
* Valve-4A: Opened partially

System-B
* 1B: Opened partially
* 2B: Closed
* 3B: Closed
* 4B: Opened partially

Issue 3: How had the tsunami and complete loss of AC/DC power affected IC functions? => As its internal valves (AC driven) were designed to close in case of power loss (= fail-close), these valves were closed and its cooling function was lost.



Power Source for IC Valve

- External Valves (Drive for 2A/B, 3A/B, Control Circuit)： DC
- Internal Valves (Drive for 1A/B, 4A/B, Control Circuit)： AC
- Logic Circuit：DC
  => Send signals to close valve in time of pipe rupture, power loss, etc.
- Make-up water line (Control, drive, logic circuit)： AC

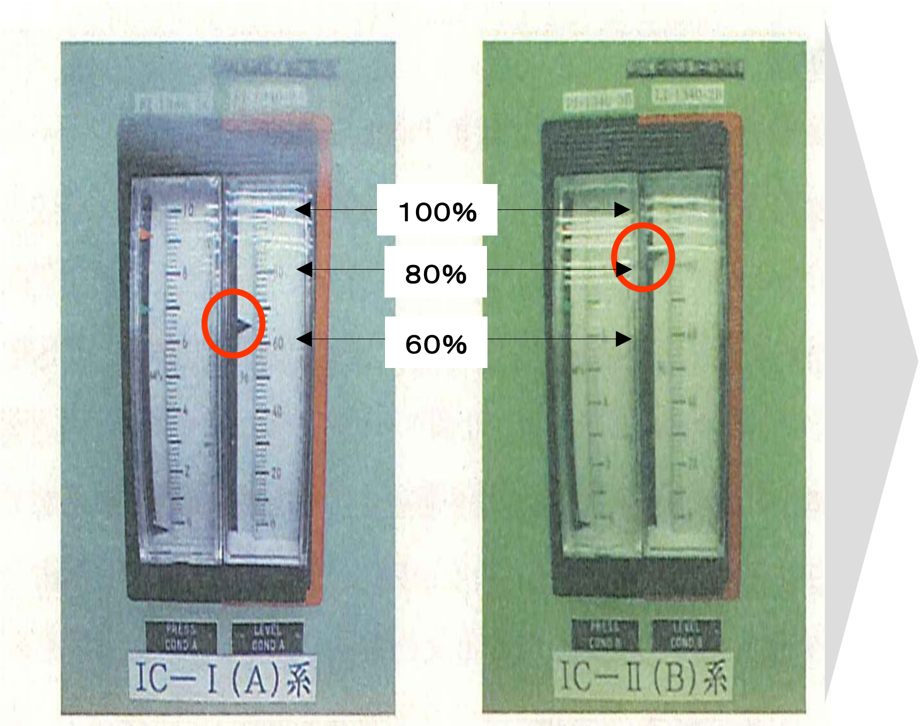
Sequence of IC Function after Tsunami (Presumption)

- DC power was lost due to ground fault after tsunami.
  => A signal to close all valves was sent due to power loss of logic circuit (driven by DC).
- DC driven valves (valves-2&3) were activated and closed before DC was lost. (Valve 3: kept closed. Valve 2: opened => closed)
- AC driven valves (valves-1&4) were also activated then closed before power loss.
- Then, the possibility of recovery from ground fault was recognized only for DC.
  - Valves-2A&3A were opened manually. Then, 3A was closed manually.
  - Again, valve-3A was opened around 21:30, and kept opened since then. Staff on site believed it functioning.
- According to later verification, the records indicated the internal valves (1,4) as <u>partially opened</u>. (In actuality, <u>mostly closed</u>.)
- The make-up water line also lost its functions due to all AC power loss.

This had accelerated the accident progression in reactor No.1 much faster than No. 2, 3, and 4.

Issue 3: How long was the assumed IC cooling time, according to the records? => Deduced from the reduction in water level, the IC had cooled for only about 45 minutes.

IC water level indicator shows 65% in system-A and 83% in system-B.



IC(A) Pressure/Water Level Measure

IC(B) Pressure/Water Level Measure

Based on these water reduction, it is assumed that the IC had functioned for only about 45 minutes after the scram.

- **IC is designed to cool for a total of 8 hours.**
  - — 4 hours for each system-A&B. (Total 8 hours)
- **On daily operation, they maintained the water level around 80%.**
  - — Thus, water level is 80% if nothing happens.
- **As shown on the left, about 15% of water has been reduced in system-A, and almost none reduced in system-B. This means that it had cooled about 45 minutes.**
  - — 4 Hours (240 minutes)×15%÷80% ＝ 45 minutes
- **Observing the water reduction and heat exchange, only system-A of IC had cooled for about 45 minutes after the earthquake, before tsunami, and thereafter.***
  - — System-B: Valve-3B was closed right after IC activation by the scram in accordance with operation manual. With valve-3B closed, Tsunami hit and valves-1B&4B were also closed due to AC loss. Therefore, IC system-B had hardly cooled.
  - — System-A: IC had functioned by open/close operation of valve-3A after earthquake before Tsunami. As AC power lost by tsunami, valves-1A&4A were mostly closed. After that, it had not functioned much at all.
  - — After Tsunami, system-A had activated for 7 minutes from 18:18. Valve-3A was indicated as <u>opened</u> from 21:30. However, it is assumed that valves 1A & 4A were mostly closed at that time.

* Actual timing of evaporation of cooling water depends upon the effectiveness of heat exchange (= boiling and evaporating) under different conditions. Further investigation is necessary.

Issue 4: What could have been done to reactor No.1 in order to avoid the hydrogen explosion and leakage of radioactive materials? – This issue was examined from the following perspective.

What had significantly accelerated the event progression in reactor No. 1?

- Loss of parameters in the central control room due to complete loss of all AC/DC power by the earthquake and tsunami.
- Loss of all the high pressure cooling functions (IC, HPCI). Disability to maintain the water level of the core under high pressure.
- If that function had been maintained, there was a possibility to bring in emergency power source and equipments to keep the core stable.
- Simultaneous accidents in reactors No. 1-4 made the accident management even harder and worsened the situation.

What would have been effective to avoid the event progression?

- Secure multiplicity and diversity of power sources and cooling systems under any severe circumstances.
- Practical trainings to ensure effective and prompt use of the above (e.g. set up alternative power within X hours).

What actions should have been taken to avoid the explosion and radioactive leakage?

- See the following pages for more specific details.

Issue 4: What had significantly accelerated the event progression in reactor No. 1 are the following.

Events

Emergency shutdown of the reactor

3/11 14:46

Earthquake occurred (level 6+)
(M9.0. 4th in recorded history)

- **14:46 Automatic shutdown of the reactor** => 14:52 IC activated automatically & opened/ closed manually.
- **Loss of all external power** => 14:47 Emergency DG activated.

Loss of all power & important functions

15:35

Tsunami hit
(Tsunami-M9.1. 4th in recorded history)
(Immersion height: 11.5~ 15.5m)

- Emergency DG & power panels flooded => **all AC power lost** => Unable to use electrical equipments.
- Battery room submerged => **DC power lost** => Electrical boards, measuring & control facilities lost => **Cooling function lost** (IC, HPCI), **Pressure control function lost** (open SRV remotely etc.)
- Seawater pump lost => **Function for cold-shutdown lost** (ultimate heat sink lost)

Right after tsunami: Isolation Condenser lost
=> Core water level started to drop.

Secure emergency power.

Prepare for coolant injection.

Prepare for ventilation

17:12 Plant manager ordered to consider water injection by fire pump system & fire truck

18:46 Core damage started (estimated)

21:19 Core water level became readable (TAF + 200mm*0)
23:00 Rise in radiation level in turbine bldg confirmed.
Around then, 1st power supply vehicle arrived.

3/12

00:06 Plant manager ordered to prepare vent.
(as Dry-well of PCV pressure possibly over 600k Pa)
01:30 Requested to execute vent & approved by the country.

02:30 Confirmed 'RPV pressure is low & PCV pressure is high'*1.
05:46 Started to inject fresh water by fire trucks.
07:20 RPV damaged. (simulation)

Tried water injection.

Tried ventilation.

Hydrogen built up.

09:04 Workers departed for site for ventilation.
10:17 Started PCV vent.
14:30 PCV vent succeeded (D/W pressure decreased)

14:53 Completed freshwater injection (80,000 l in total).
14:54 Plant manager ordered sea water injection.

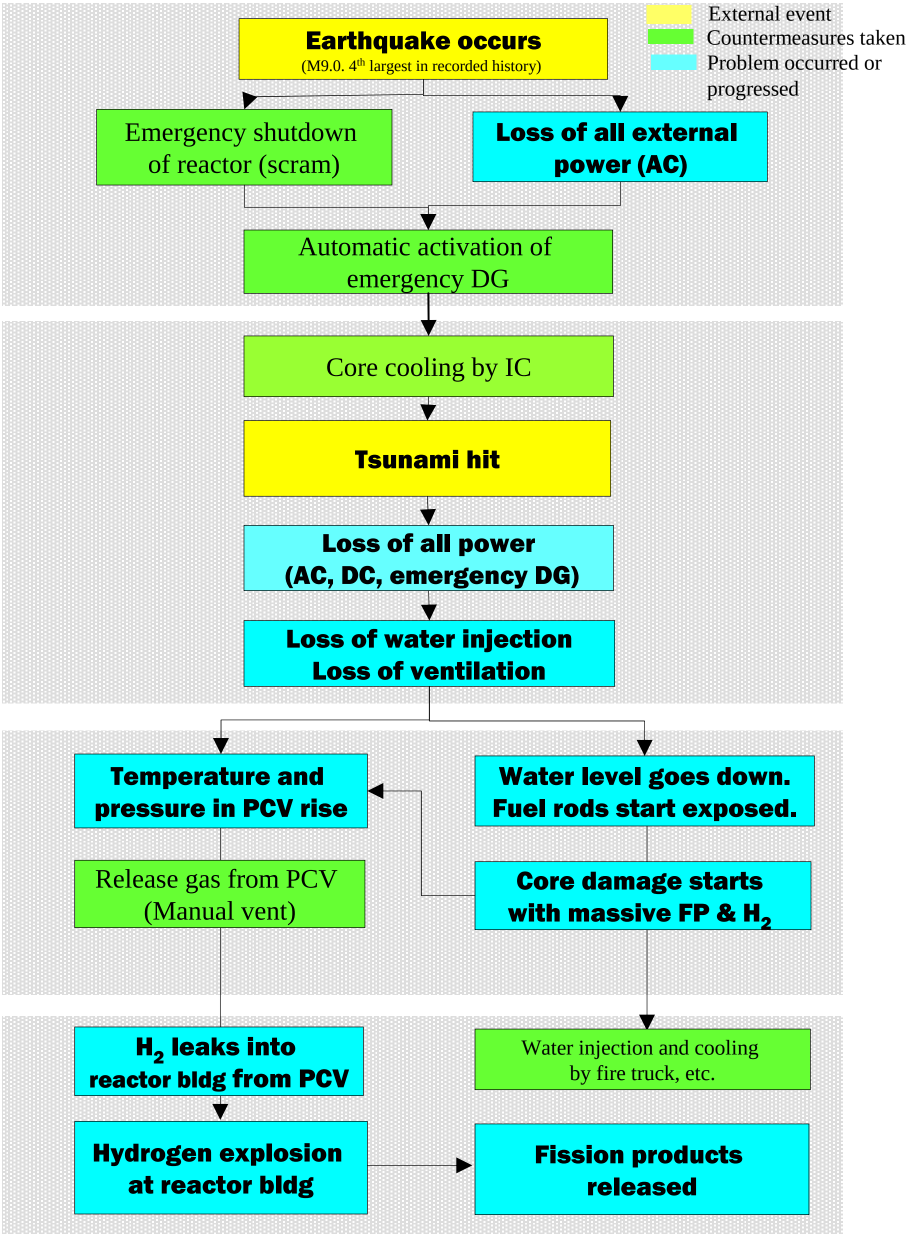
Hydrogen Explosion & radiation leak

15:36

Reactor building exploded (5th floor)

19:04 Started sea water injection.
20:45 Started sea water injection with boric acid.

Progression of accident (conceptual)



🟨 External event
🟩 Countermeasures taken
🟦 Problem occurred or progressed

Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by IC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection
Loss of ventilation

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core damage starts with massive FP & H_2

H_2 leaks into reactor bldg from PCV

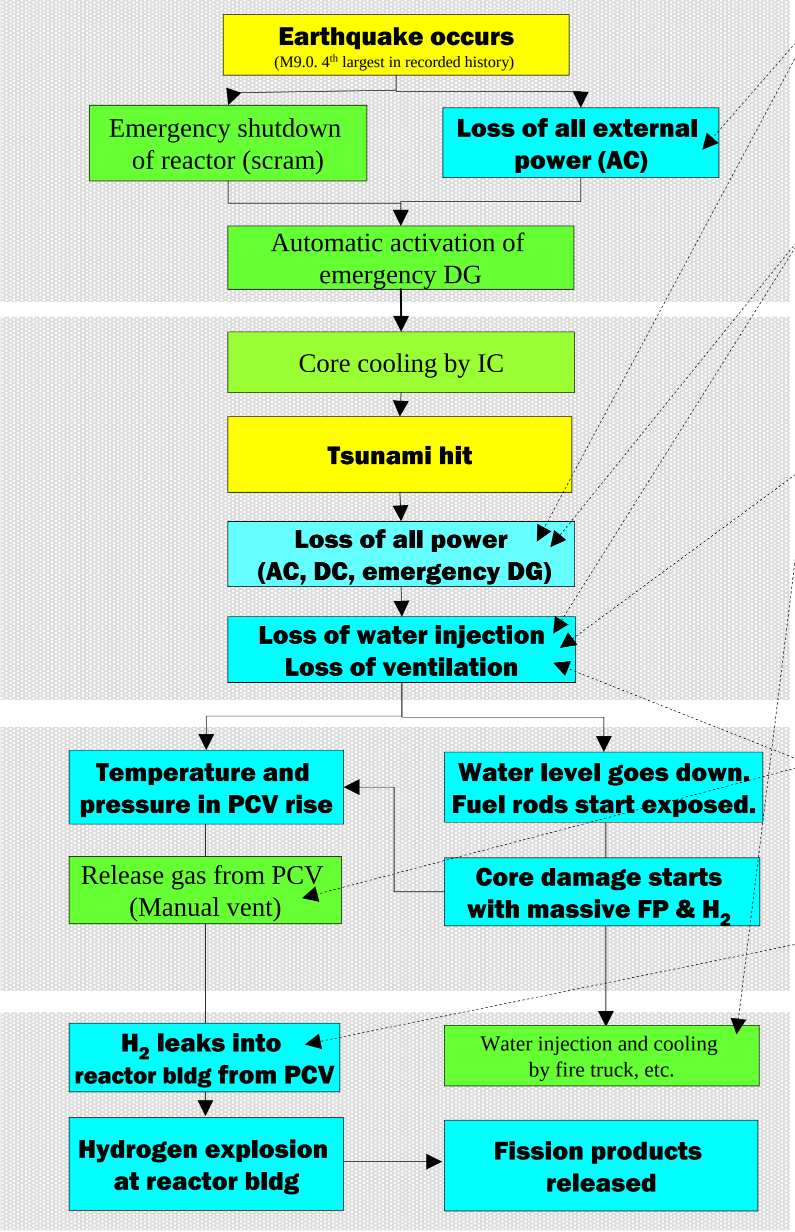
Water injection and cooling by fire truck, etc.

Hydrogen explosion at reactor bldg

Fission products released

Problems deduced from the events: Simultaneous loss of all power and cooling & vent functions had disabled the recovery operations, and taken the 'cool and shut-down the core' function away.

Progression of accident (conceptual)



Earthquake occurs
(M9.0. 4th largest in recorded history)

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Loss of all external power (AC)

Automatic activation of emergency DG

Core cooling by IC

Tsunami hit

Loss of all power (AC, DC, emergency DG)

Loss of water injection
Loss of ventilation

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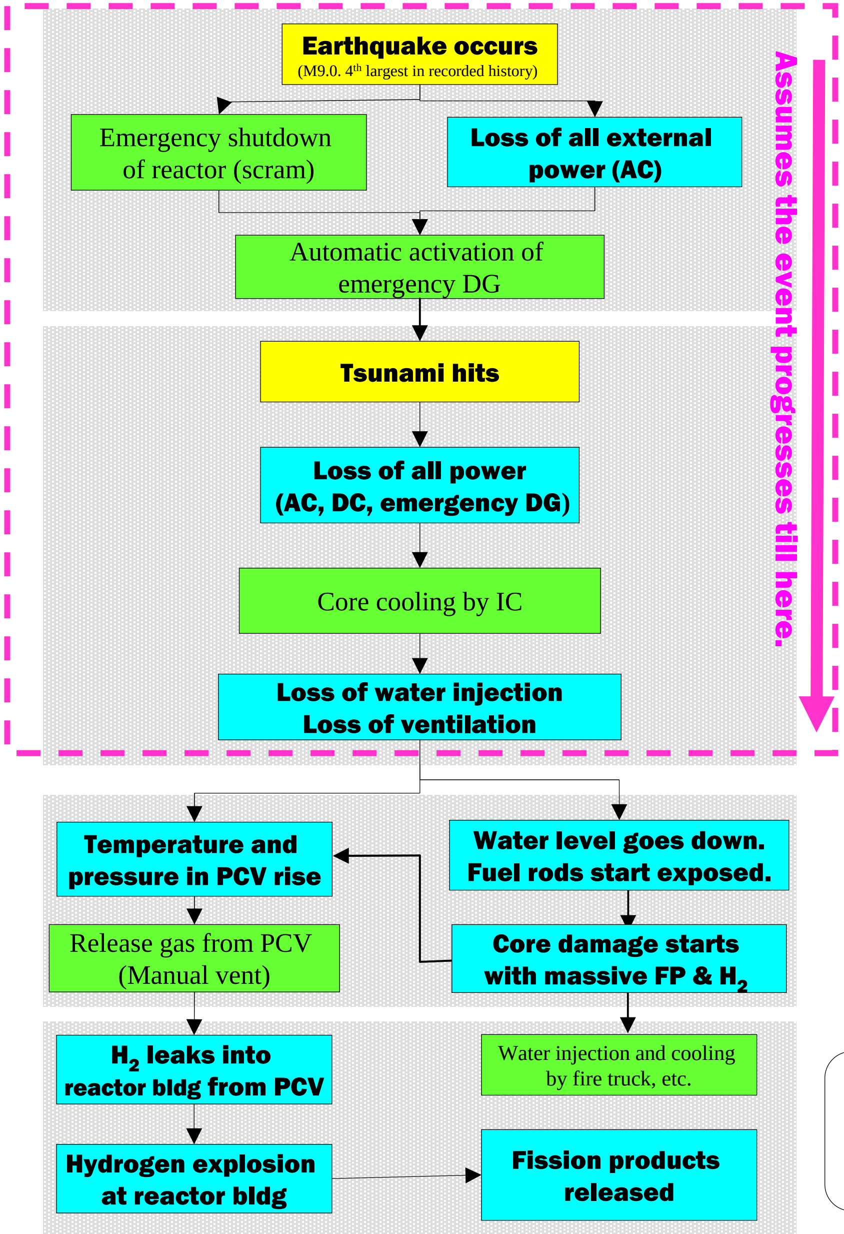
Hydrogen explosion at reactor bldg

Fission products released

Problems	Countermeasure
AC power was lost over the long-term due to earthquake and tsunami. ● As Unit 2 also lost power, the power could not be shared with Unit 1. ● Due to submergence, there was no electrical panel to be connected with the power supply vehicle. ● Due to extremely bad environment, even after the power supply vehicles arrived, reaching power connection port, and connection itself was difficult.	● **Secure power supply vehicle, power panel, parameter-monitoring**
AM hadn't assumed the simultaneous loss of all AC/DC power (=DC won't be lost for long-term). ● As IC is DC driven, along with DC loss, MSIV was closed (unable to access to internal valves for vent). ● Due to all power loss, they could not remotely open the valves for ventilation. ● There was no specific AM procedure defined for SBO with simultaneous loss of DC (procedure handbook for SBO only assumed that DC power was normal).	● **Secure back-up battery** ● **Diversify DC power source** ● **Improve operability of ventilation**
Securing alternative cooling water source was insufficient and delayed. ● Due to power loss, core depressurization was delayed (battery depletion, insufficient pressure of air compressor). ● Lack of easy depressurization method under DC loss. Not prepared for working under high radiation (alternative method other than SRV necessary?). ● There was a malfunction in diesel-driven fire extinguishing pump. ● Liquefaction & debris caused extreme difficulty in accessing & constructing external water injection line. ● Insufficient injection ability of external water pump. ● Securing and supplying alternative water source was prolonged.	● **Station fire truck, portable pump, heavy machinery** ● **Diversify & multiplex water source & route** ● **Enhance high pressure water injection**
PCV vent function was lost. Manual ventilation was delayed. ● Lack of easy depressurization method under DC loss. Not prepared for working under high radiation. ● Other than W/W vent, there was no operation procedure or device to prevent fission products from leaking outside, when conducting dry-well vent or other direct ventilation.	● **Review location & operability of vent valve** ● **Store cylinder for valve**
Lack of precaution, monitoring, and actions against building explosion (hydrogen explosion). ● No preparation for building ventilation in case of long-term AC power loss. ● No mechanism to detect hydrogen generation. ● No method to release accumulated hydrogen outside of the reactor building.	● **Ventilation for reactor building** ● **Hydrogen detector**
Emergency facilities at sea side were so vulnerable that they could not do almost anything after the loss of ultimate heat sink. ● Though overall AM procedure of 'high pressure cooling => core depressurization => water injection by low pressure cooling => PCV depressurization" was defined, specific AM/operational procedures in case of simultaneous loss of all power & vent functions were not clearly defined.	● **Practical training** ● **Review AM manual**

Issue 4: Couldn't the accident development in reactor No.1 have been prevented or mitigated if the following countermeasures were possible?

Assumed Event Progression



Earthquake occurs
(M9.0. 4th largest in recorded history)

Emergency shutdown of reactor (scram)

Loss of all external power (AC)

Automatic activation of emergency DG

Tsunami hits

Loss of all power (AC, DC, emergency DG)

Core cooling by IC

Loss of water injection
Loss of ventilation

Assumes the event progresses till here.

Temperature and pressure in PCV rise

Water level goes down. Fuel rods start exposed.

Release gas from PCV (Manual vent)

Core damage starts with massive FP & H_2

H_2 leaks into reactor bldg from PCV

Water injection and cooling by fire truck, etc.

Hydrogen explosion at reactor bldg

Fission products released

Example

AM actions (On-site)

Initial Action (W/in 2 hrs)

Secure power (for initial use), functions of control room & IC. Prepare for hydrogen explosion

- Switch to emergency batteries (small, portable, can bring in & connect w/in 2 hr).
- Secure parameter monitoring system in central control room (by battery).
- Establish system to overview the availability of all the power source.
- Open reactor-building vent (to prevent hydrogen explosion) before water level reaches at TAF.
- Redesign internal valves (AC driven) of IC to Fail-Open.
- Bring in equipments and devices to repair high pressure cooling systems.

Recover HPCI (W/in 8 hrs)

Recover & maintain high pressure cooling to buy more time. Secure more power source (for second use)

- Transport and connect batteries (Recovery of DC).
- Activate high pressure cooling systems (IC or HPCI).
- Prevent core damage by high pressure cooling till off-site support arrives.
- Transport & connect power supply vehicles (DC/AC) for more power supply.
- Secure additional water & fuel (at least for 24 hours).
- Continuously monitor hydrogen detector.

Keep high pressure cooling (Within 24 hours)

Transport equipments for low pressure cooling while maintaining high pressure cooling. Secure sufficient power supply. Clear access routes

- Maintain high pressure cooling (HPCI/RCIC) to buy more time.
- Clear & secure access routes for heavy machineries.
- Transport and secure sufficient power source & DG for 3-7 days.
- Maintain core pressure with SR valve & activate S/C cooling to buy more time.
- Bring in & prepare equipments for low pressure cooling system.

Prepare LPCI to cold shutdown (24 hrs – 1 wk)

Reduce core pressure & prepare for low pressure cooling system

- Set up lines & systems for low pressure cooling. Prepare for alternative water injection (alternative sea water pump, CS pump etc.)
- Prepare to de-pressurize the core with SR valve.

Reduce core pressure. Activate low pressure cooling systems for cold shutdown

- Reduce core pressure. Activate low pressure cooling systems.
- Achieve cold shutdown.

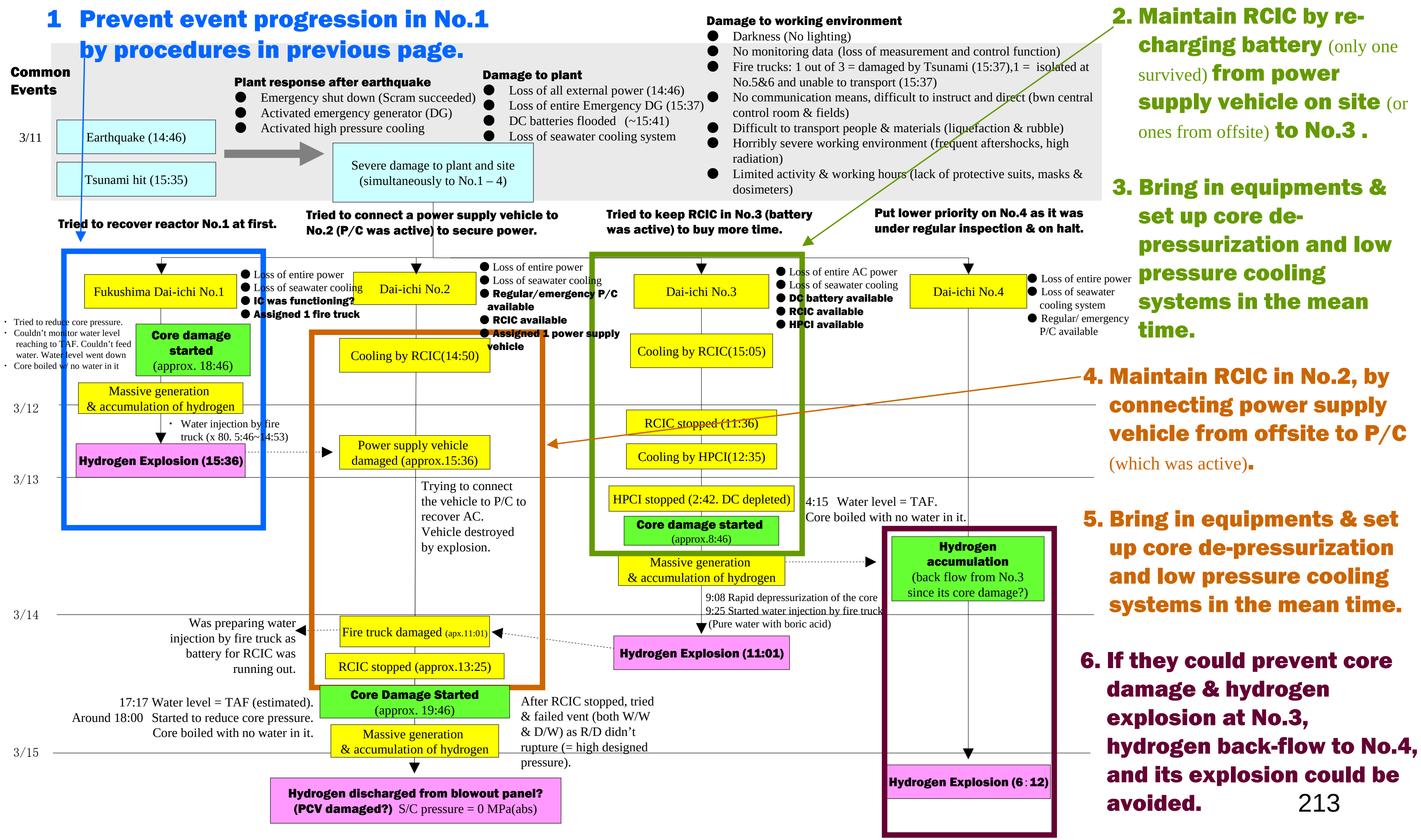
(Off-site)

- Transport back-up DG/batteries, power panels etc by air. (Have to be compact and highly portable, w/in 8 hrs by IC runs out.)
- Additional supplies and supports for heavy machineries etc. (Secure access).
- Transport extra power supply vehicles, power panels, pumps, fuel etc by air as needed (w/in 24 hrs).

Preparation

- Daily trainings. (Quantified efficiency test)
- Secure communication methods.
- Enhance seismic-durability, diversity, and flexibility of external power.
- Diversify emergency DG/DC (principle, location, height etc).
- Prepare protective clothing, masks, dosimeters etc.
- Diversify water source and path.
- Install hydrogen detector.
- Set storage for severe AM at onsite upland (power sources, power panels, pumps, fuel etc.)
- Enforce water protection (breakwater, water stops for building, watertight doors etc.)

Issue 4: In addition, couldn't the following accident management have been worth considering to reactors No. 2, 3, and 4?



1 Prevent event progression in No.1 by procedures in previous page.

Common Events

3/11

Earthquake (14:46)

Tsunami hit (15:35)

Plant response after earthquake
- Emergency shut down (Scram succeeded)
- Activated emergency generator (DG)
- Activated high pressure cooling

Severe damage to plant and site (simultaneously to No.1 – 4)

Damage to plant
- Loss of all external power (14:46)
- Loss of entire Emergency DG (15:37)
- DC batteries flooded (~15:41)
- Loss of seawater cooling system

Damage to working environment
- Darkness (No lighting)
- No monitoring data (loss of measurement and control function)
- Fire trucks: 1 out of 3 = damaged by Tsunami (15:37),1 = isolated at No.5&6 and unable to transport (15:37)
- No communication means, difficult to instruct and direct (bwn central control room & fields)
- Difficult to transport people & materials (liquefaction & rubble)
- Horribly severe working environment (frequent aftershocks, high radiation)
- Limited activity & working hours (lack of protective suits, masks & dosimeters)

Tried to recover reactor No.1 at first.

Tried to connect a power supply vehicle to No.2 (P/C was active) to secure power.

Tried to keep RCIC in No.3 (battery was active) to buy more time.

Put lower priority on No.4 as it was under regular inspection & on halt.

Fukushima Dai-ichi No.1
- Loss of entire power
- Loss of seawater cooling
- **IC was functioning?**
- **Assigned 1 fire truck**

- Tried to reduce core pressure.
- Couldn't monitor water level reaching to TAF. Couldn't feed water. Water level went down
- Core boiled w/ no water in it

Core damage started (approx. 18:46)

Massive generation & accumulation of hydrogen

3/12

- Water injection by fire truck (x 80. 5:46~14:53)

Hydrogen Explosion (15:36)

3/13

Dai-ichi No.2
- Loss of entire power
- Loss of seawater cooling
- **Regular/emergency P/C available**
- **RCIC available**
- **Assigned 1 power supply vehicle**

Cooling by RCIC(14:50)

Power supply vehicle damaged (approx.15:36)

Trying to connect the vehicle to P/C to recover AC. Vehicle destroyed by explosion.

3/14

Was preparing water injection by fire truck as battery for RCIC was running out.

Fire truck damaged (apx.11:01)

RCIC stopped (approx.13:25)

17:17 Water level = TAF (estimated).
Around 18:00 Started to reduce core pressure.
Core boiled with no water in it.

Core Damage Started (approx. 19:46)

After RCIC stopped, tried & failed vent (both W/W & D/W) as R/D didn't rupture (= high designed pressure).

Massive generation & accumulation of hydrogen

3/15

Hydrogen discharged from blowout panel? (PCV damaged?) S/C pressure = 0 MPa(abs)

Dai-ichi No.3
- Loss of entire AC power
- Loss of seawater cooling
- **DC battery available**
- **RCIC available**
- **HPCI available**

Cooling by RCIC(15:05)

RCIC stopped (11:36)

Cooling by HPCI(12:35)

HPCI stopped (2:42. DC depleted)

Core damage started (approx.8:46)

4:15 Water level = TAF.
Core boiled with no water in it.

Massive generation & accumulation of hydrogen

9:08 Rapid depressurization of the core
9:25 Started water injection by fire truck
(Pure water with boric acid)

Hydrogen Explosion (11:01)

Dai-ichi No.4
- Loss of entire power
- Loss of seawater cooling system
- Regular/ emergency P/C available

Hydrogen accumulation (back flow from No.3 since its core damage?)

Hydrogen Explosion (6：12)

2. Maintain RCIC by re-charging battery (only one survived) **from power supply vehicle on site** (or ones from offsite) **to No.3 .**

3. Bring in equipments & set up core de-pressurization and low pressure cooling systems in the mean time.

4. Maintain RCIC in No.2, by connecting power supply vehicle from offsite to P/C (which was active)**.**

5. Bring in equipments & set up core de-pressurization and low pressure cooling systems in the mean time.

6. If they could prevent core damage & hydrogen explosion at No.3, hydrogen back-flow to No.4, and its explosion could be avoided.

If a local earthquake occurs and the pipes between reactor building and turbine building are ruptured, what safety measures would be effective?

Presumed Accident Development

Large & local earthquake happens	
Reactor scram. Main steam piping ruptured.	・ Pipe between reactor building and turbine building is ruptured.
Rupture detected & main steam isolation valve closed	・ The main steam isolation valve will be closed due to increase of main steam flow volume, high radiation dosage, lowering pressure, etc. ・ Reactor water level will increase due to growth of void and steam will flow out in two layers until the isolation valve is closed.
Water level in reactor goes down. Signal sent for automatic shut down.	・ The reactor water level will not reach to TAF. ・ Core pressure will be maintained at high level. ・ As the main steam isolation valve is closed (more than 10%), a signal for automatic shut-down will be sent to the reactor.
PCIS activated (due to low water level).	・ Approximately 60 valves in PCIS (primary containment isolation system) will be closed.
Cooling by IC.	・ If IC is not automatically activated, it will be done manually.
Cooling by shut-down cooling mode.	・ Core pressure will be reduced, and low pressure cooling will be maintained.
Cold shut down	

- **What if it is impossible to close the main steam isolation** (MSI) **valve?**

⇒ Bring in the equipments (valve jig, power source, nitrogen cylinder, etc.) and close the MSI valves manually.

- **What if MSI valves malfunction and entire AC power is lost due to Tsunami or other accident?**

⇒ ・ Close external valves of MSI valve system to avoid leaking.
・ Secure power source and ultimate heat sink to avoid decrease in water level and core exposure.
・ Prepare gas-turbine generator, power supply vehicle, alternative cooling system, etc.
・ Maintain monitoring and water injection to the core.
・ Eliminate rubble by frontend loader, etc.

- **It is also important to enhance the major access roads to the site in terms of seismic strength.**

As for the accident like this, our proposal, multiplicity and diversity of power and ultimate heat sink, would be effective.

Other Questions

Q. 1: Why was the radiation level increased around March 20, 2011?
Is it because the ventilation was operated in Fukushima Dai-ichi reactor No.2?

Q. 2: Could seawater injection to Dai-ichi No.1 have been operated much earlier?
Was there any delay in decision making?

Q. 3: Was the hydrogen explosion in Dai-ichi No.4 caused by hydrogen back-flow from No.3?

Question – 1: Why was the radiation level increased around March 20, 2011? Is it because of the ventilation operated in reactor No.2? => No ventilation was operated in individual plants. It is estimated that radiation dosage was affected by direction and velocity of the wind.

- Radiation Dosage： On March 15 and 16, approximately 12000 μ Sv/hr were recorded temporarily in front of the main gate of Fukushima Dai-ichi. Other peaks were; approx. 5000 μ Sv/h on March 18, approx. 4000 μ Sv/h on March 19, and approx. 3400 μ Sv/h on March 20 (all in front of the main office building). Since then, the radiation dosage decreased.

- Wind Direction： Fission products could be floated towards Niigata area, by winds from: the northeast, east-northeast, east, east-southeast and southeast. Record histories of wind from northeast to southeast around March 20 around Fukushima Dai-ichi were as follows:

- March 18	12:20~16:40	(4 hours 20 mins)	Maximum radiation dosage level: approx.	4400 μ Sv/h, wind velocity:	2.0 m/s
- March 19	3:30~10:30	(7 hours)		700 μ Sv/h,	1.5 m/s
- March 20	5:40~14:30	(10 hours 10 mins)		3000 μ Sv/h,	1.9 m/s
- March 21	5:10~ 6:50	(1 hours 40 mins)		2300 μ Sv/h,	0.7 m/s
	11:40~18:30	(6 hours 40 mins)		2100 μ Sv/h,	1.5 m/s

- Not only a wind with a high radiation dosage had blown longest from the east on March 20, but also strong wind (maximum 6.8m/s) with a high dosage had blown from the east on March 21. The causes of high radiation dosage around March 20 and 21 could be the wind direction and velocity during these days.

  - According to the Asahi Shimbun on August 11, wind direction was toward the south on 3/20 A.M., southeast on 3/20 P.M., and northeast on 3/21~22.

- Isn't it because of the vent operation in Dai-ichi No.2?

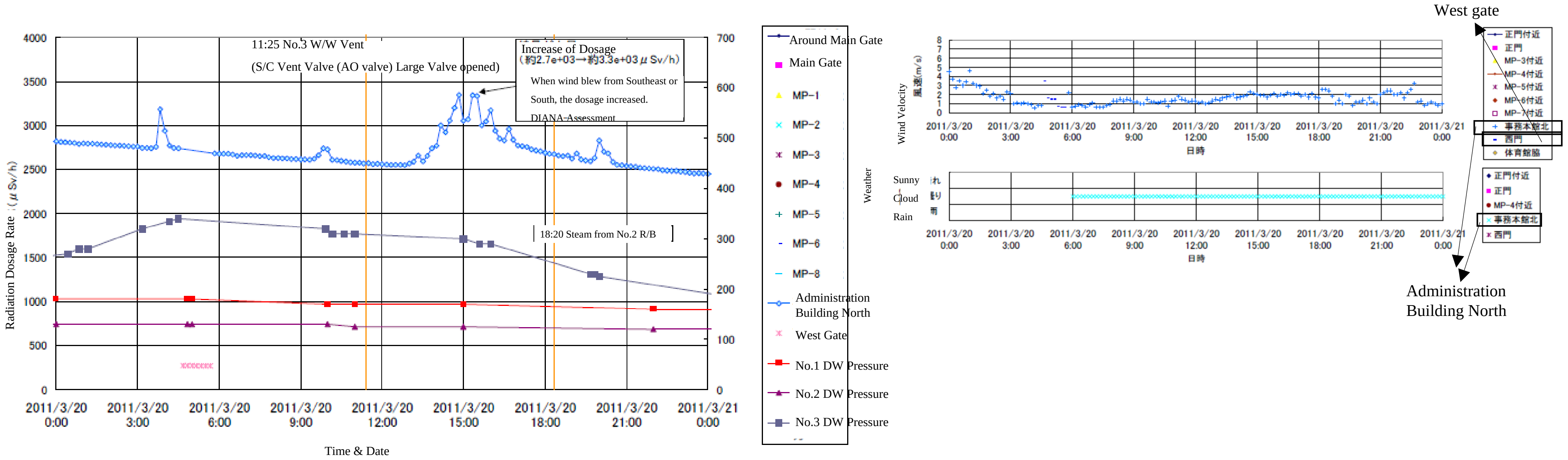
  - No vent operation had been conducted since March 15.

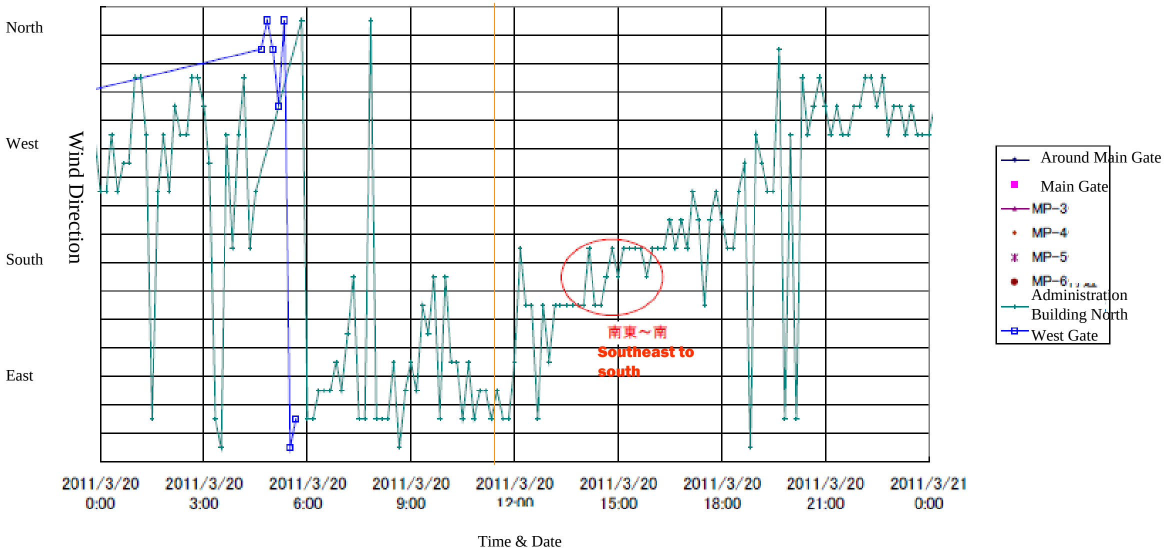
- Examination on the parameters in Dai-ichi No.2

  - Since 6:00 AM on 3/15, pressure in Suppression Chamber (S/C) were immeasurable and the dry-well pressure was lowered to atmospheric pressure. Based on this data, PCV could have been damaged. Then, it is most likely that the vent system would not function even if it had been performed.

(Cont.) No Ventilation for PCV was operated in Dai-ichi No.1, 2, and 3 on March 20, 2011.

Radiation dosage levels, and wind direction/velocity in Fukushima Dai-ichi (March 20, 2011)





- After 2:30pm on 3/20, radiation dosage in north of administration building had increased.
- It is assumed that this increase was due to winds blowing toward southeast to south. (from the hearing with TEPCO).
- In Dai-ichi No.1,2, and 3, no PCV ventilation was operated on March 20, 2011. (from the hearing with TEPCO).

Question - 2 : Could seawater injection to Dai-ichi No.1 have been operated much earlier? Was there any delay in decision making?

=> It could be done around the time of the explosion. However, the explosion retarded so much that it was delayed 4 hours after instruction.

March 12 5:46 **Plain water injection started with fire truck from Fire Protection system line.**

Two fire trucks arrived in the morning
(from Kashiwazaki Kariwa Nuclear Power Plants, Self-Defense Force)

March 12 around 12:00 **Started to prepare for sea water injection (permitted by CEO of TEPCO)**

March 12 14:53 **Plain water injection ended**

March 12 14:54 **Seawater injection was ordered.**

March 12 15:36 **Explosion of Reactor No.1**

Some injured. Operation suspended. Order of evacuation. Safety confirmation. Radiation dosage increase. Situation confirmation. Damage of hoses for injection line. Reconstruction of the line.

March 12 19:04 **Started seawater injection into core by fire trucks.**

March 12 20:05 **Seawater injection ordered by Article 64 in Regulations**

- Started preparation of seawater injection around 12:00
- By 15:30, the injection line was almost set up. They used reverse-valve pit of No. 3 as water source (seawater carried by Tsunami) and connected three fire trucks in order to secure lift height. The set up was almost finished.
- Due to the explosion in No.1 around 15:36, some staff were injured. Even though the plant manager ordered to confirm fire protection pump for water injection, staff were also busy confirming safety and radiation dosage within the plants. They started checking fire trucks and buildings around 17:20.
- Around 18:30, report on field situation began. With scattered rubble with high radiation dosage, and the damage of hoses for the injection lines, they found that they could not use them.
- The staff gathered hoses in hydrants around the area, connected them, and reconstructed the injection line. They started the seawater injection around 19:04.

Question – 3: Was the hydrogen explosion in Dai-ichi No.4 caused by hydrogen back-flow from No.3?

Consideration from Additional Research

Ventilation pipes of No. 3 had ruptured by the explosion, would hydrogen in No. 3 still flow back to No. 4?

- From photos of reactors No. 3 & 4, SGTS pipelines in both reactors had not ruptured. (See other sheet)

If we calculate the amount of hydrogen, which were generated and detonated in No.3, and shifted to No. 4, could the explosion in No. 4 explosion occur?

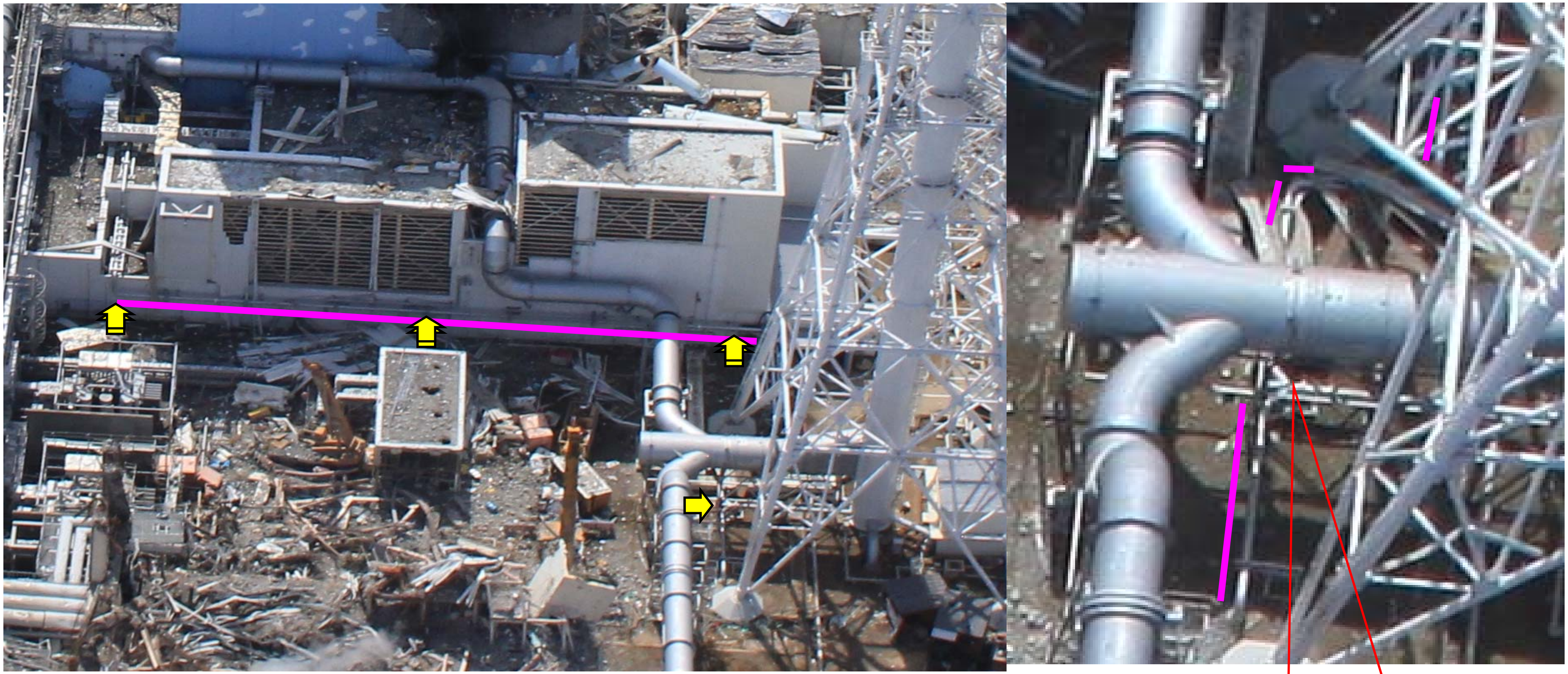
- TEPCO calculated that the amount of hydrogen generated in No. 3 from the time of meltdown to explosion was about 600-700 kg.
- This amount needs to be sufficient to destroy the floor 4 & 5 of No. 3, and floor 4 & 5 of No. 4. => 12% of hydrogen level destroys 400 mm concrete on 4th floor. 4% of hydrogen level destroys 250 mm concrete on 5th floor.
- Theoretically, 600-700 kg of hydrogen could accumulate in the level above (more than 12% on 4th Fl., and 4% on 5th Fl.). However, approximately more than 13% of hydrogen level is necessary for detonation. Further verification is necessary.

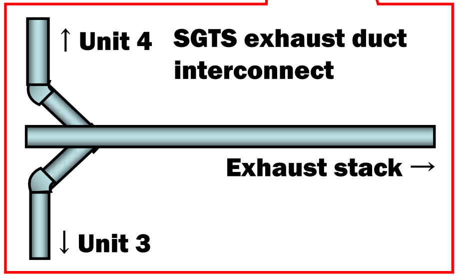
TEPCO Announcement

Supporting Data of Hydrogen in Reactor No.3 shifted to No.4

- Because the radiation dosage at the exit side of SGTS filter train in No. 4 is higher than at the entrance side, they assume that hydrogen had shifted from No. 3 to No. 4.
- According to the photographs of water level in the spent fuel pool in No. 4, and data on nuclear species identified in the pool, they assumed the very low possibility that a large volume of hydrogen were generated in the pool.

(Reference) Unit 3 & 4 SGTS exhaust duct





↑ Unit 4

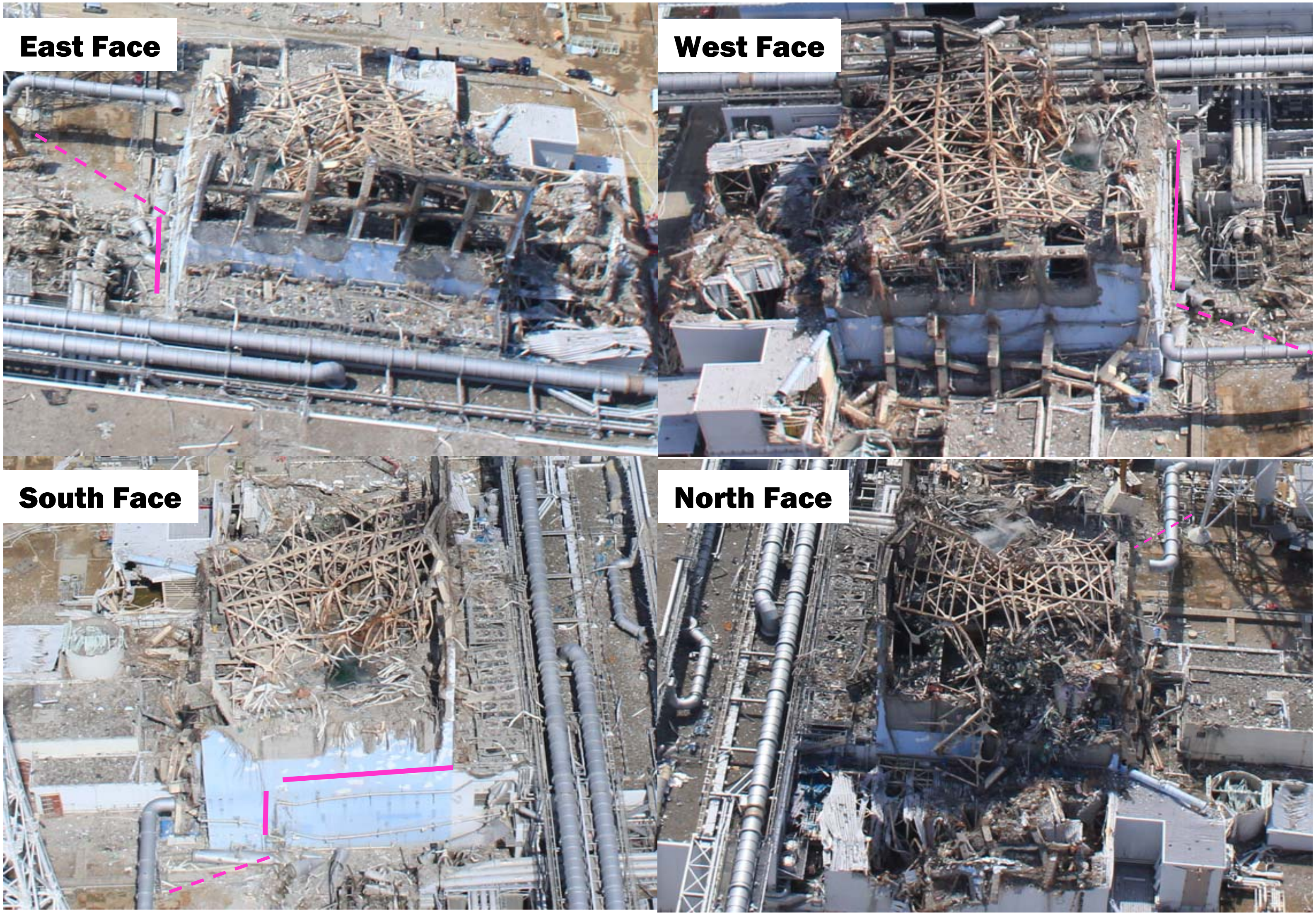
SGTS exhaust duct interconnect

Exhaust stack →

↓ Unit 3

(Reference) Unit 3 & 4 SGTS exhaust duct

Dai-ichi No.3: After Explosion



PWR

The project formation on the PWR are the following:

Kenichi Ohmae

Head Office

- Ohmae and Associates, Inc.
  Partner, Mr. Iwao Shibata
- Japan Nuclear Fuel Ltd.
  General Manager,
  Reprocessing Planning Dept.,
  Reprocessing Business Div.,
  Mr. Manabu Yusa

Those who cooperated with interviews, hearings and data-gathering:

Kansai Electric Power Company

- Kansai Electric Power Co., Inc. Manager, Nuclear Accident Management and Nuclear Power Div., Mr. Kensuke Yoshihara
- Kansai Electric Power Co., Inc. Project Manager, Plant & Maintenance Engineering Group, Nuclear Power Div.,
  Mr. Toshihiko Tanaka
- Kansai Electric Power Co., Inc. Tokyo Office
  Manager, Mr. Toshikazu Sendo
  Assistant Manger, Mr. Takahiro Ohgami

Mitsubishi Heavy Industries

- Mitsubishi Heavy Industries, Ltd. Acting Manager, Advanced Plant Safety Dept., Nuclear Energy Systems Div.,
  Mr. Daisaku Okuno

Purposes of this Research on PWR (Pressurized Water Reactor)

- **To show General Features and Differences** between Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR)
- Whether lessons-learned from **Analyses on Fukushima Dai-ichi and Dai-ni Nuclear Accidents are applicable to PWR or not**
- **Specific Considerations Necessary only for PWR** in order to prevent reoccurrence of accidents
- **To show if Diversity and Multiplicity** of safety measures instructed currently by the Nuclear and Industrial Safety Agency (NISA) in the Ministry of Economy, Trade, and Industry are sufficient.

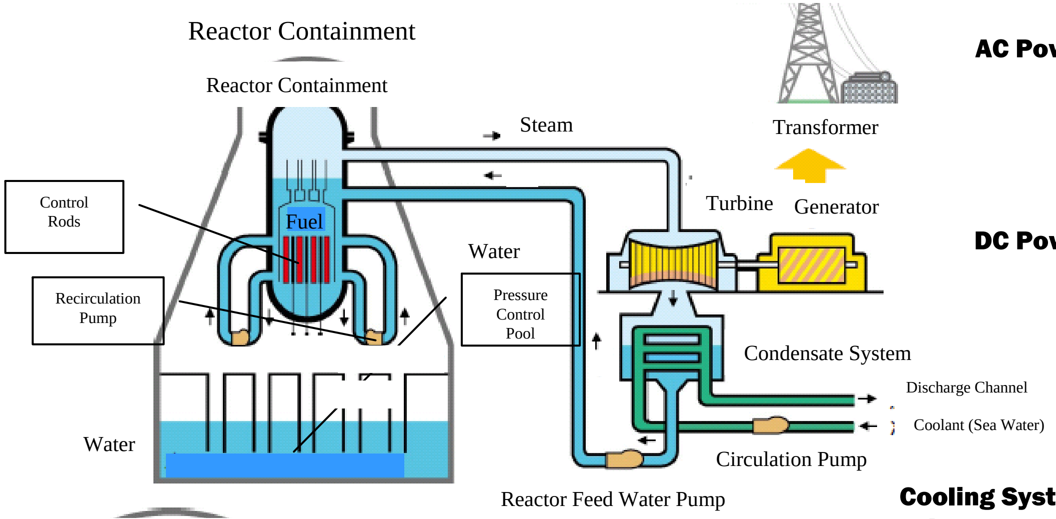
The following pages discuss the above points.

Features of BWR and PWR:

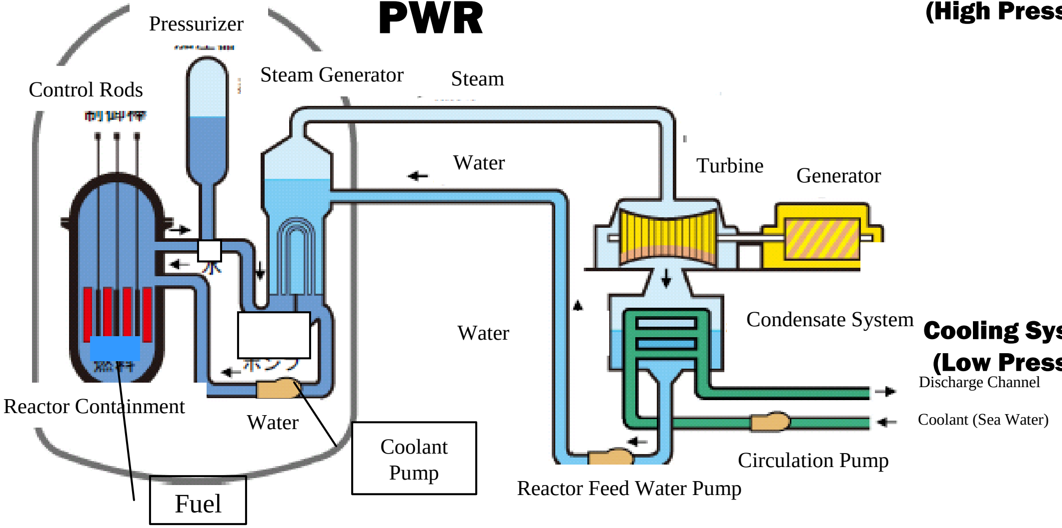
Are Lessons-Learned from BWR applicable to PWR?

Differences Between BWR and PWR: Despite several functional differences, they must control water and pressure level after the scram to use high-pressure cooling, reduce core pressure, and use low-pressure cooling for cold shutdown.

BWR



PWR



External Power

- Both BWR and PWR have the same power receiving system via the switching station, in which there are **no differences**.

AC Power

- **No differences** in the systems for the Diesel Generators (DG) for Emergencies, and the AC Power Source.
- **Location** of emergency DGs and AC Power Panels are different in each plant. Usually, **power sources for BWR are installed below ground level, and those for PWR are at ground level**.

DC Power

- In both BWR and PWR, the setup of DC Power, **converting from and charged by AC power source, is same**.
- In case of Extreme Emergency, **BWR** is designed to maintain **approximately eight hours** of power source for the High Pressure Coolant Injection System, Control System, and Supervisory Devices.
- **PWR** is designed to maintain **approximately five hours** of power source for plant and Supervisory Devices.

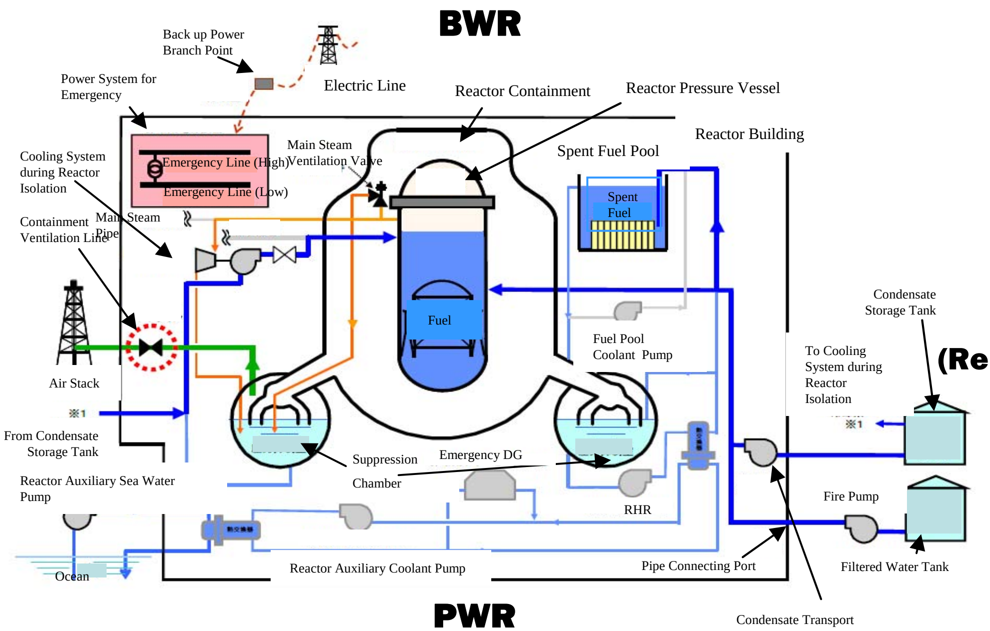
Cooling System (High Pressure)

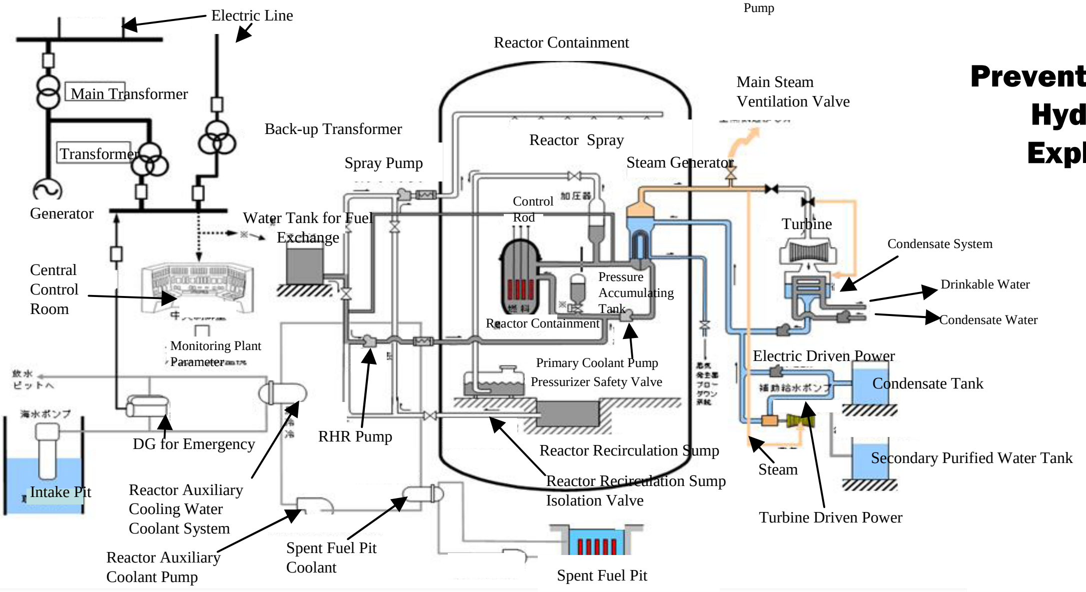
- With high pressure in the reactor pressure vessel, **BWR maintains its normal water level via IC, RCIC, HPCI, HPCS and so on while the SR Valve controls the pressure in the core**.
- In PWR, **the water level of the Steam Generator (SG) is maintained by electrical/turbine-driven auxiliary feed-water pump, and the plant cools down and lowers pressure by emitting radioactivity-free steam through the Main Steam Relief Valve.**
- One difference from BWR, PWR can release steam to the air, and the Turbine-Driven Auxiliary Feed-Water Pump can maintain its functions even after DC batteries are drained.

Cooling System (Low Pressure)

- Water pump in ECCS (RHR, etc.) operates for coolant injection.
- **In BWR, after pressure in the vessel is released by the SR valve, water is injected to the reactor** for cooling and shutting down.
- **In PWR, after injection of highly concentrated boric acid, either water supply and drainage, or residual heat removal pump will be operated for cooling and shutting down**.

(Cont.) In PWR, radioactive coolant circulates only within containment vessel, therefore only uncontaminated coolant water (and steam) is released to the outside ocean and air.





Pressure Reduction

- BWR **reduces pressure in the core by transferring steam in the pressure vessel to the suppression chamber (S/C, S/P)** in the containment vessel.
- PWR reduces pressure by **releasing steam (without radioactive materials) which has exchanged heat in the Steam Generator (SG) through the Main Steam Relief Valve** to the open air.
- Main Steam Relief Valve in PWR is located outside of the containment vessel and can be opened both mechanically and by hand.

Ultimate Heat Sink (Release valve)

- **For both BWR and PWR, the ocean is the ultimate heat sink so the pumps are located at ocean-side**.
- Further, **PWR** can **release heat to the open air** as another ultimate heat sink.

Ventilation Function

- BWR contains vent lines from **S/C and D/W as vent for containment vessel**. Rupture disks are set in these lines so as to open when the pressure reaches its set level.
- **The volume of the containment vessel in PWR is roughly five times (*) greater than the BWR, and vent lines are not installed** for decreasing pressure. (*: Compared with a BWR with the same output)

Prevention of Hydrogen Explosion

- BWR **prevents hydrogen detonation by encapsulating nitrogen into the containment vessel**.
- In the Fukushima Dai-ichi, it is presumed that hydrogen explosion occurred due to hydrogen leaks from containment vessel through various penetrations and pipelines into the reactor building. This leakage was not assumed.
- PWR **prevents hydrogen detonation by having a larger containment vessel**. For plants with smaller vessel, the hydrogen igniters are set in order to lower hydrogen level.
- Though PWR does not assume hydrogen leakage to the containment annulus, it has the annulus filter units if leakage occurs.
- There is a research which reports the amount of zirconium, the generation source of hydrogen, in PWR is less than half that utilized in BWR.

One study in U.S. reported that the amount of zirconium in the PWR is less than half of that in the BWR, since PWR does not have a channel box for the fuel rods like BWR does.

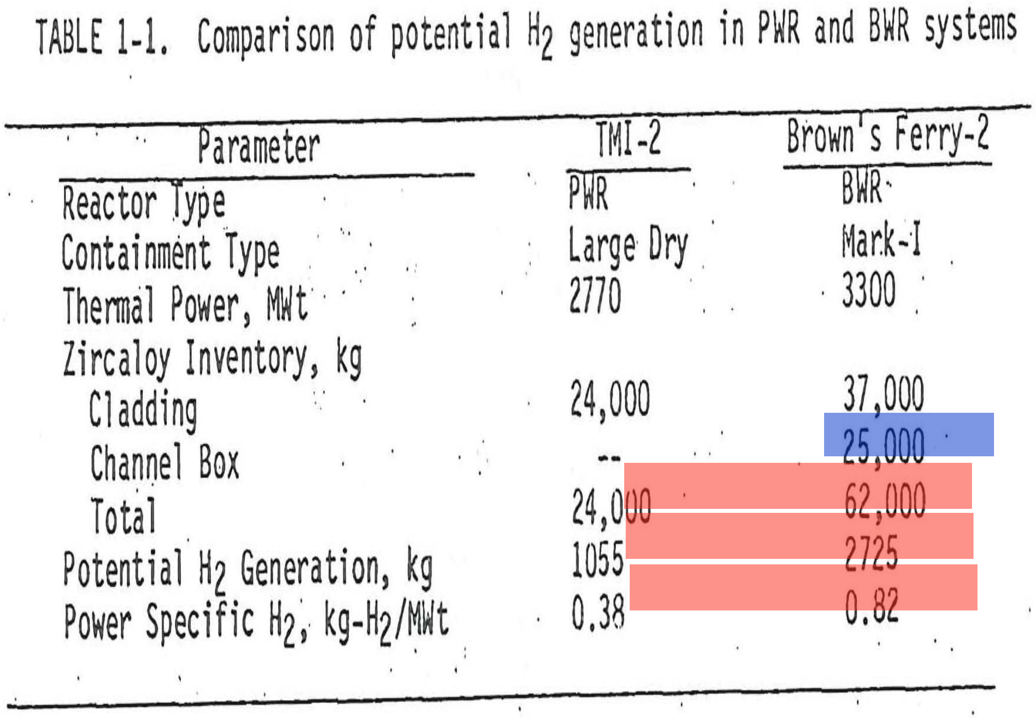


TABLE 1-1. Comparison of potential H_2 generation in PWR and BWR systems

Parameter	TMI-2	Brown's Ferry-2
Reactor Type	PWR	BWR
Containment Type	Large Dry	Mark-I
Thermal Power, MWt	2770	3300
Zircaloy Inventory, kg		
Cladding	24,000	37,000
Channel Box	--	25,000
Total	24,000	62,000
Potential H_2 Generation, kg	1055	2725
Power Specific H_2, kg-H_2/MWt	0.38	0.82

Reference: In-Vessel Zircaloy Oxidation/Hydrogen Generation Behavior During Severe Accidents
Prepared by A.W. Cronenberg September 1990. NUREG/CR-5597

The report indicates that the hydrogen level in PWR is much less than that for BWR, because the absolute quantity of hydrogen in PWR would be much less, and the containment vessel in PWR is five times larger than BWR.

Are Lessons-Learned from the analyses of BWR in Fukushima applicable to PWR? => Yes, it is applicable and the importance of "Supplying enough power and cooling function under any severe circumstances" is the same for PWR.

Summary of Lessons-Learned from the Research on BWR, and its Applicability to PWR*

Category	Lessons-Learned (Approx.)	Applicable to PWR?	Comments
Earthquake and Tsunami	20	O	- All Applicable
Loss of Power Source	31	O	- All Applicable
Loss of Sea Water Cooling System	6	O	- All Applicable
Comparison with other plants	7	O	- All Applicable
High Pressure Cooling System	22	O	- All Applicable - PWR does not require external power for the cooling system using a turbine-driven auxiliary feed-water pump.
Ventilation	29	O	- All Applicable for Main Steam Relief Valve. - Not Applicable in regards to the rupture disk and ventilation of PCV since PWR doesn't have equivalent devices.
Low Pressure Cooling System	10	O	- All Applicable
Overall	25	O	- Not Applicable for ventilation since PWR doesn't have an equivalent rupture disk or ventilation of containment vessel. - Except for the above, most categories are Applicable.

* See appendices for more details.

Specific considerations necessary for PWR

Is there any specific point to be considered for PWR, in order to prevent the accidents like the one in Fukushima Dai-ichi?

- During the history of large earthquakes in Japan including the Tohoku - Pacific Ocean Earthquake on March 11, all BWRs in Japan have succeeded in performing scram of the nuclear reactor following the earthquakes. **Can PWR scram react in the same way during earthquakes of the same level?** (Refer to the following pages.)

- In the event of loss of all AC power, is it possible for the primary reactor coolant to leak from the pump seals, **which may cause the major loss of coolant, and lead to the nonfunctioning of the high pressure cooling system in the core?** (Refer to the following pages.)

- PWR is designed to prevent the rise of pressure in containment vessel and hydrogen detonation by using a larger containment vessel, and by releasing most of the heat in the core through the main steam relief valve to the open air. The containment vessel of PWR is five times larger than that of BWR with the same output. Therefore, **PWR do not have ventilation systems to lower the pressure in the vessel. Also, they do not require pressure reduction of the core during the operation for cold-shutdown.**

- In PWR, spent fuel pits are placed outside of the containment vessel and at the ground level. **Compared to that in BWR, it is more accessible from outside of the building**. (For both access and level.)

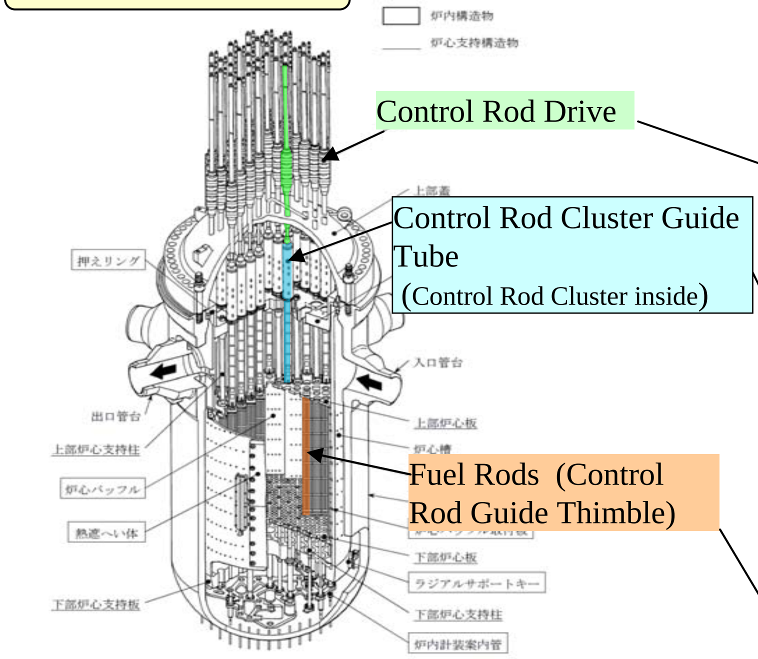
- There are **two ultimate heat sinks** in PWR, the ocean and open air.

Insertion of Control Rods – The top 20 cm of the control rods are inserted into the fuel rods at all times. These rods will react with earthquake motion of 160 gal (1/5 of the designed value) and will drop into the fuel rods within 2 seconds by gravity.

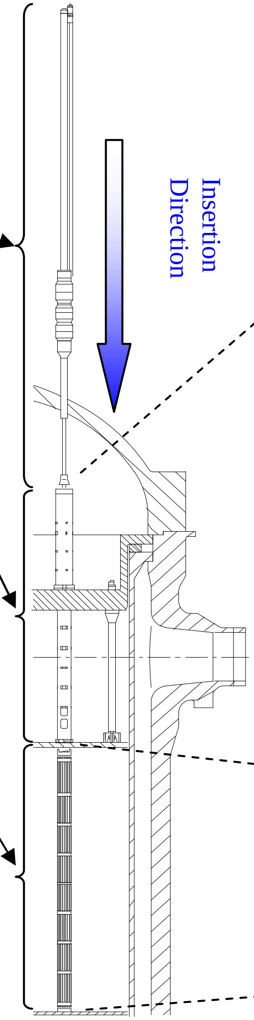
- ● **The securement of pathway is important for control rod insertion.**

=> **The pathway is secured as the chart below, and has been verified in tests.**

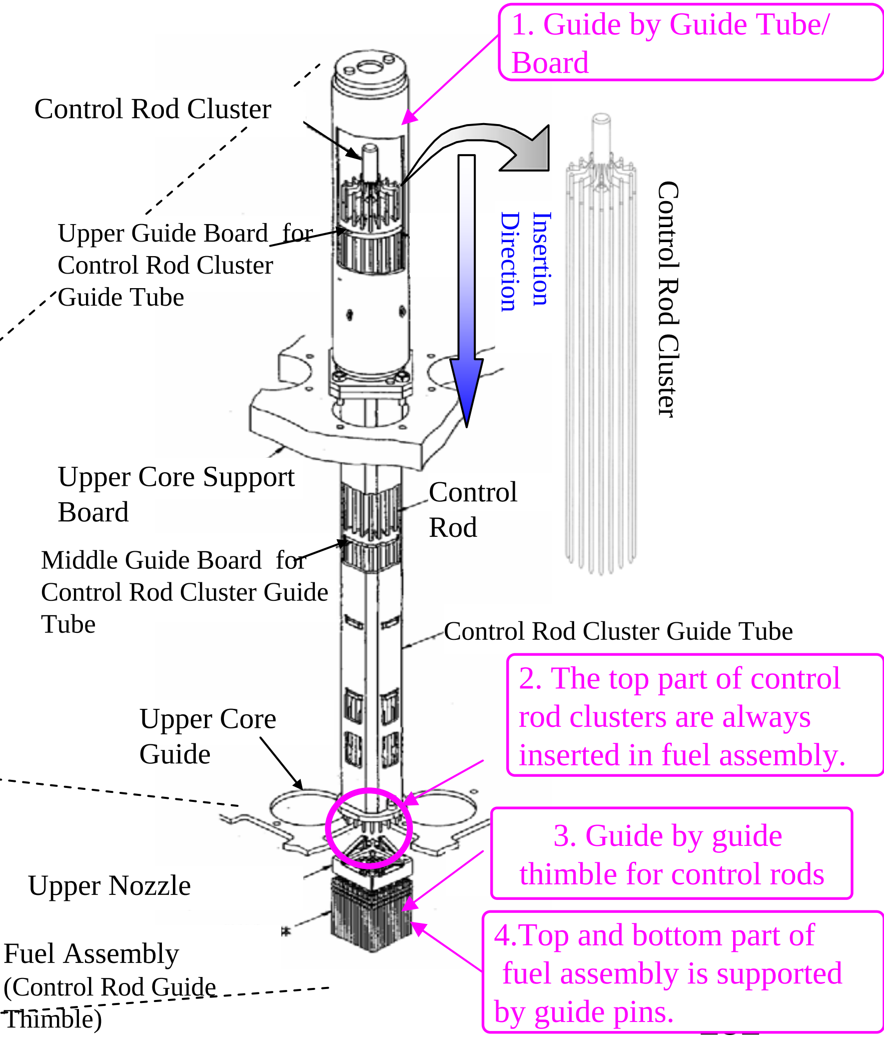
Insertion Pathway



(a) Reactor Core



(b) Insertion Pathway of Control Rod Cluster



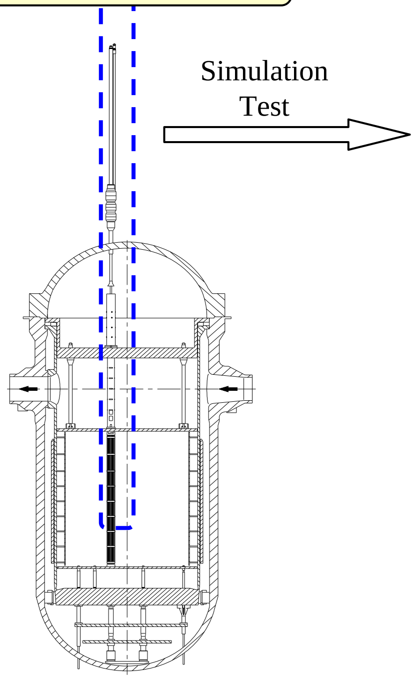
(c) Insertion Guide

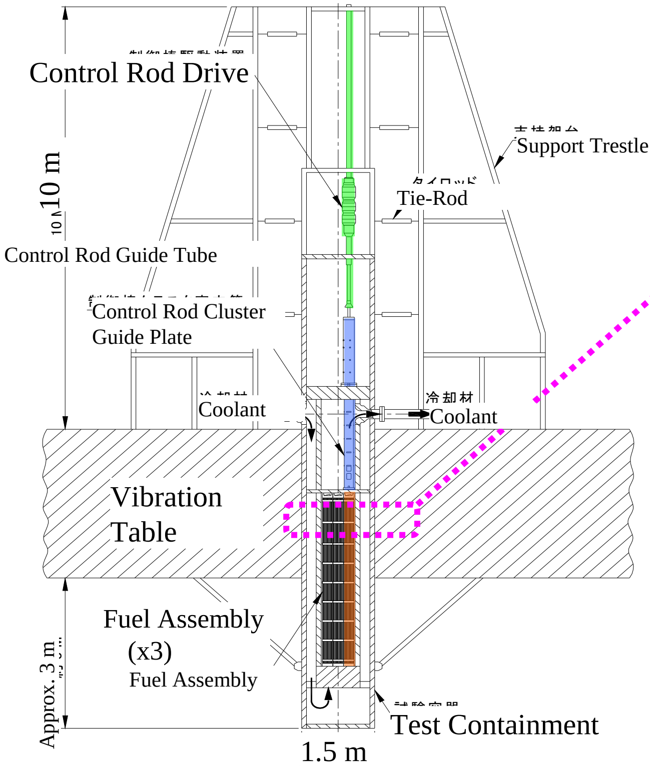
- **Insertion pathway is supported by various guide boards and tubes.**
- **Fuel assembly is supported by upper and lower core boards to avoid sideslip or uplift. (BWR has no support for vertical movement.)**
- **During the reactor trip*, the control rod cluster will drop by gravity. (In BWR rods will be inserted from the bottom.)**

*: An example of the designed value of the core trip in earthquake = 160Gal (The settings differ from plant to plant.)

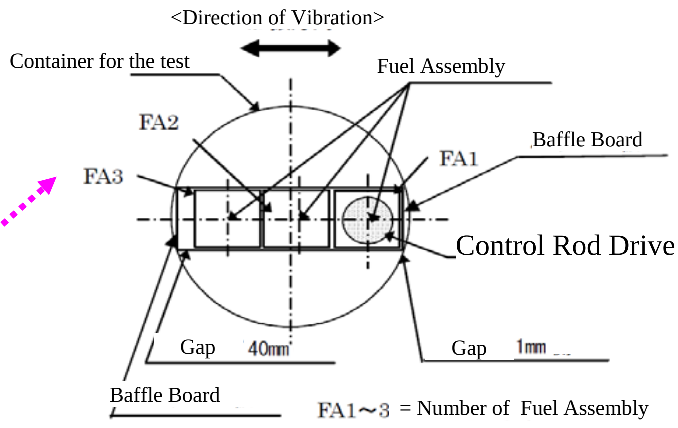
(Cont.) On the insertion during earthquake, the vibration test with real size* verified that control rods are inserted even with simulated seismic wave 3.3 times of the designed value. (It will be activated at 1/5 of the designed value.)

Overview of the Test



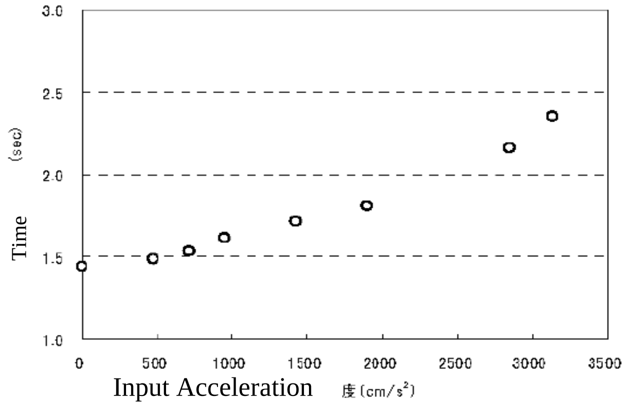


(a) Overview of Vibration Test



(b) Arrangement of Fuel Assembly

＜Result＞



(c) Correlation between insertion time of control rods and input acceleration

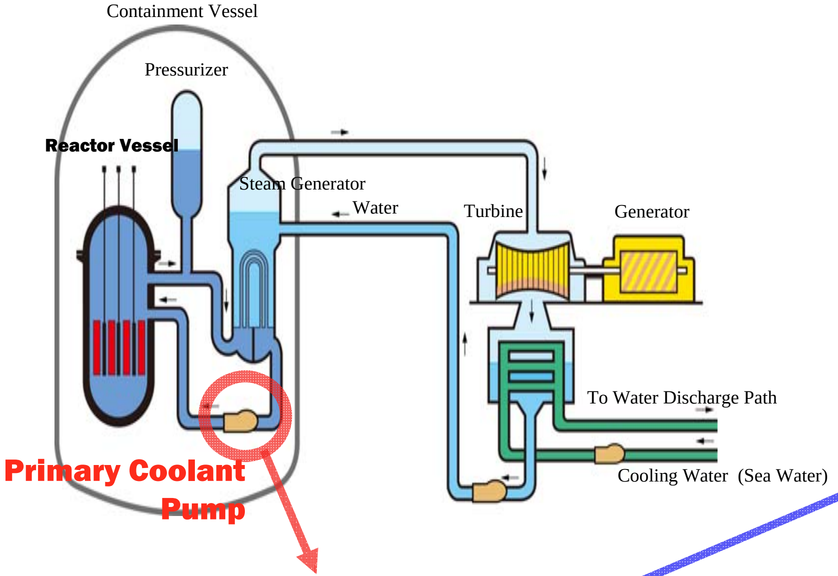
<Condition of Vibration>

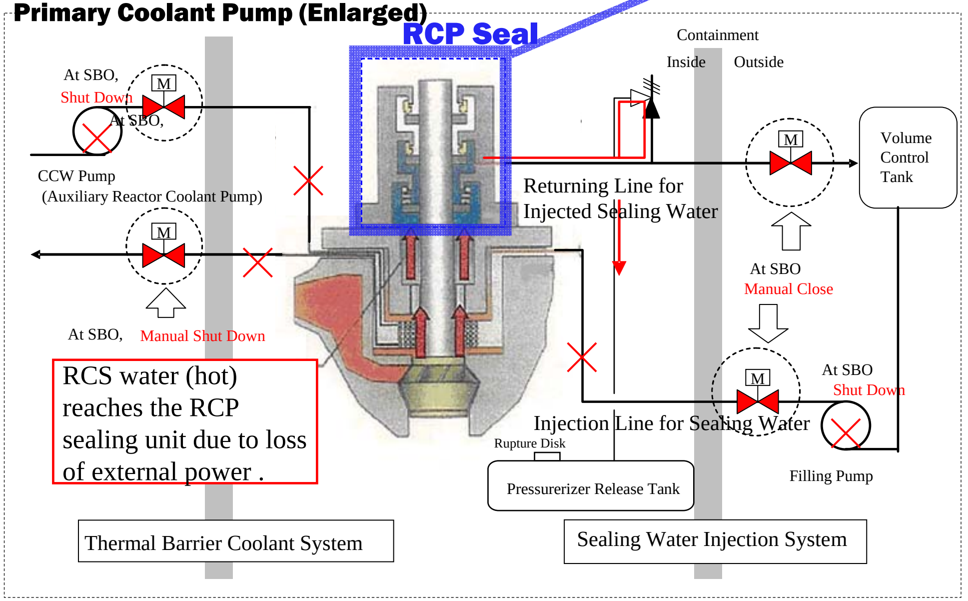
- Simulation of the seismic wave: The test was designed so that the vibration at fuel assembly and control rods becomes the severest by modeling real plant. (S2 Envelope Wave)
- Maximum acceleration of simulated seismic wave is 950 Gal.
- The test verified whether the control rods are inserted with the simulated seismic wave up to 3.3 times of the designed value.

Control rod cluster is inserted along with guide tube during the simulated seismic wave (3.3 times as large as S2) without any damage.

(*2005 JNES Report「Equipment Endurance 2 “PWR Simulation Test of Control Rod Insertability”)

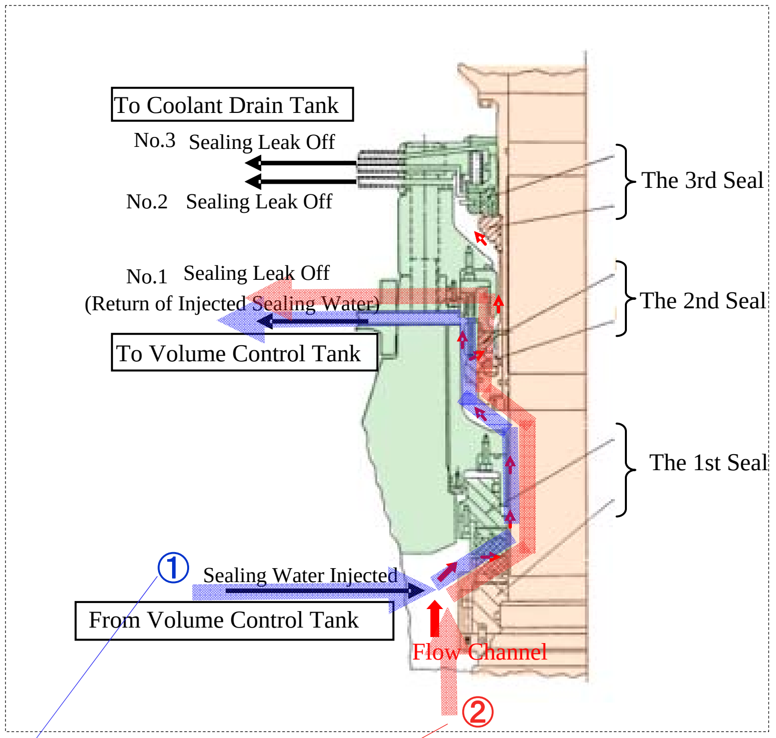
Reduction of Primary Coolant: There is a possibility that if SBO happens the core cooling does not properly function because water injection to the primary coolant pump does not work and the coolant starts leaking through the sealing of the pump.





RCS water (hot) reaches the RCP sealing unit due to loss of external power .

RCP Seal Unit (Enlarged)



① Normally: **High-pressured sealing water is injected** from the volume control tank **and circulates along the blue path. This prevents primary coolant from leaking** from the core.

② At Loss of All AC Power: **Because the circulation of sealing water in the blue path stops, the primary coolant in the core could possibly leak through the red path.**

(Cont.) If the core is cooled down to the hot-stable state*2 by TDAFWP*1 , and even if the primary coolant leaks from RCP seal, almost same amount of water will be injected from the accumulator tank. The core will remain stable.

(*1 Turbine-Driven Auxiliary Feedwater Pump. *2 approx. 170℃、0.7MPa)

Assumptions For Analysis

Item	Condition
Target Plant	• 4 Loop Plant
Primary Condition	• Output of power generation, core-pressure, average temperature of the primary coolant are the most probable value.
Disturbance	• External power loss at 0 seconds, turbine trip, loss of primary water injection, and coast-down of RCP. • The reactor is tripped by the signal of low RCP revolutions.
Back-up Water Injection	• Back-up water injection starts after one minute (To 4SG) • The volume of back-up water injection is adjusted so as to maintain the water level in SG.
Operation by operator	• Starts compulsory cool down by opening all the MSR valves after 30 minutes.
Accumulator Tank	• Injects boric acid solution to RCS as the pressure in the core drops. • Close the exit valve of accumulator tank when RCS pressure drops to 1.7MPa [gage].
Decay Heat	• FP: Recommended value from the Atomic Energy Society of Japan • Actinide: ORIGEN2
Leak Volume	• Leaks from RCP

Assumptions of Event Progress

T	Event Progress and Operation	Time	Comments
—	･SBO occurs ･Start leaking from RCP	0 sec	Initial leak rate from RCP is 21gpm/RCP
1	Reactor Trip	1.5 sec	—
2	Activate turbine-driven auxiliary feed water pump	1min	—
3	Start opening MSR valve	30 min	Cool down RCS aiming at 208℃
4	Activate accumulator tank	approx. 1 hr	RCS pressure: 4.2MPa[gauge]
5	Manually close the exit valve of accumulator tank	approx. 12 hrs	RCS pressure: 1.7MPa[gauge]
6	Manually open/close MSR valve	approx. 12 hrs	Cool down RCS aiming at 170℃
7	Stop leakage from RCP	approx. 14 hrs	RCS pressure 0.83MPa[gauge]
8	Achieve stable-cooling status	approx. 19 hrs	RCS pressure 0.7MPa[gauge] (RCS = 170℃)

Chart A： Volume of Primary Coolant Leakage from RCP Seal

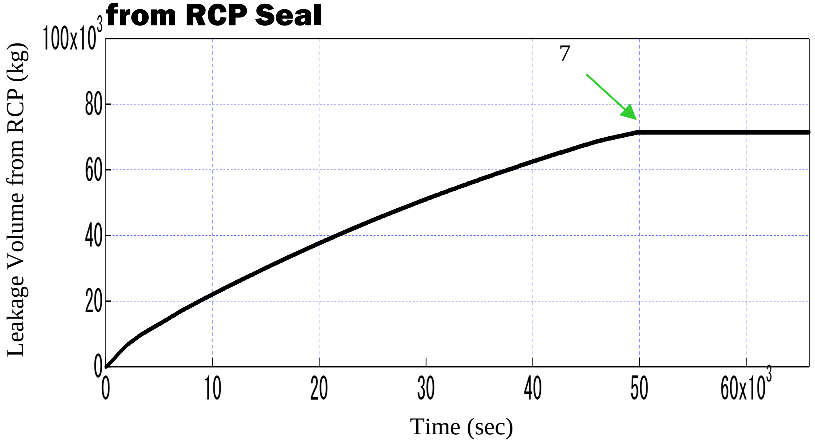
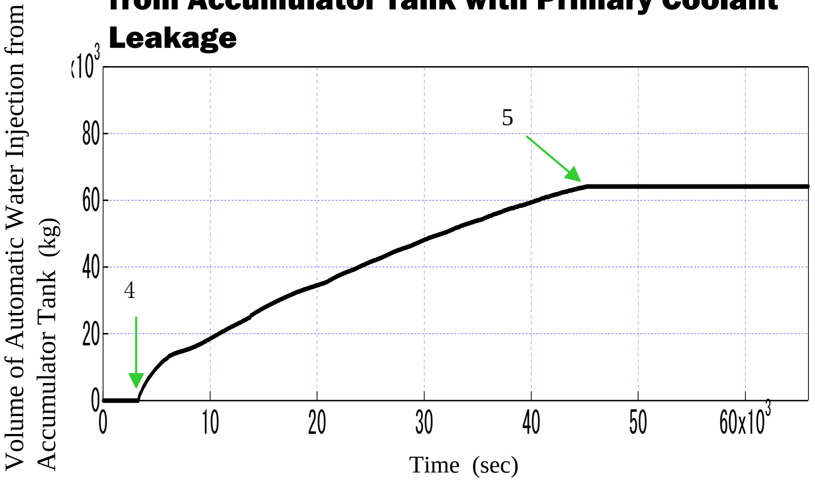


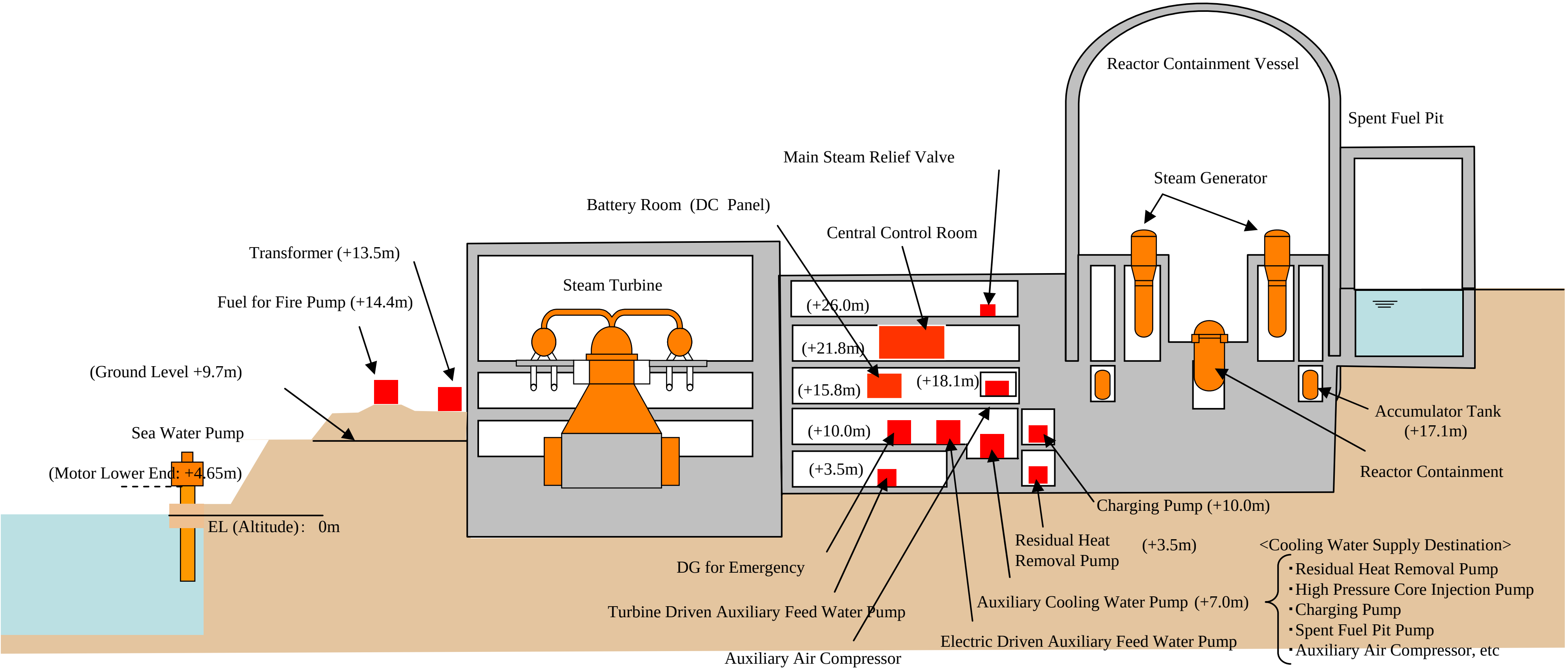
Chart B: Volume of Automatic Water Injection from Accumulator Tank with Primary Coolant Leakage



- **In complete loss of all the AC power, the primary coolant leaks through the sealing of RCP (Chart A)**
- **Then, about the same amount of cooling water will be injected into the core automatically from the accumulator tank . (Chart B)**
- **As a result, cooling function of the core would be maintained without major reduction of primary coolant.**

Current Situation of PWR:
Case Study of Ooi Nuclear Power Plant
Reactors No.3 and No.4

Position and Altitude of Major Equipments: Main buildings are constructed at 9.7m altitude. Batteries and major power panels (M/C, P/C) are at 15.8m, the emergency generators are at +10m, and sea water pumps are at +4.65m.



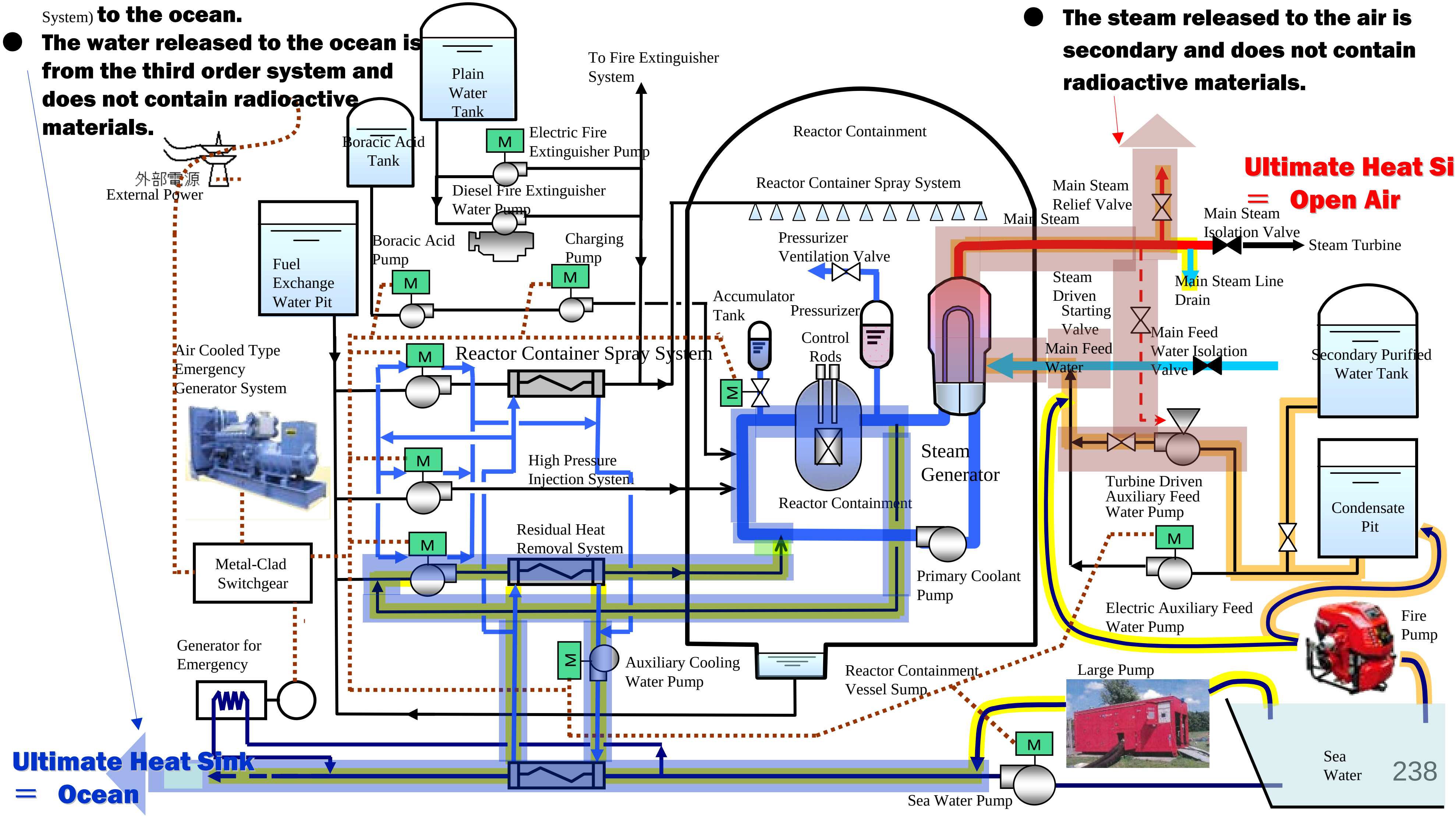
<Cooling Water Supply Destination>

- Residual Heat Removal Pump
- High Pressure Core Injection Pump
- Charging Pump
- Spent Fuel Pit Pump
- Auxiliary Air Compressor, etc

Core Cooling System: PWR has two ways to release heat, the open air and ocean as ultimate heat sinks. Both can lead to low-heat shutdown without releasing radioactive materials.

- **Release the heat (cooling water) exchanged in ECCS** (Residual Heat Removal System) **to the ocean.**
- **The water released to the ocean is from the third order system and does not contain radioactive materials.**

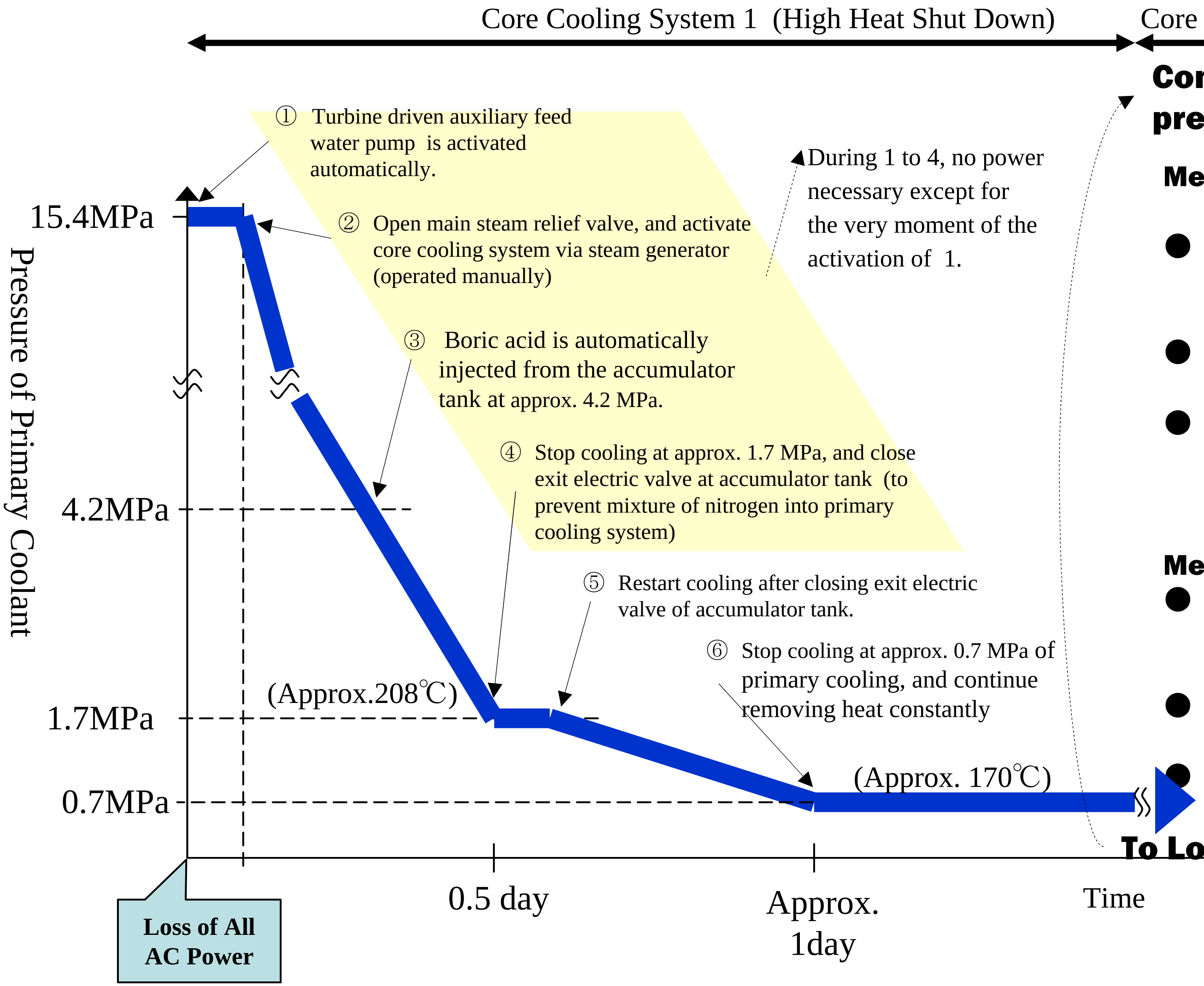
- **Release the heat (steam) by exchanging heat in steam generator to open Air**
- **The steam released to the air is secondary and does not contain radioactive materials.**



Ultimate Heat Sink ＝ Open Air

Ultimate Heat Sink ＝ Ocean

Cooling Procedure at SBO (Station Blackout): There are 2 steps: High Heat Shutdown (to 0.7MPa、170℃), and Low Heat Shutdown (to 93℃). Both ultimate heat sinks, ocean and open air, are available for the latter.



① Turbine driven auxiliary feed water pump is activated automatically.

② Open main steam relief valve, and activate core cooling system via steam generator (operated manually)

③ Boric acid is automatically injected from the accumulator tank at approx. 4.2 MPa.

④ Stop cooling at approx. 1.7 MPa, and close exit electric valve at accumulator tank (to prevent mixture of nitrogen into primary cooling system)

⑤ Restart cooling after closing exit electric valve of accumulator tank.

⑥ Stop cooling at approx. 0.7 MPa of primary cooling, and continue removing heat constantly

During 1 to 4, no power necessary except for the very moment of the activation of 1.

Conduct either one of below after preparation to low-heat shutdown

Method 1: (Heat Sink to Open Air = Feed & Bleed Method**)**

- Inject boric acid to primary cooling system in the core by boric acid pump. (0.5 MPa, down to Approx. 159℃)
- Feed sea water to steam generator directly by fire pump.
- Simultaneously, drain sea water, injected from drain line in main steam line, to lead to low-heat shutdown. (Approx. 93℃)

Method 2: (Heat Sink to Ocean)

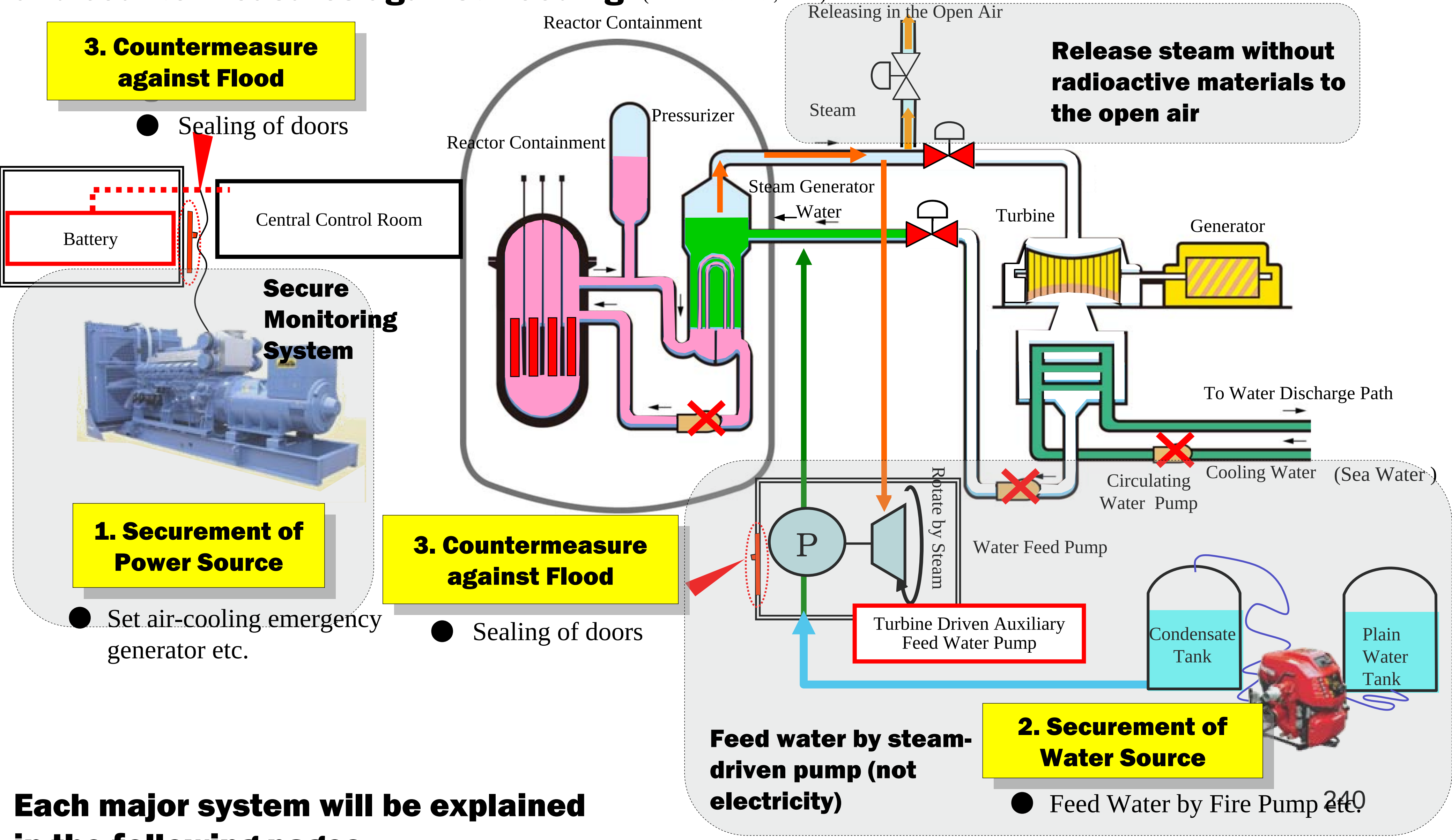
- Activate core auxiliary cooling system, after setting up the sea-water supply line from the large pump to auxiliary water cooler.
- Inject boric acid to primary coolant system by charging pump.
- Operate residual heat removal system to low-heat shut down (to Approx. 93℃).

To Low Heat Shut Down

In PWR, the core is stably controlled at approx. 170℃. Cooling shutdown below 100℃ has less technical significance as is in BWR.

Overview of Safety Measures: Since March 11, 2011, they have been strengthening the multiplicity and diversity of safety measures in three areas, security of power, coolant, and countermeasures against flooding.

(As of November, 2011)



3. Countermeasure against Flood

- Sealing of doors

Secure Monitoring System

1. Securement of Power Source

- Set air-cooling emergency generator etc.

3. Countermeasure against Flood

- Sealing of doors

Release steam without radioactive materials to the open air

Feed water by steam-driven pump (not electricity)

2. Securement of Water Source

- Feed Water by Fire Pump etc.

Each major system will be explained in the following pages.

1. Securement of Power Source: To strengthen multiplicity and diversity, large air-cooling emergency generators are set at 33.3m. Trainings enabled onsite staff to start feeding power to entire reactors within 78 minutes after SBO.

Hardware : Multiplexing and Diversification of Power Sources

In order to secure necessary power source for all reactors No.1 - 4 (Diversify cooling methods)

Total : 2310kVA
Power Supply to Monitoring Devices

14600kVA
More Core Cooling Methods

More Diversified Systems
(Mid to long term plan)

・Central Control Room

Power Supply Vehicle

* All numbers are per plant

・Boric Acid Pump
・Residual Heat Removal System etc.

Air Cooling Emergency Generator: 8 units

・Emergency Core Cooling System
・Sea Water Pump etc.

Permanently Installed Emergency Generator: 4 units

- **Measures for quick and secure connections**
  - Connection port and cables are installed right next to the DG to avoid unnecessary transportation
  - Located in altitude of over 30m.

- **Battery**
  - Stocked on-site

Software : Training Enforcement

In order to connect power supply vehicles and emergency DGs as quick as possible

Holiday/Night	6 Staffs are always assigned

- **Establish organizations**
- **Prepare manuals and operate training**
  - Set up power supply vehicles.
  - Connect power cables.
  - Drive power supply vehicles.
  - Fuel to power supply vehicles.

Number of trainings conducted (as of Oct 28, 2011)

Weekdays	14
Night	3
Weekends	2

Connecting with power supply vehicles

Night Training

- **Reflection of Training**

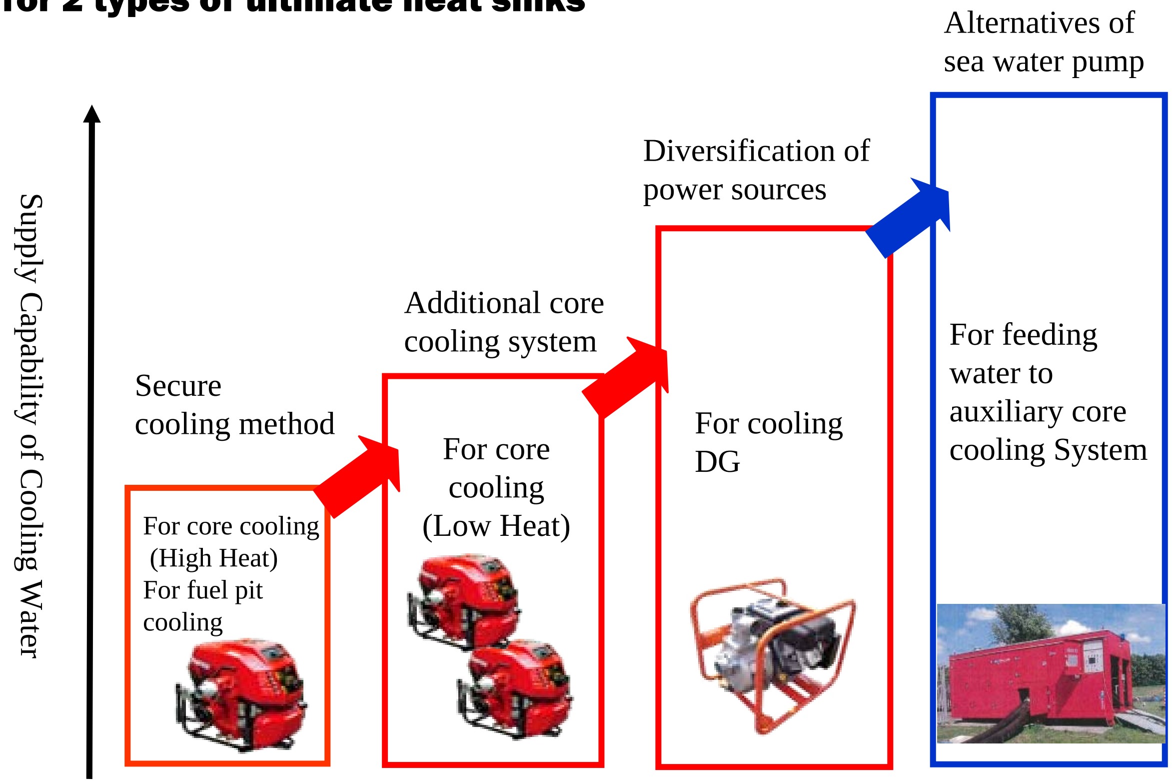
・Prepare head lamps for night operation
・Improve the shape of connection terminal for quicker connection, etc.

- **Quicker connection as a result of training**
  - Power supply vehicles : 135 mins
  ⇒Air Cooling Emergency DG : 78 mins
  (Time to start power supply to all reactors)

2. Secure Cooling Sources: Cooling water for 16 days of operations are secured. Fire pumps with high portability and large pump* with extremely high capacity are set up for more multiplicity and diversity. (*: Implemented December, 2011)

Hardware: Multiplexing and Diversifying of Cooling Sources

In order to secure low and high heat cooling, and coolant source for 2 types of ultimate heat sinks



Fire Pump: 25 units

Additional Pump: 28 units added

Total fire pumps: 88 units (Including back-ups)

Portable Engine Driven Sea Water Pump: 30 units

Total: 32 units (Including back-ups)

Large Pump: 1 unit (DG driven, gas oil, self-propelled) (To be installed in Dec, 2011)

* All numbers are per plant

Software: Training Enforcement

In order to operate installed fire pumps and other equipments smoothly

- **Establish organizations : Quick assembly under emergency**
- **Prepare manuals and operate training**

Numbers of trainings conducted (as of Oct 28, 2011)

- Install pumps
- Lay down hoses
- Operate pumps
- Fuel pumps

SG Feed Water	20
SFP Feed Water	12
Cold Shut Down	4

● Reflection of Training

- Put marks on the points to install pumps.
- Prepare transceivers for closer communication

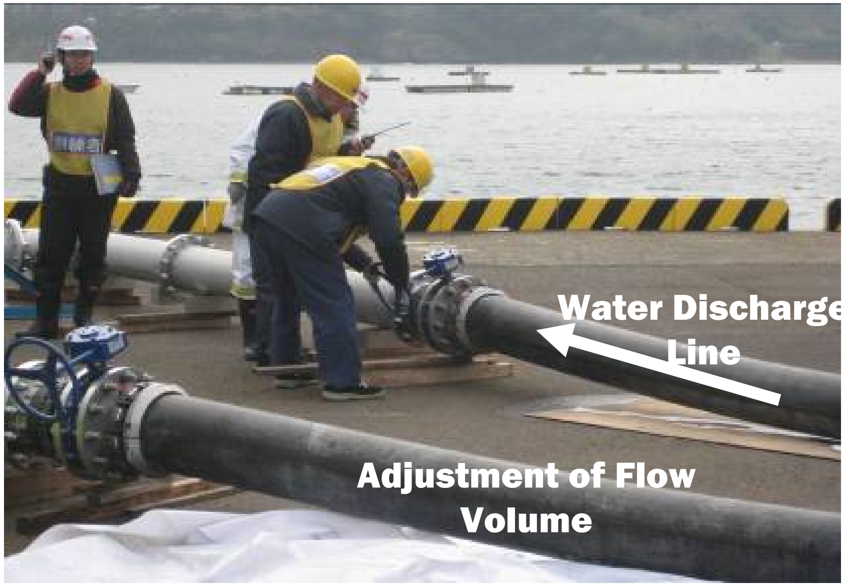
● Back-up of Sources and Equipments

- Required fire pumps: 53 units => Total of 88 units were set
- Required hoses: 631 units => Total of 670 units were set

2. Securement of Cooling Water: Training for the large volume pump, installed in December, 2011, and currently in the process of implementation.

(Continued)


指揮者
Large Volume Pump


Water Discharge Line
Adjustment of Flow Volume

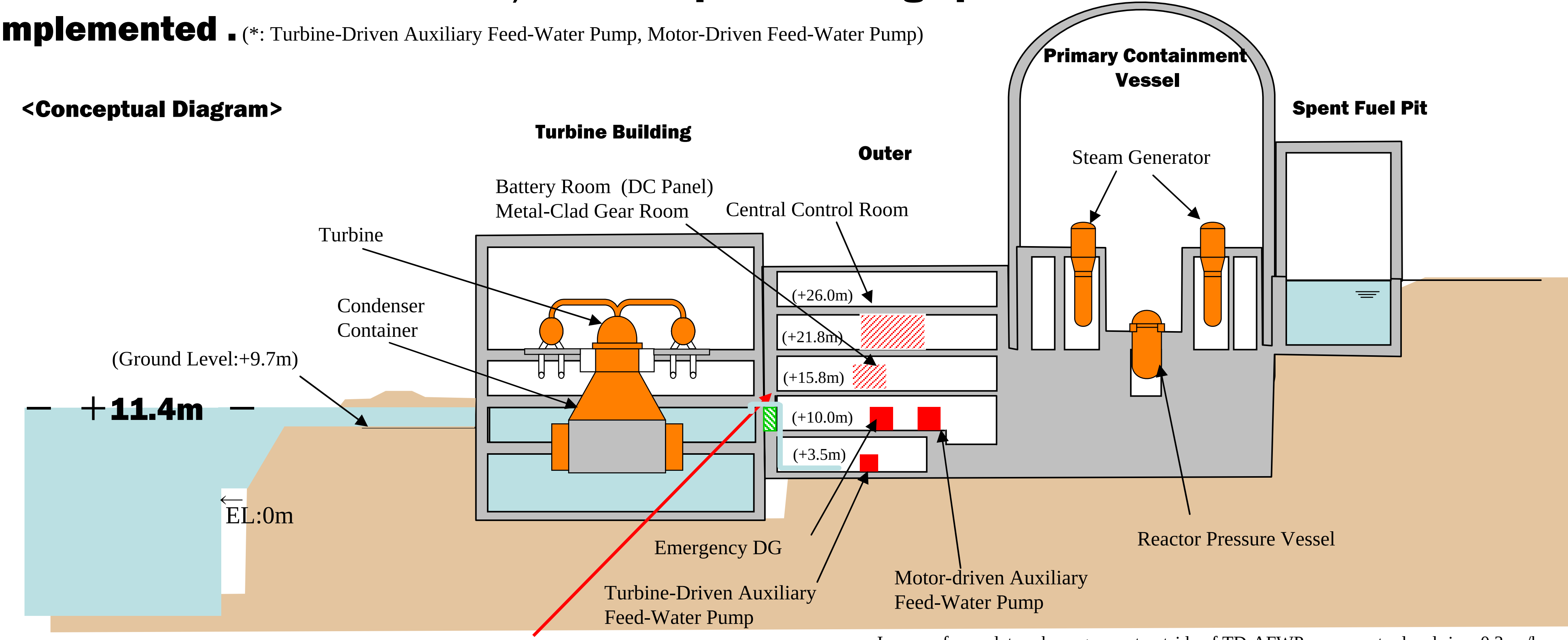

TOSHIBA
1322.6
m³/h
OVER 125%
POWER
Water Discharge Flow Meter


Water Discharge Outlet

3. Countermeasure against Flooding: In order to protect emergency DG's and TD/MD-AFWP's* located at lower level, the waterproof sealing up to the altitude of 11.4m were implemented .

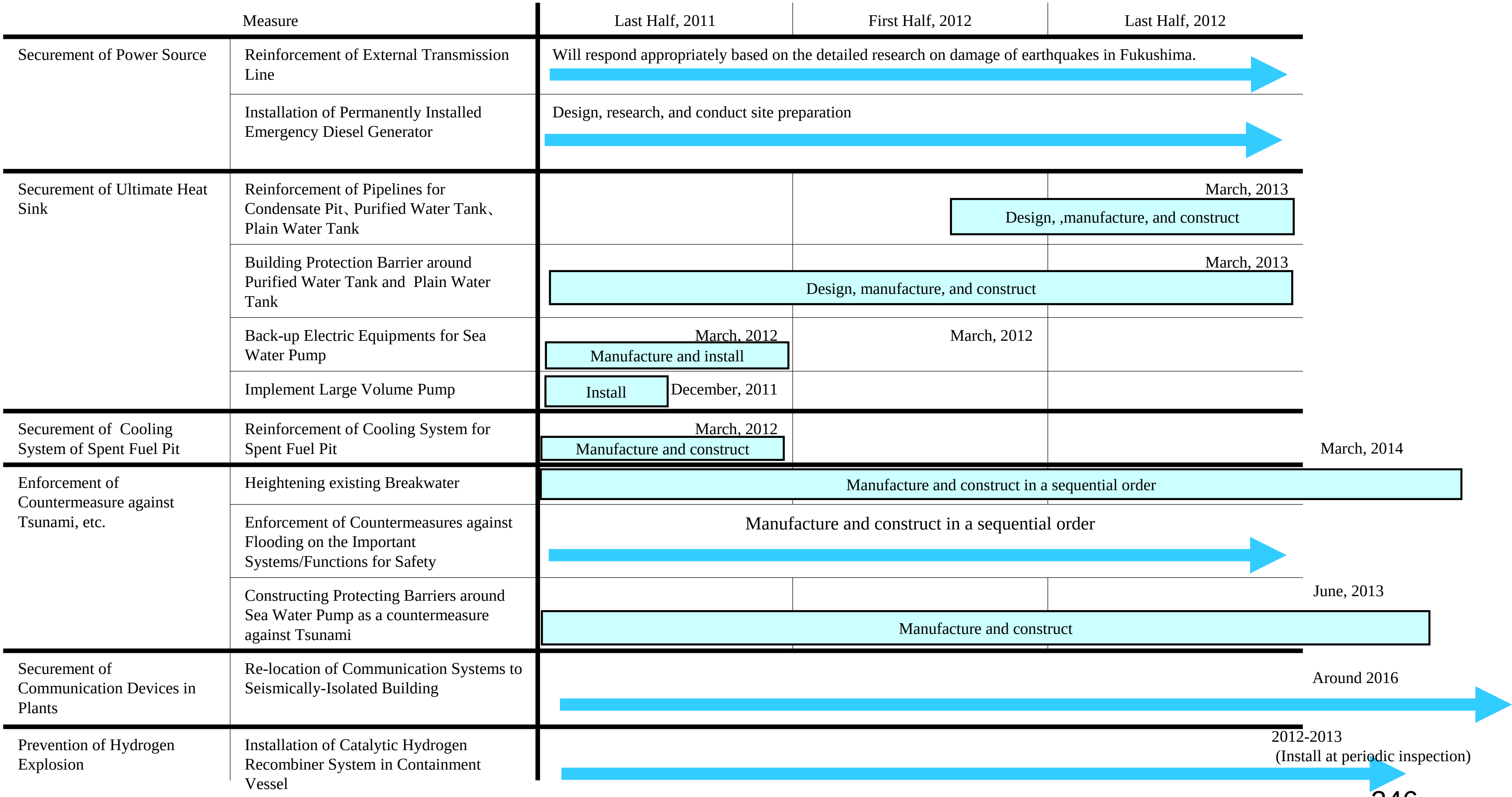
(*: Turbine-Driven Auxiliary Feed-Water Pump, Motor-Driven Feed-Water Pump)

<Conceptual Diagram>



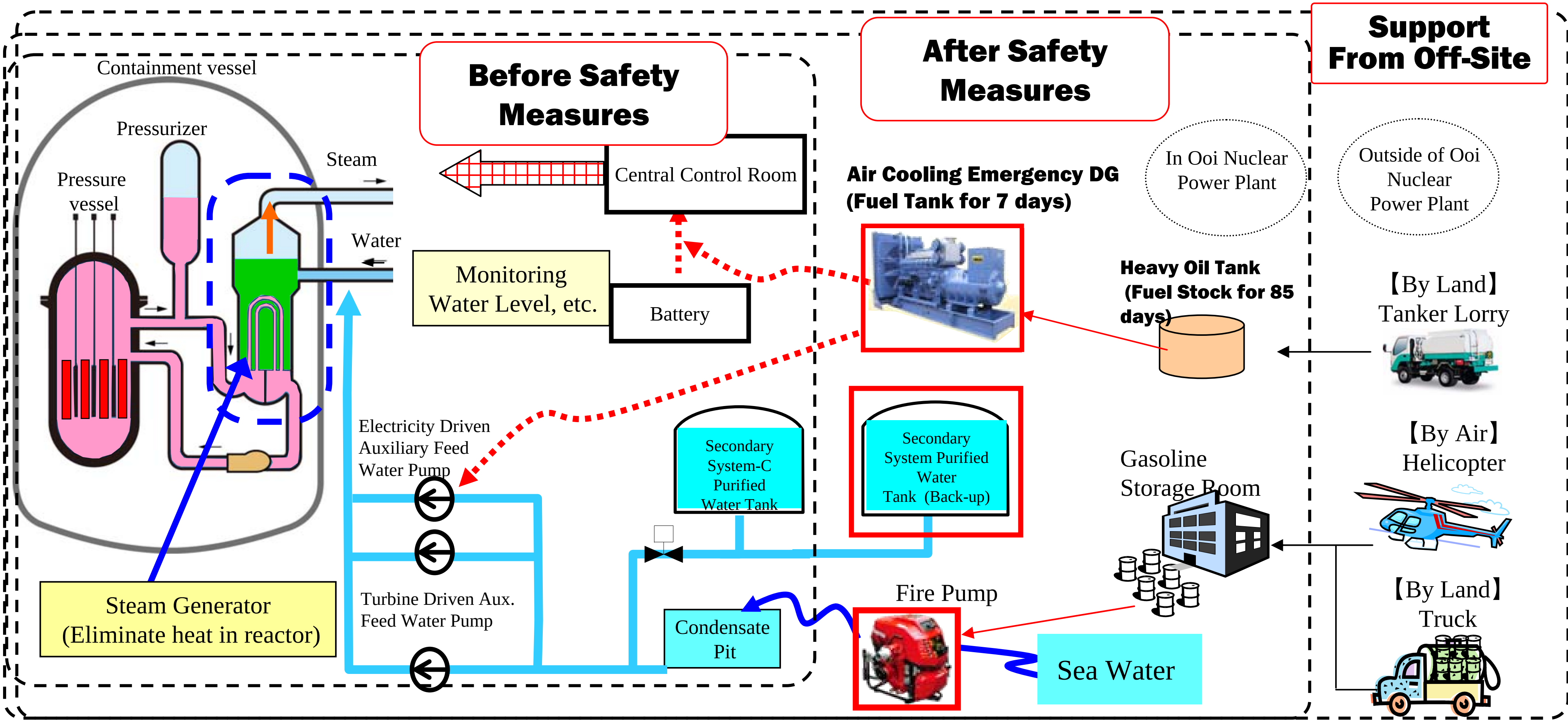
In case of complete submergence at outside of TD-AFWP room, water level rises 0.3cm/hr. (from experimental data)

Planned Countermeasures: It is planned or considered to introduce permanently installed emergency DG at a high place and seismically-Isolated major buildings, as well as to enable all plants to share any of their power sources each other.



	Measure	Last Half, 2011	First Half, 2012	Last Half, 2012	
Securement of Power Source	Reinforcement of External Transmission Line	Will respond appropriately based on the detailed research on damage of earthquakes in Fukushima.			
	Installation of Permanently Installed Emergency Diesel Generator	Design, research, and conduct site preparation			
Securement of Ultimate Heat Sink	Reinforcement of Pipelines for Condensate Pit、Purified Water Tank、Plain Water Tank		Design, ,manufacture, and construct	March, 2013	
	Building Protection Barrier around Purified Water Tank and Plain Water Tank	Design, manufacture, and construct		March, 2013	
	Back-up Electric Equipments for Sea Water Pump	March, 2012 Manufacture and install	March, 2012		
	Implement Large Volume Pump	Install December, 2011			
Securement of Cooling System of Spent Fuel Pit	Reinforcement of Cooling System for Spent Fuel Pit	March, 2012 Manufacture and construct			
Enforcement of Countermeasure against Tsunami, etc.	Heightening existing Breakwater	Manufacture and construct in a sequential order			March, 2014
	Enforcement of Countermeasures against Flooding on the Important Systems/Functions for Safety	Manufacture and construct in a sequential order			
	Constructing Protecting Barriers around Sea Water Pump as a countermeasure against Tsunami	Manufacture and construct			June, 2013
Securement of Communication Devices in Plants	Re-location of Communication Systems to Seismically-Isolated Building				Around 2016
Prevention of Hydrogen Explosion	Installation of Catalytic Hydrogen Recombiner System in Containment Vessel				2012-2013 (Install at periodic inspection)

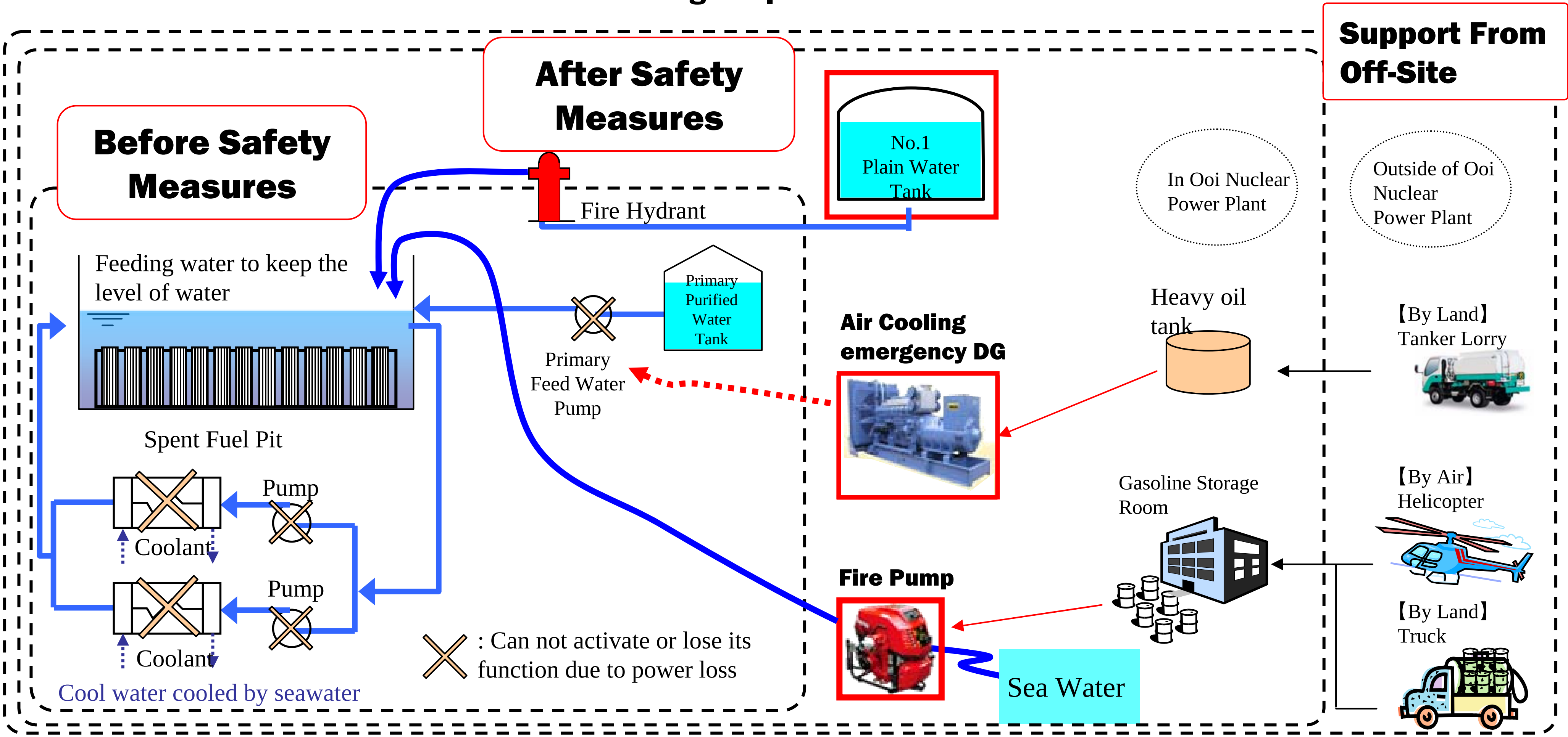
Prevention of Core Damage (SBO, Loss of Ultimate Heat Sink): It is now possible to keep cooling the core for 16 days without any off-site supports because of the newly introduced air-cooling emergency DG and enforced water feed systems.



Furthermore, it would also be possible to keep cooling the core beyond 16 days with additional supplies such as gasoline for fire pump from off-site.

(Cont.) It is also possible to keep cooling the spent fuel pit for 10 days without any off-site supports with the air-cooling emergency DG, water source from various tanks, and fire pump.

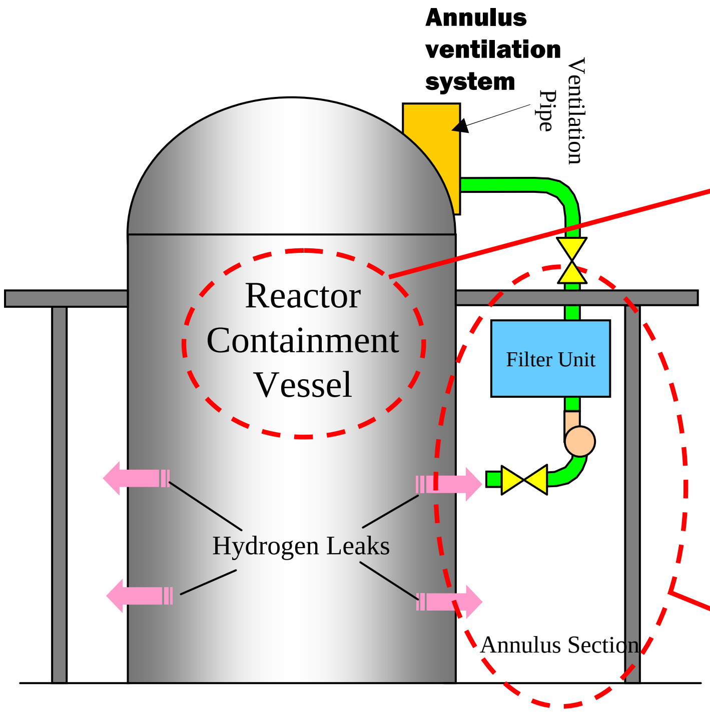
Cooling of Spent Fuel Pit



Furthermore, it would also be possible to keep cooling the pit beyond 10 days with additional supplies such as gasoline for fire pump from off-site.

Prevention of Hydrogen Explosion: KEPCO* simulates that the hydrogen would not accumulate to its detonation density even if 75% of all the zirconium used in the fuel rods were reacted because of the large volume of containment vessel.

(*: Kansai Electric Power Company)



Volume: Approx. 72,900m^3 (Ooi No. 3,4)

Volume of containment vessel of Ooi reactor No.3 is about 5 times as large as the one of BWR with the same output of 1,100,000 kW.

Findings from Fukushima Dai-ichi accident

Inside of Containment

- An enormous amount of hydrogen was generated due to core damage, and accumulated in the containment vessel.

Outside of Containment

- Hydrogen leaked to the reactor building surrounding the containment vessel, and exploded.

Countermeasures

- **The large volume of PWR's vessel reduces hydrogen concentration and increase the safety allowance against explosion.**
- In the future, static catalytic hydrogen recombiner will be installed in the vessel to lower hydrogen density.

- **Hydrogen would be ventilated to outside by preparing ventilation procedure in the annulus Section.**
- The air cooling emergency DG supplies power for the ventilation.

The vessel will be further reinforced by installing a static catalytic recombiner in the future.

Multiplicity and Diversity in Safety Measures of Nuclear and Industrial Safety Agency (NISA)

Case Study in Ooi Nuclear Power Plant
Reactors No. 3 and No. 4

The project examined the multiplicity and diversity of safety measures directed by NISA at the end of March and at the beginning of April, 2011, in terms of ten categories which had the greatest impact on the event progression in the Fukushima Dai-ichi accident.

Infrastructure

Supply of Power

- External Power Source
- AC Power Source
- DC Power Source

Supply of Coolant

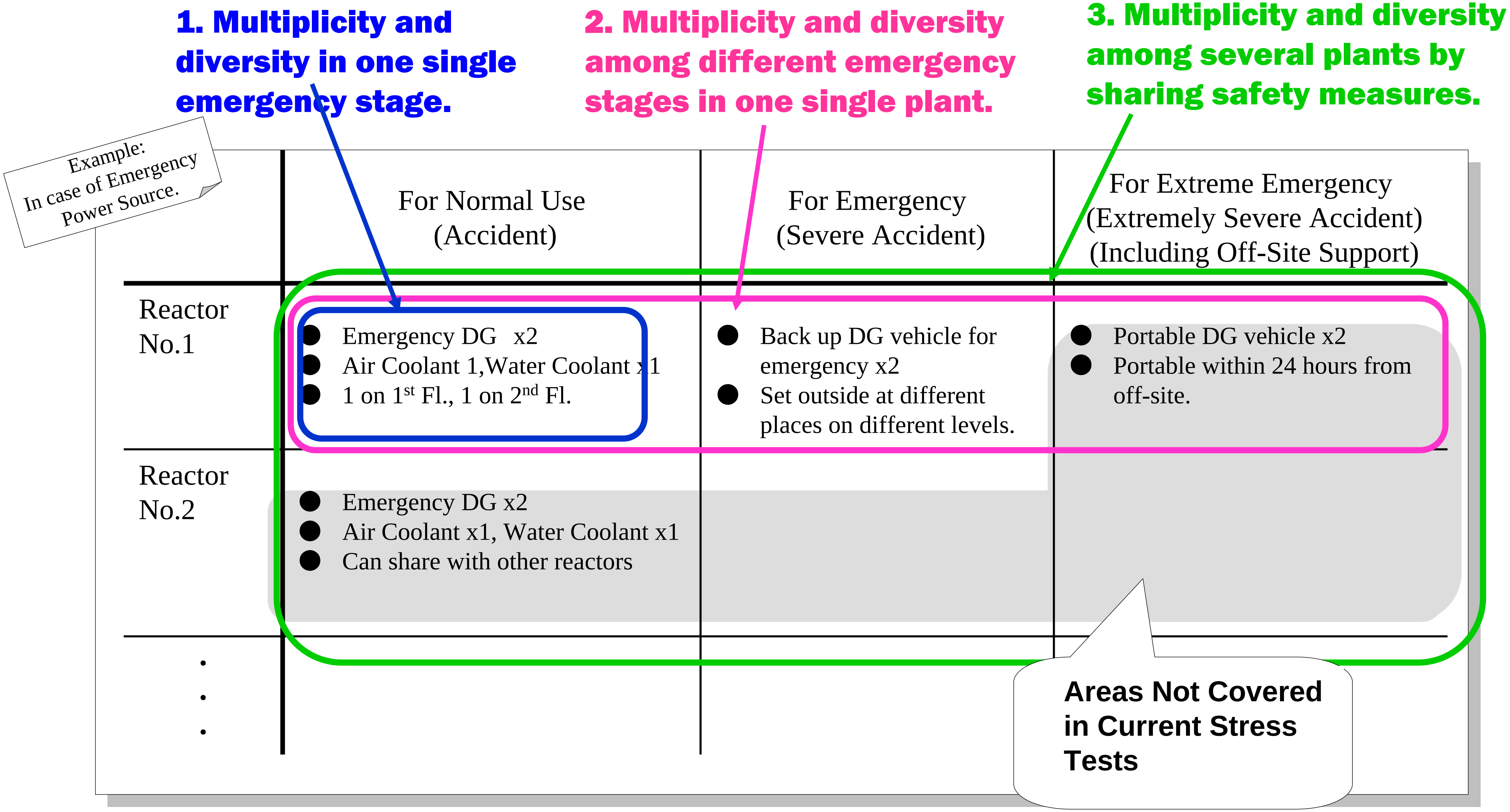
- Sources of Coolant
- Fuel (Heavy Oil, Light Oil, Gasoline)
- Sea Water Related System (Ultimate Heat Sink)

×

Primary Functions of Reactor

- Parameter Monitoring (Central Control Room)
- Core Cooling
- Pressure Reduction of Steam Generator (SG)
- Prevention of Hydrogen Explosion

It is important to examine three different levels of the multiplicity and diversity.



1. Multiplicity and diversity in one single emergency stage.

2. Multiplicity and diversity among different emergency stages in one single plant.

3. Multiplicity and diversity among several plants by sharing safety measures.

Example:
In case of Emergency
Power Source.

	For Normal Use (Accident)	For Emergency (Severe Accident)	For Extreme Emergency (Extremely Severe Accident) (Including Off-Site Support)
Reactor No.1	● Emergency DG x2 ● Air Coolant 1,Water Coolant x1 ● 1 on 1st Fl., 1 on 2nd Fl.	● Back up DG vehicle for emergency x2 ● Set outside at different places on different levels.	● Portable DG vehicle x2 ● Portable within 24 hours from off-site.
Reactor No.2	● Emergency DG x2 ● Air Coolant x1, Water Coolant x1 ● Can share with other reactors		
⋮			

Areas Not Covered in Current Stress Tests

Level of importance in education and training to operate safety measures for severe accidents.

Large

Continuous education and training, and proficiency-check are also important to increase multiplicity and diversity of safety measures.

Summary of Multiplicity and Diversity: Safety measures for “normal” and “emergency” have been established. Further enhancements are necessary for “extreme emergency” and trainings.

Normal Use (Design Basis)

- **Power Source**
  - ・External power (4 lines from 2 systems)
  - ・Emergency DG (2 units)
  - ・DC power (batteries) (2 systems)
- **Cooling Systems: High Heat Shut Down**
  - ・TD-AFWP (1 unit)
  - ・MD-AFWP (2 units)
  - ・Primary steam relief valve (4 units)
- **Cooling Systems: Low Heat Shut Down**
  - ・Residual heat removal pump (2 units)
  - ・Reactor Building Auxiliary Cooling Water Pump (4 units)
  - ・Sea Water Pump (3 units)
- **Water Source**
  - ・Condensate Pit (1 unit)
  - ・Pure Water Tank for Secondary System (5 units in a whole plant)

Emergency (Accident Management)

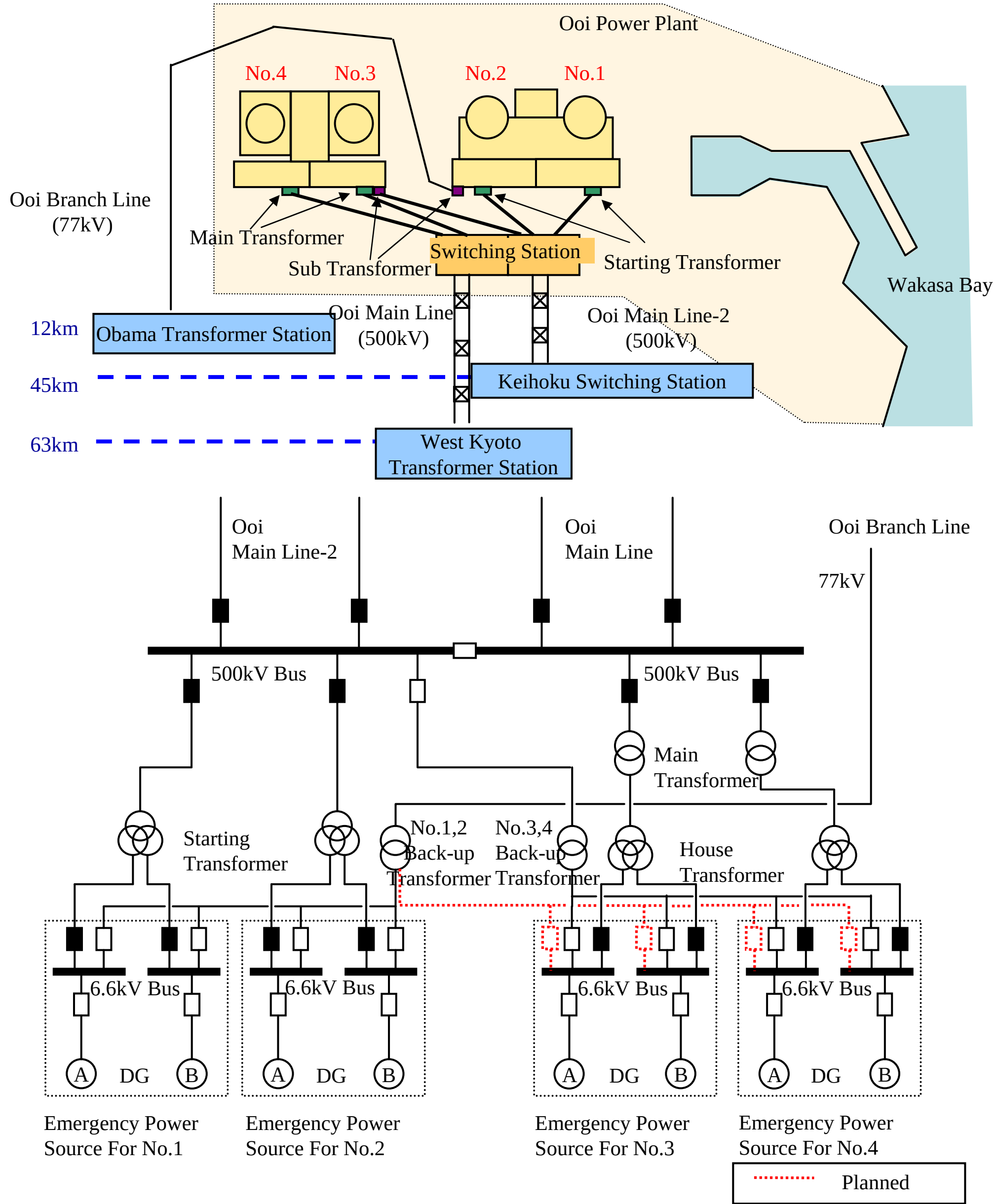
- **Power Source**
  - ・Power supply vehicle upland (1 unit)
  - ・Air-Cooling emergency DG (2 units)
  - ・Permanently-installed emergency DG (1 unit)
- **Cooling Systems: High Heat Shut Down**
  - ・MD-AFWP (2 units. Powered by air-cooling emergency DG)
  - ・(Makeshift medium-pressure pump (Under planning))
- **Coolant System: Low Heat Shut Down**
  - ・Large Volume Pump (1 unit in a whole plant) (as alternative for sea water pump)
  - ・Portable fire pump (Direct water supply to SG. 1 unit)
- **Water Source**
  - ・Water tank (5 units in a whole plant)
  - ・Sea water
  - ・Portable fire pump (Supply sea water to condensate pit)

Extreme Emergency (Off-Site Support)

- **Power Source**
  - ・Carry in necessities such as batteries, and fuel from off-site by helicopter etc.
- **Cooling Systems**
  - ・Carry in fuel etc from off-site.
- **Water Source**
  - ・(Carry in water from off-site.)
  - ・(Supply from nearby river, lake, ponds.)

From the next page, the multiplicity and diversity in each primary function will be examined based on the Accident in Fukushima Dai-ichi.

Multiplicity and Diversity of External Power: They plan to enable all the reactors to share any of external power sources based on the Fukushima Dai-ichi accident.



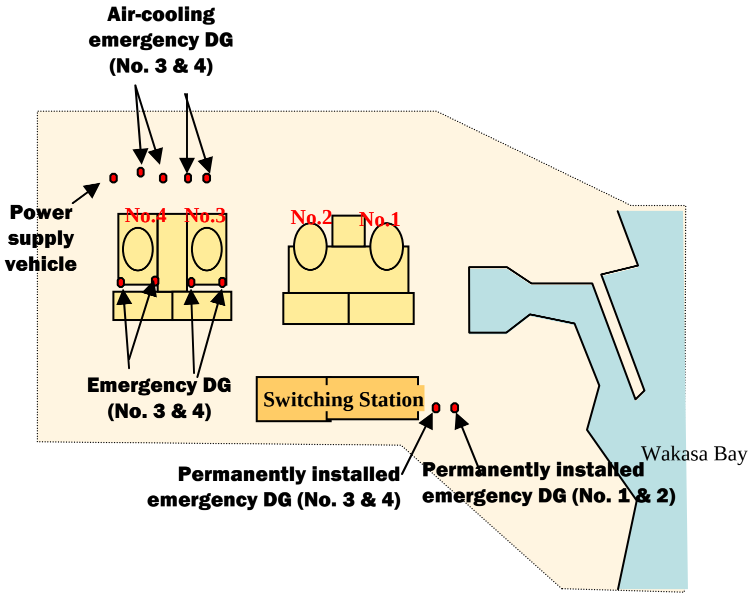
- Three independent lines from three different transformer stations serve the Ooi Nuclear Power Plant.
  - Two independent lines from only one transformer station served the Fukushima Dai-ichi Nuclear Plant.

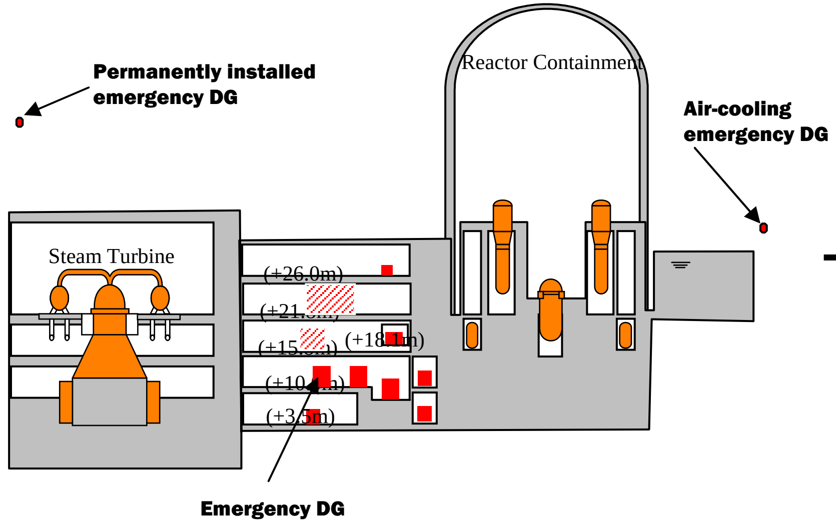
- If either of the switching stations does not function, reactors No. 1 and 2 can share their 6.6 kV AC power with the other. Reactors No. 3 and 4 can do the same.

- In addition, there is a plan to enable all the reactors No. 1 to 4 to share their 6.6 kV AC power with each other.

  (Underground cable is being considered as a mid-to long-term plan.)

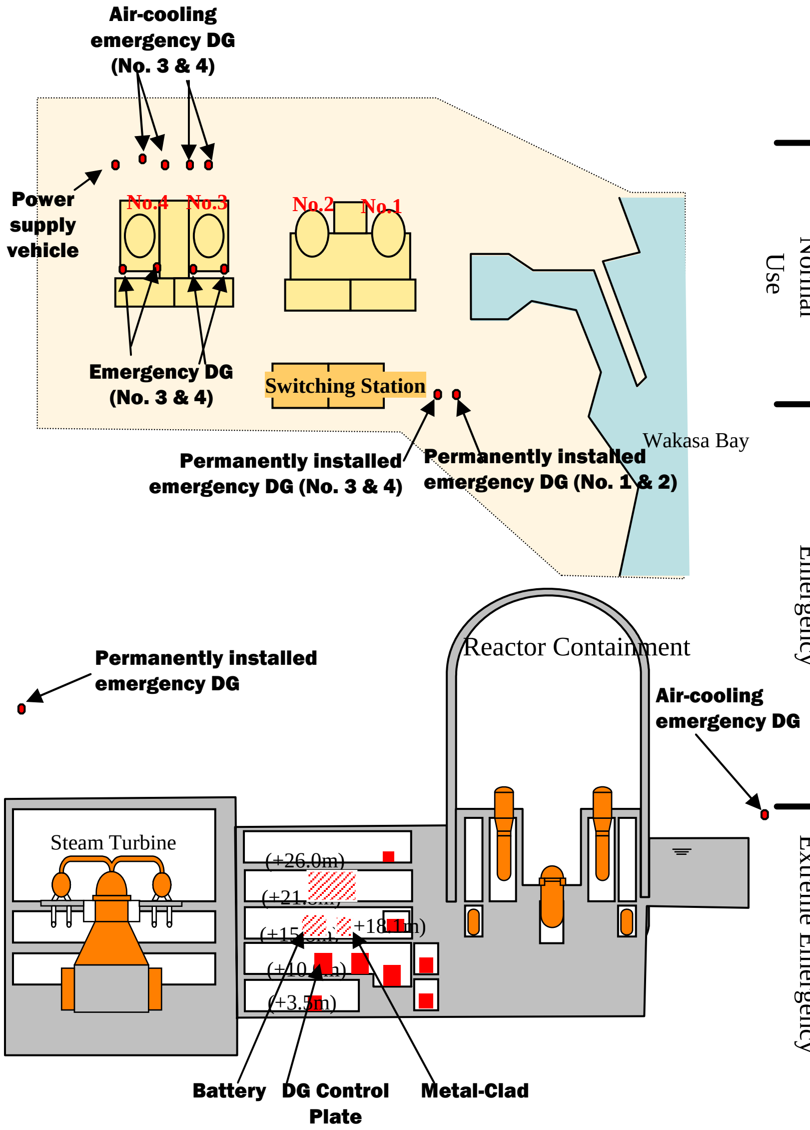
Multiplicity and Diversity of **AC Power: The safety allowance has been improved by power supply vehicles and air-cooling emergency DG's. Further enhancement is planned to introduce permanently installed emergency DG.**





	Equipment	#	Install Location	Altitude (m)	Drive Method	Water Protection
Normal Use	• Emergency DG	2	E/B	10.0	Water-Cooled	In Operation
Emergency	• Power supply vehicle	2	Outdoor	33.3	Air-Cooled	Upland
	• Air-Cooling emergency DG	2	Outdoor	33.3	Air-Cooled	Upland
	• Permanently installed emergency DG (Planned)	1	Indoor	Upland	Air-Cooled	Upland
Extreme Emergency	• Generators for emergency (off-site)					

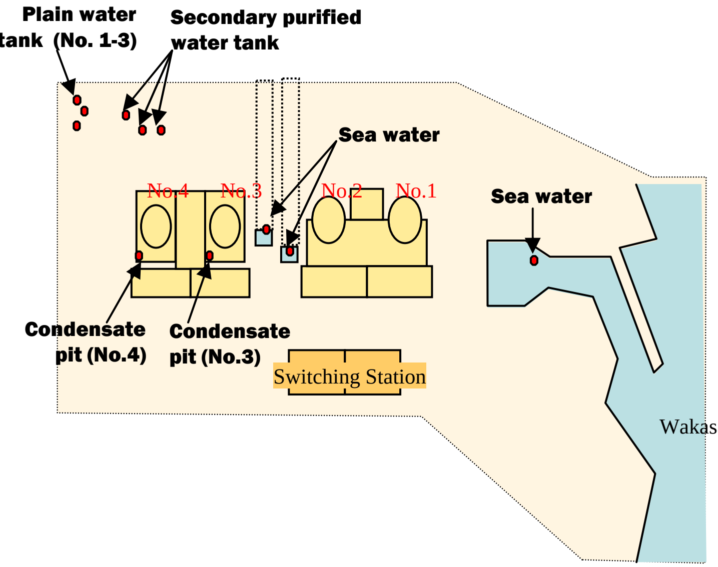
Multiplicity and Diversity of **DC Power: Methodology to secure DC is biased on charging from AC, though DC batteries are set at 15.8m, where flooding is less likely. It would be necessary to enhance the availability of highly portable batteries*.**

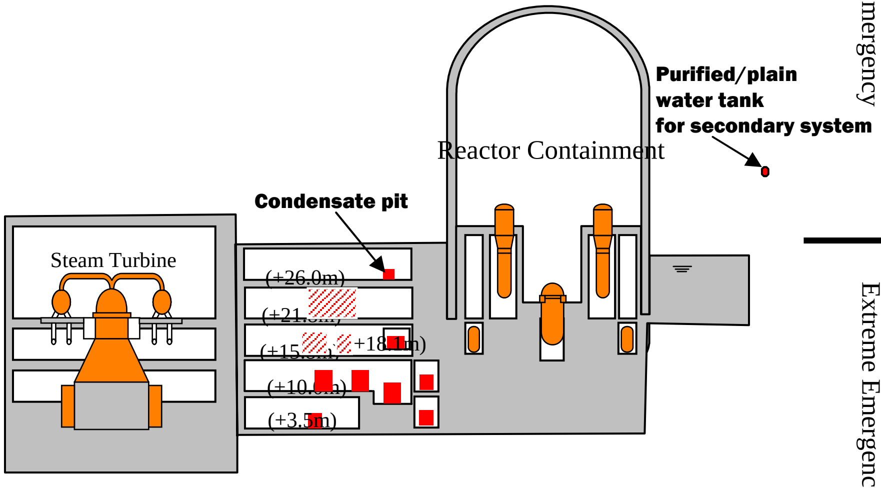


	Equipment	#	Install Location	Altitude (m)	Drive Method	Water Protection
Normal Use	• DC Power Source (Safety System)	2	C/B	15.8	DC	Done
	• Charge from DG (Metal-Clad) (DG Control Panel)	2	 E/B C/B	 15.8 10.0	AC	Under construction
Emergency	• DC Power Source (Normal Use)	1	C/B	15.8	DC	Done
	• Charge from air-cooling emergency DG	1	C/B	15.8	AC	Done
	• Charge from permanently installed emergency DG (Metal-Clad)	1	C/B	15.8	AC	Upland
Extreme Emergency	• Back-up Battery (Carry in from off-site by helicopter. Land route and sea route are being planned.)				DC	

※: For example, portable batteries, connection port, and cables could be stored in the central control room in order to secure parameter-monitoring function.

Multiplicity and Diversity of **Cooling Water: Since all the coolant sources are set above 18.5m and hold for 16-days of amount, its safety margin is high.**

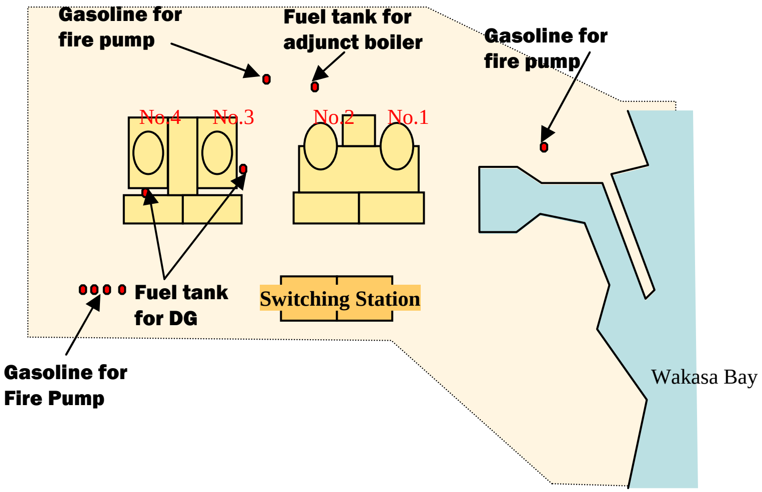


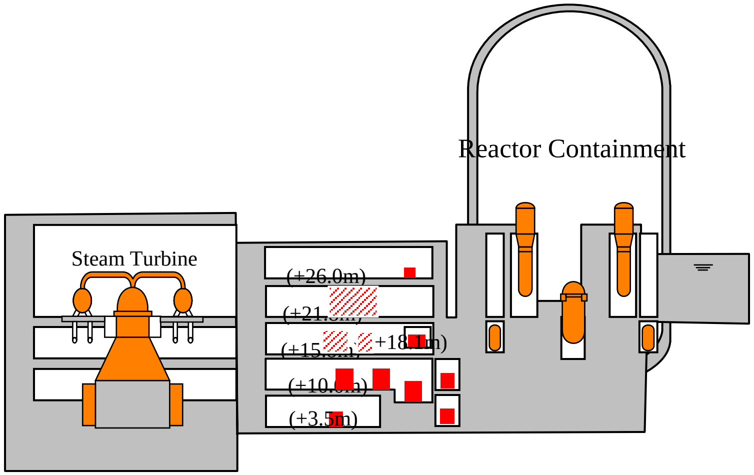


	Equipment	#	Install Location	Alt. (m)	Drive Method	Water Protection
Normal Use	• Condensate pit	1	E/B	26.0	Unnecessary	Done
	• Secondary pure water tank	1	Outdoor	80.5	Unnecessary	Upland
Emergency	• Plain water tank*	3	Outdoor	80.5	Unnecessary	Upland
	• Sea water	-	—	—	Unnecessary	—
	• Water pit for fuel exchange	1	E/B	18.5	Unnecessary	Done
	• Make-up purified water tank (Back-up)*	2	Outdoor	80.5	Unnecessary	
Extreme Emergency	• Make-up water from off-site				Unnecessary	

*: Numbers per plant

Multiplicity and Diversity of **Fuel (heavy oil, light oil, gasoline): The stockpile offers an adequate safety margin. It would be important to enforce operations and trainings for on-site and off-site logistics under extremely severe accidents.**

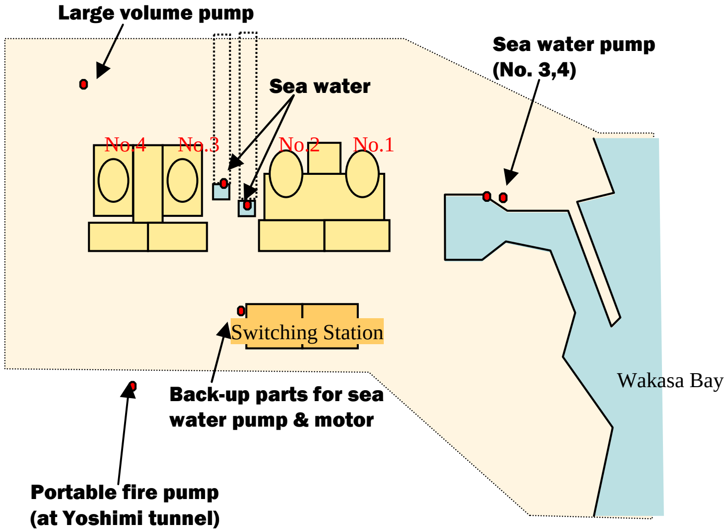


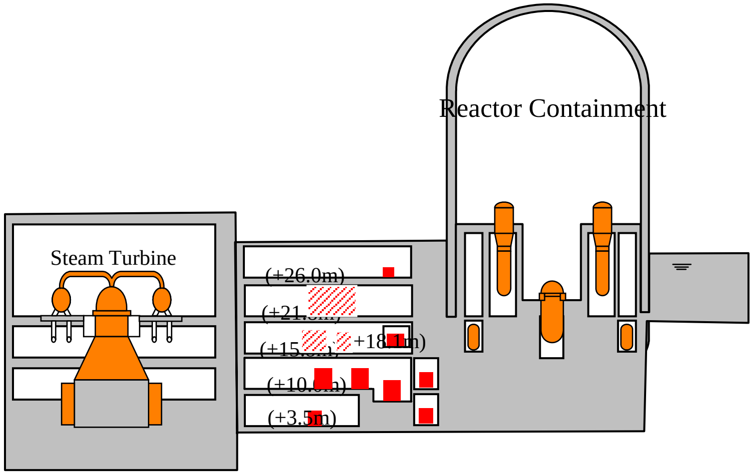


	Equipment	#	Install Location	Altitude (m)	Drive Method	Water Protection
Normal Use	• Stock tank for DG fuel (Heavy Oil)	2	Outdoor (Underground)	2.6	Unnecessary	Done
	• Fuel tank for back-up boiler (Heavy Oil)	2 ※	Outdoor	33.3	Unnecessary	Upland
Emergency	• Fuel storage (Drum cans for fire pumps are stored in 6 different locations)	1 1 4	Outdoor Outdoor Outdoor	14.4 33.3 45.0	Unnecessary Unnecessary Unnecessary	Upland Upland Upland
Extreme Emergency	• Fuel for emergency (Carry gasoline, or light oil from off-site by helicopter, land route or sea route.)	—	—	—	—	—

* Numbers per plant

Multiplicity and Diversity of **Ultimate Heat Sink: While the safety margin of sea water pump** (normal use) **is low as located near the sea, the margin for large volume pump** (emergency use) **is high. It is also effective to have the open air as the ultimate heat sink.**

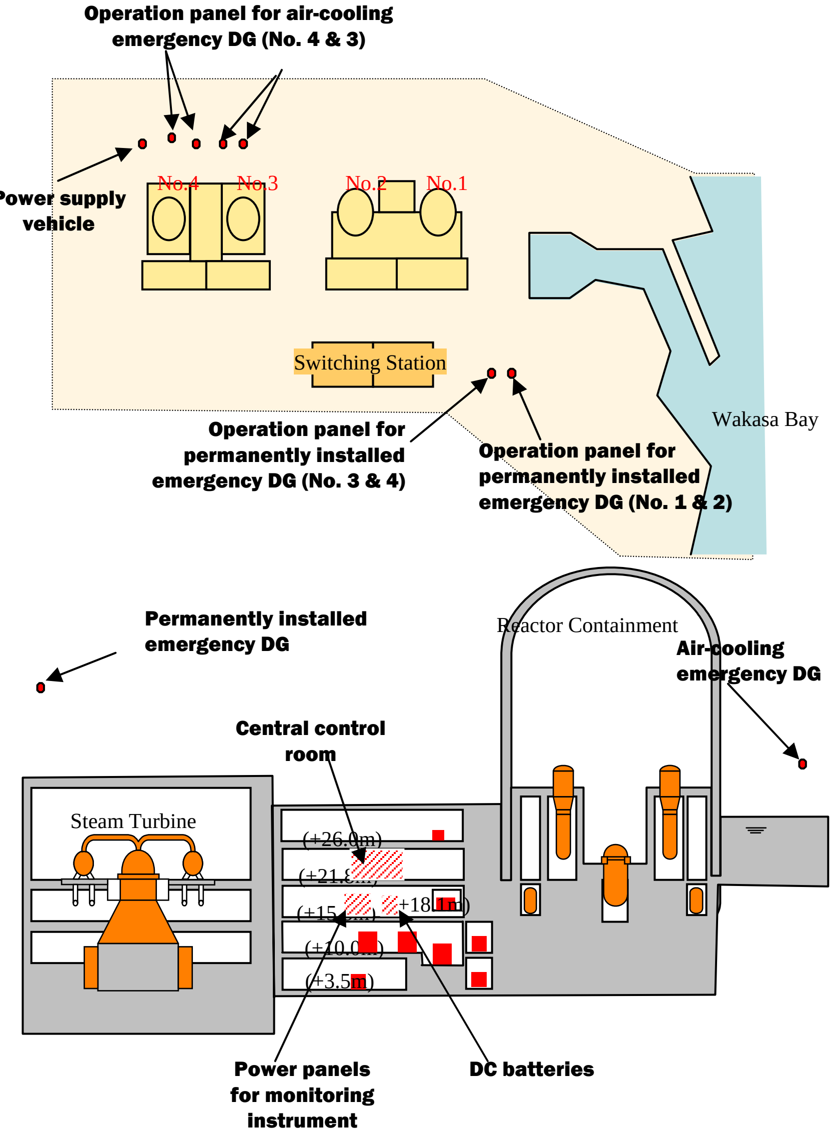




	Equipment	#	Install Location	Altitude (m)	Drive Method	Water Protection
Normal Use	• Sea water pump	3	Sea Water Pump Pit (Intake)	4.65	Electricity driven	Protection wall from Tsunami
Emergency	• Large volume pump	1*	Outdoor	33.3	Heavy oil	Upland
	• Portable fire pump	88 *	Outdoor (In Tunnel)	62.8	Gasoline	Upland
	• Motors for sea water pump (Back-up)	1	Outdoor	32.0	Electricity driven	Upland
Extreme Emergency	• Portable waterproof pump (Water intake from watering pit)				Electricity driven	

* Numbers per plant

Multiplicity and Diversity of **Parameter-Monitoring** (Central Control Room): **Since the function to monitor essential parameters must not be lost in any situation, DC power supply to the central control room is extremely essential.**

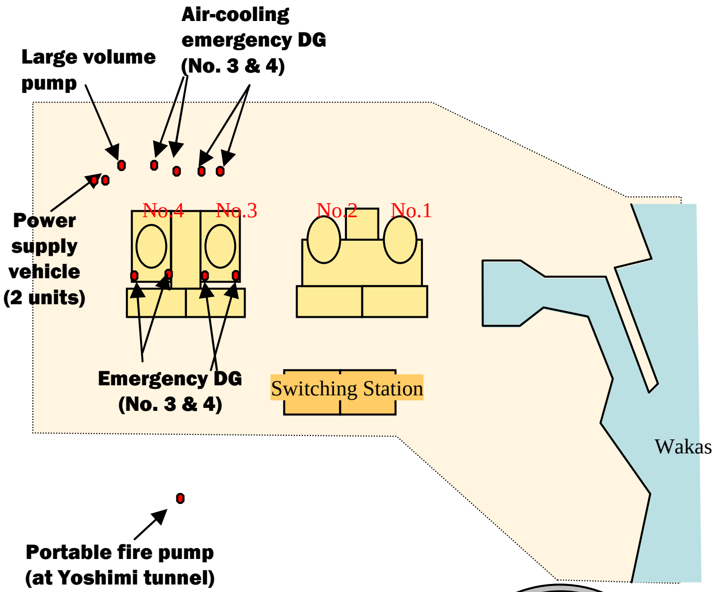


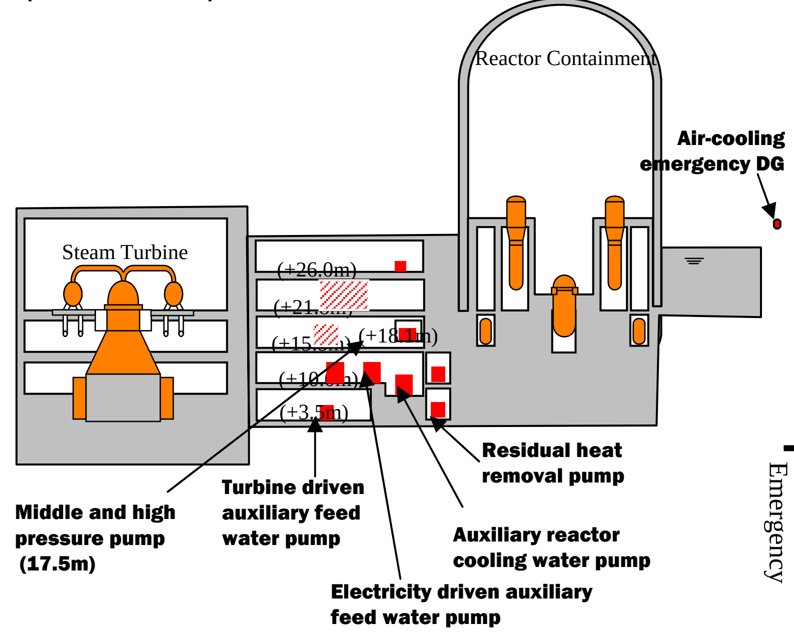
	Equipment	#	Install Location	Alt. (m)	Drive Method	Water Protection
Normal Use	• Central control room	1	C/B	21.8	DC、AC	Done
	• Power panels for monitoring instrument	4	C/B	15.8	DC、AC	Done
	• DG	2	E/B	10.0	AC	Under installation
	• DC batteries (Rechargeable Battery)	2	C/B	15.8	DC	Done
Emergency	• Air-cooling emergency DG	2	Outdoor	33.3	AC	Upland
	• Power supply vehicle*	2	Outdoor	33.3	AC	Upland
	• Permanently installed emergency DG (Installed in the future)	1	In Building	Upland	AC	Upland
Extreme Emergency	• Portable batteries (Connected to the instrument directly)	—	C/B	21.8	DC	Done

* Numbers per plant

Multiplicity and Diversity of **Core Cooling: As both open air and ocean are available for UHS***1**, safety margins (both normal and emergency) are high. TDAFWP***2**, which does not need any power is extremely important among high-pressure cooling functions.**

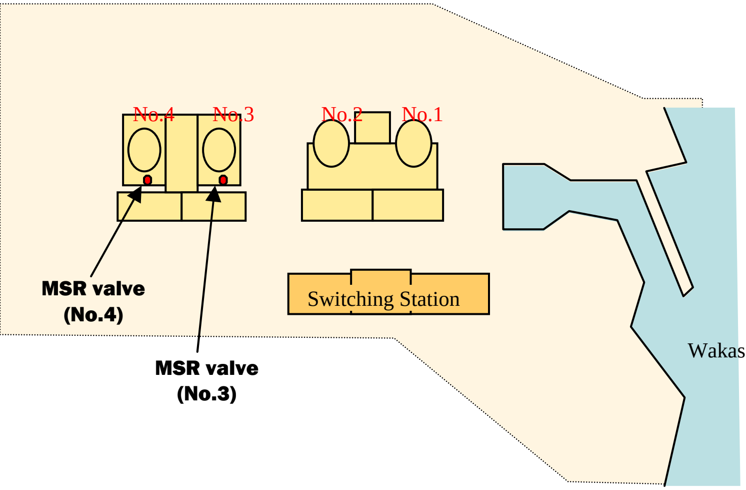
(*1: ultimate heat sink. *2: turbine driven auxiliary feed water pump)

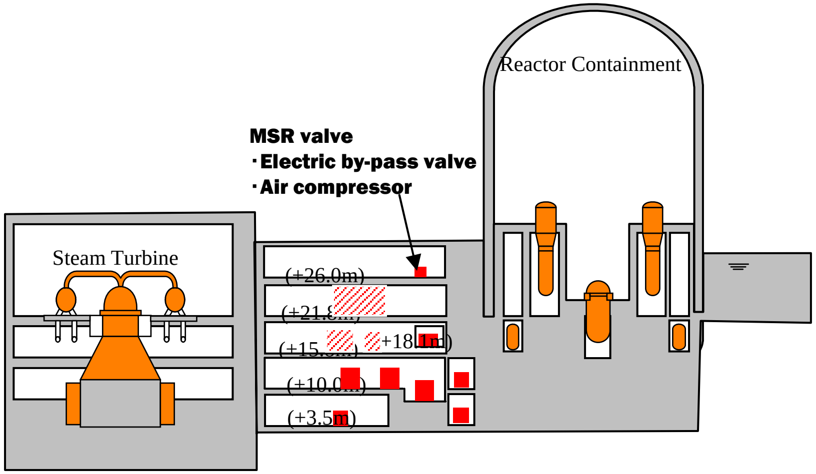




	Equipment	#	Install Loc.	Altitude (m)	Drive Method	Water Protection
Normal Use	High Heat Shut Down					
	• Turbine driven auxiliary feed water pump	1	E/B	3.5	Steam	Done
	• Electricity driven auxiliary feed water pump	2	E/B	10.0	Electricity	Done
	Low Heat Shut Down					
	• Residual heat removal pump	2	E/B	3.5	Electricity	Done
Emergency	High Heat Shut Down					
	• Makeshift middle pressure pump (under planning)	1	E/B	17.0	Heavy Oil	Done
	• Electricity driven auxiliary feed water pump (powered by air-cooling emergency DG)	1	E/B	10.0	Electricity	Done
	Low Heat Shut Down					
	• Large volume pump	1	Upland	33.3	Heavy Oil	Upland
	• Residual heat removal pump (Powered by air-cooling emergency DG)	1	E/B	3.5	Electricity	Done
	• Auxiliary reactor cooling water pump (Powered by air-cooling emergency DG)	1	E/B	3.5	Electricity	Done
	• Portable fire pump (Directly feed water to SG)	4	Upland	63.0	Engine	Upland
Extreme Emergency	• Water pump vehicle (Transferred from other plants)					

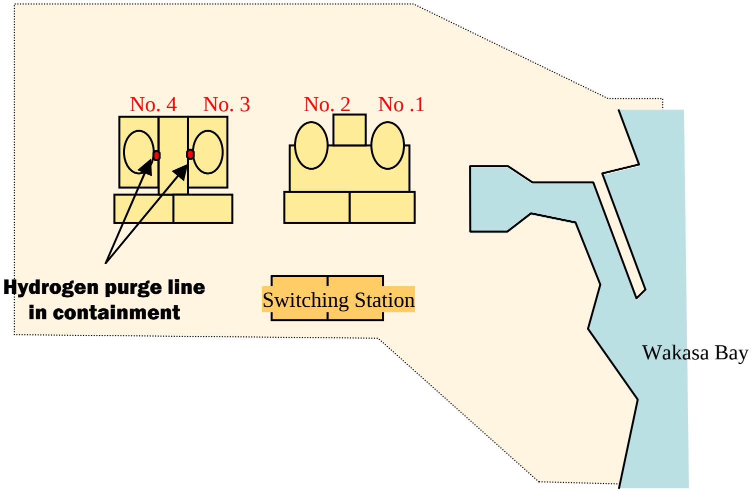
Multiplicity and Diversity of **Pressure Reduction of SG*1: Safety allowance of MSR*2 valve (air-pressure) is high since it can be operated by hand. It will be further enhanced with back-up compressor and greater emphasis on operational training.** (*1: steam generator. *2: main steam relief)

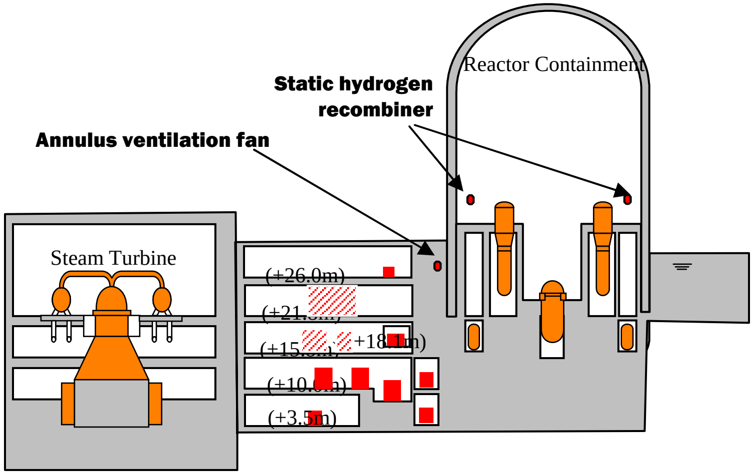




	Equipment	#	Install Location	Alt. (m)	Drive Method	Water Protection
Normal Use	• Main steam relief valve (air-pressured)	4	Main steam control room in control building	33.6	Air	Done
Emergency	• Main steam relief valve (Manual operation)	4	Main steam control room in control building	33.6	Manual handle	Done
	(Air compressor)				Makeshift air	
	(Setting of electric by-pass valve, etc.)				DC battery (charged by air-cooling emergency DG)	
Extreme Emergency	• Carry in compressor from off-sites					

Multiplicity and Diversity of **Prevention of Hydrogen Explosion: This is the comprehensive assessment of each function. The most important is that "the power source and coolant shall be secured no matter how severe a circumstance is."**



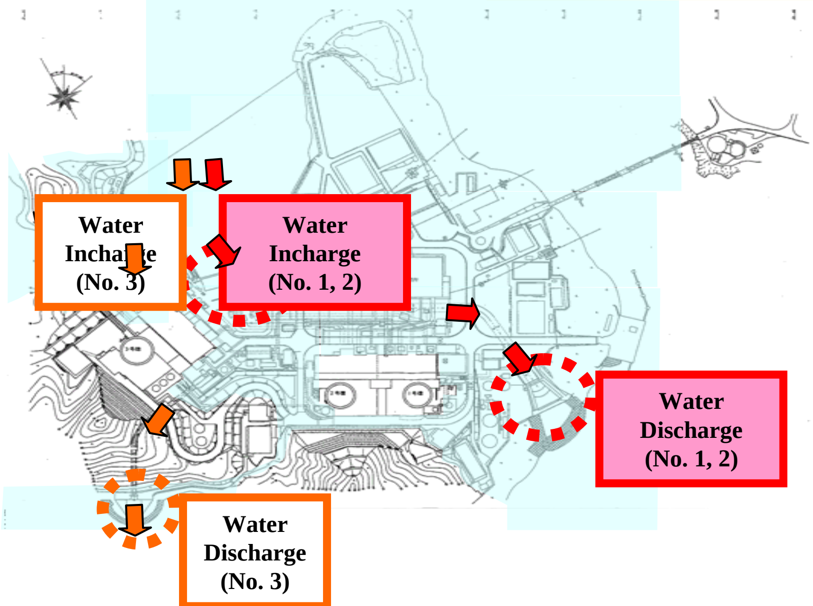


	Equipment	#	Install Loc.	Alt. (m)	Drive Method	Water Protection
Normal Use	• Containment vessel	1	—	—	—	Done
Emergency	• Annulus air ventilation fan	2	E/B	22.0	Electric	Done
	• Hydrogen purge line in containment	1	E/B	33.6	Air-operated	Done
Extreme Emergency	• Static catalytic hydrogen recombiner (Being planned)	5	C/V	—	Unnecessary	Unnecessary (In Containment)

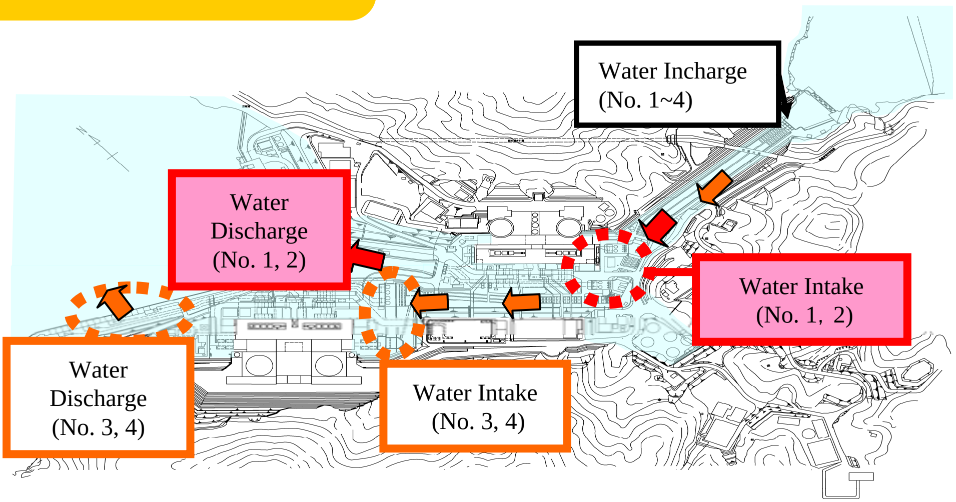
Path of Sea Water: Since paths for water intake/discharge are located in the same place in all plants, diversification would be more effective such as portable pumps etc.

Ooi Nuclear Power Plant

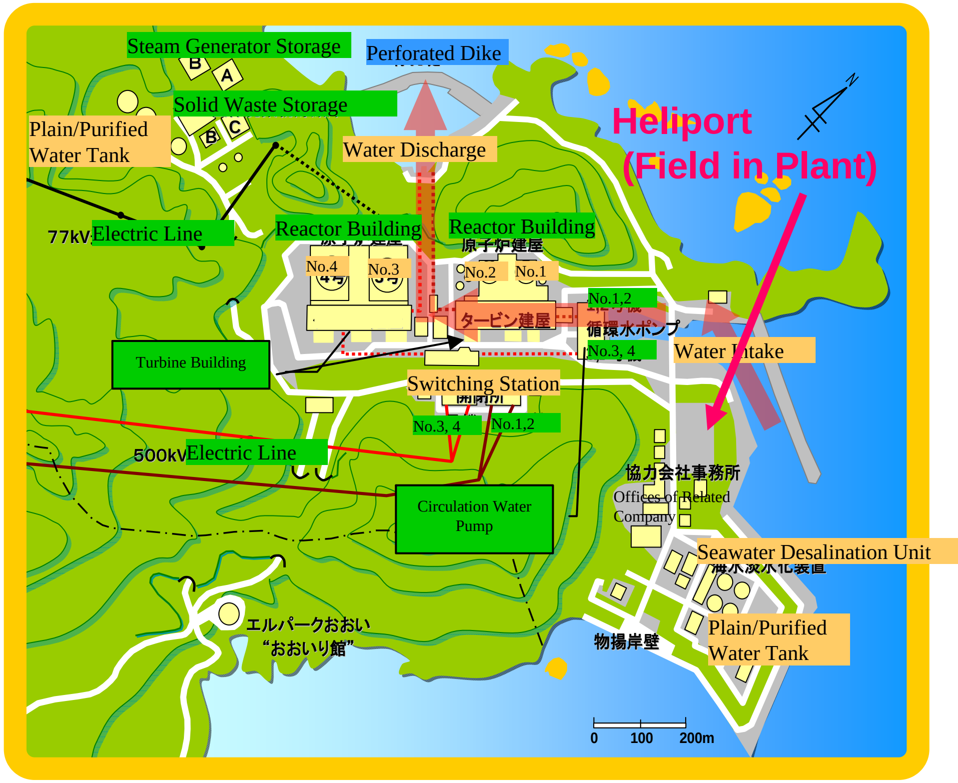
Mihama Nuclear Power Plant

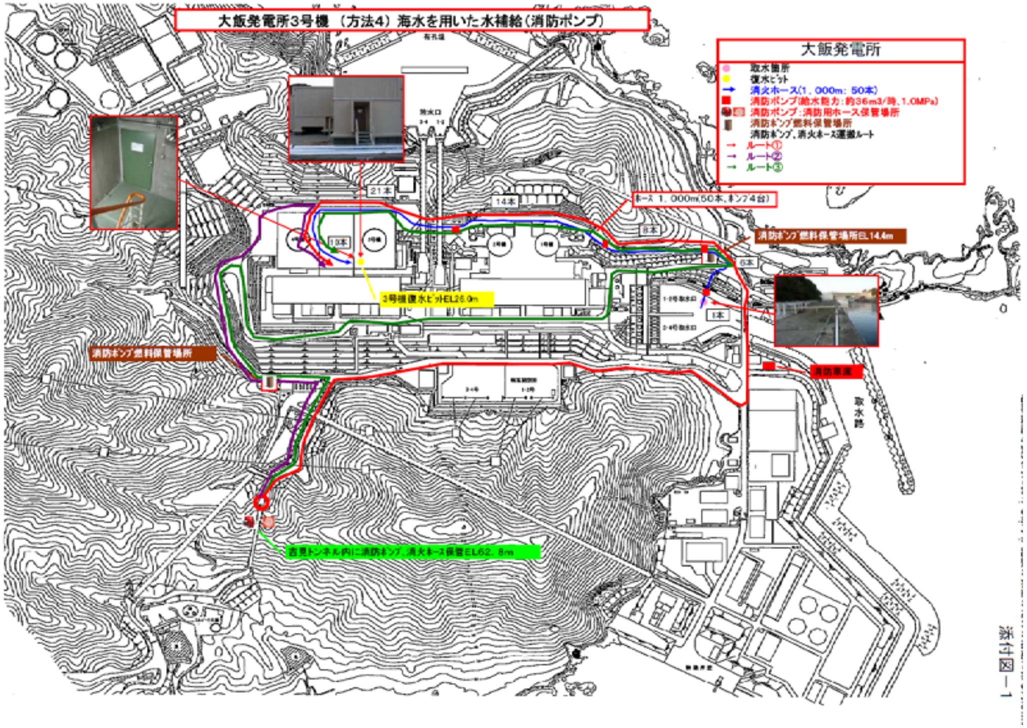


Takahama Nuclear Power Plant



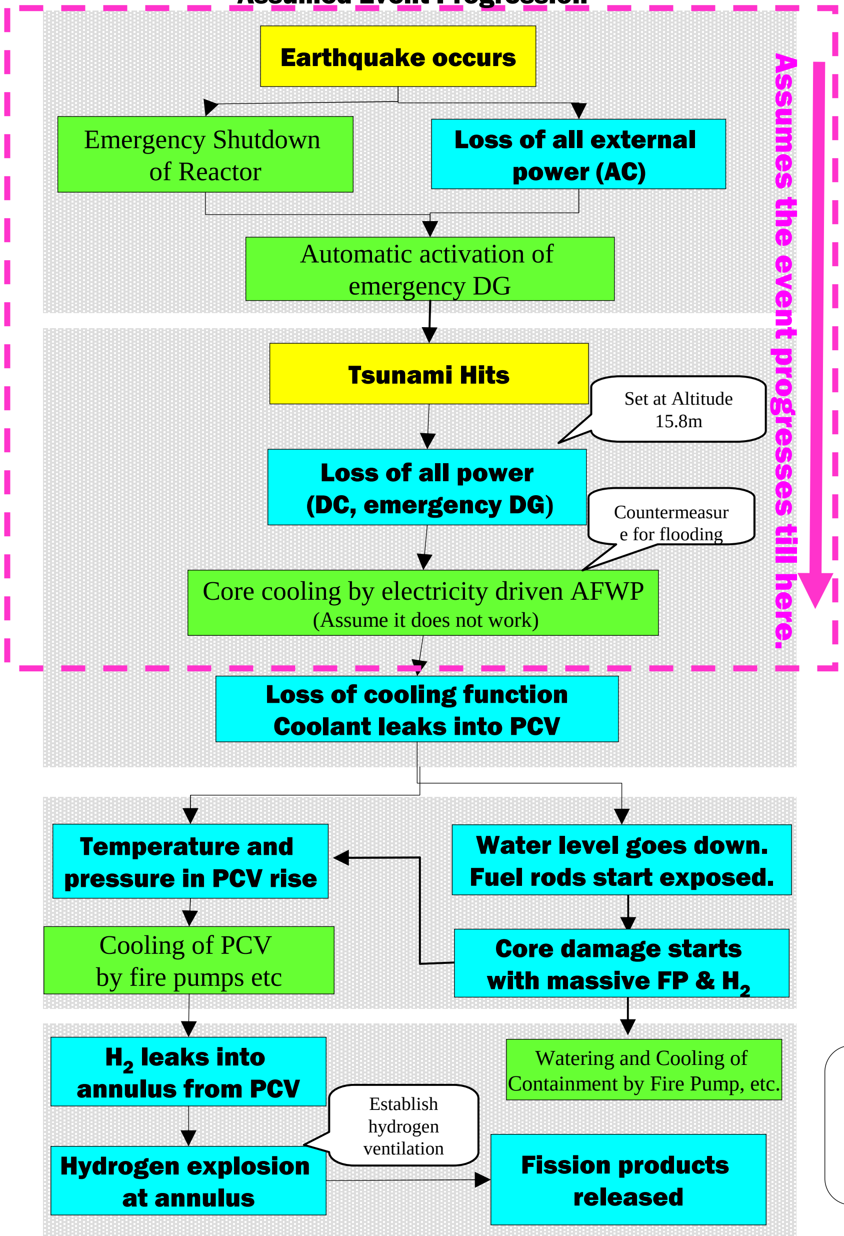
Logistics for Emergency such as Heliport & Fire Pumps: Though their locations, carry-in route, and procedures are defined in the manual, it is important to enhance their proficiencies through trainings.





Assuming the same accident in Fukushima Dai-ichi reactor-1, most of the current safety measures in Ooi reactor 3 & 4 would be effective and most likely could avoid a major accident.

Assumed Event Progression



Example

AM actions (On-site)

Initial Action (W/in 3 hrs)

Secure power (for initial use) & functions of control room and TD-AFWP (turbine-driven auxiliary feed water pump).

- Scram is assumed to succeed.
- Open MSR valve and activate TD-AFWP by DC power (= start High Pressure Cooling System) before Tsunami hits (=DC is active).
- Stand-by or connect portable batteries in the central control room.
- Establish system to overview the damage of all power systems.

HPCI (W/in 5 hrs)

Secure power (for second use). Continue cooling by HPCI

- Activate & connect air-cooling emergency DG to panels (Secure communications).
- Bring in & connect additional batteries (Enhance DC power source).
- Continue high pressure cooling (TD-AFWP) (= Need no power).

Keep high pressure cooling (Within 24 hours)

Bring in more supplies to continue high-pressure cooling. Secure sufficient power source. Repair accesses.

- Continue high-pressure cooling (TD-AFWP) (= No power needed).
- Secure back-up high-pressure cooling (MD-AFWP) (Activate air-cooling DG).
- Boric acid is injected automatically from accumulator tank at 4.2MPa of core pressure. (No power needed).
- Open/close MSR valve as core pressure drops. (Secure communication means).
- Temporarily stop cooling at 1.7 MPa (secure communication means). Close electric exit-valve of accumulator tank (use air-cooling emergency DG).
- Then, open MSR valve & restart cooling (secure communication means).
- Repair & secure access by heavy machineries.
- Prepare to inject sea water into condensate pit.
- Carry in and secure DC power & fuel for a few days to a week.

Prepare LPCI & low-heat shutdown (24 hrs – 1 wk)

Prepare to transfer to core de-pressurization & low-pressure cooling

- Set up low-pressure-cooling lines. Prepare alternative water source (fire pump etc).
- Open/close MSR valve & maintaining 0.7 MPa of core pressure (secure communication means). Prepare alternative sea water source (large volume pump).

Reduce core pressure. Start low-pressure cooling to low-heat shut down.

- Use feed-and-bleed to SG or RHRS to low-heat shutdown.

(Off-site)

- Transport back-up DG/batteries, power panels etc by air. (Have to be compact and highly portable, w/in 5 hrs by on-site DC runs out.)
- Additional supplies and supports for heavy machineries etc. (Secure access).
- Transport extra power supply vehicles, power panels, pumps, fuel etc by air as needed (w/in 24 hrs).

Red= Current safety measures are effective.

Preparation

- Daily trainings. (Quantified efficiency test)
- Secure communication methods.
- Enhance seismic-durability, diversity, and flexibility of external power.
- Diversify emergency DG/DC (principle, location, height etc).
- Prepare protective clothing, masks, dosimeters etc.
- Diversify water source and path.
- Install hydrogen detector.
- Set storage for severe AM at onsite upland (power sources, power panels, pumps, fuel etc.)
- Enforce water protection (breakwater, water stops for building, watertight doors etc.)

Key findings from the simulation in the previous page.

- **Assuming the same accident with Fukushima Dai-ichi reactor-1, safety measures of Ooi reactors 3&4, emergency DG's, high-pressure cooling, manual operation of valve, automatic injection of boric acid, and ultimate heat sink would be effective.**
  - Cooling systems and ultimate heat sink (open air) do NOT require functions near sea side. The heat radiation doesn't include radioactive materials.
  - High pressure cooling system (Turbine-Driven Auxiliary Feed Water Pump) doesn't require any power. 16-days amount of water is stocked already.
  - Valves for high-pressure cooling (Main Steam Relief valve) can be operated manually. They are outside of the containment vessel and easy to access.
  - As cooling goes, boric acid is automatically injected into the core without any power at a set pressure level. (Accumulator tank)
  - 2 air-cooling emergency DG for each reactor are set up far from sea (at 33.3m). Connecting ports are ready to plug in just next to the DG.

- **The activation of air-cooling DG and TD-AFWP must be done as soon as possible after disaster occurs. No failure is allowed.**
  - Right after the reactor scram (before Tsunami, DC is still active), TD-AFWP must be activated (needs DC), and MSR valve (needs air-pressure, or by hand) must be opened (= completion of ultimate heat sink & high-pressure cooling system). These are designed to start automatically during scram.
  - Air-cooling emergency DG must be activated and connected to the panel next to it by hand (= set-up of emergency AC power supply).
  - Portable batteries (easy to carry) for the central control room must be prepared to be plugged in for DC power loss (= secure monitoring).

- **There are No alternatives to DC battery and TD-AFWP. They must not be lost.**
  - There is only one DC battery room (with 2 systems). If it is lost, the essential parameters can not be monitored. Even though the room is located at 15.8m, it is important to enhance its multiplexity and diversity.
  - TD-AFWP (at the bottom floor) is the only means for supplying high-pressure coolant under power loss. Absolute safety measures to secure its functionality are essential. (If air-cooling DG works, two MD-AFWP (Motor-Driven Auxiliary Feed Water Pump) would be available.)

- **As the plant is at the end of peninsula, it is very important to secure the robustness and accessibility of the transportation route to carry in machineries or other necessities from each storage depot. (Enforce off-site supports).**

supports).

A respectable extent of diversification and multiplexing of power source and coolant is taking place. For further enhancement, the following issues would be effective.

- **Sharing of equipments and functions among several reactors.**

* Flexible power source (external power, emergency DG, battery, power plate). (This is being planned).
* Flexible water source (condensate water pit, pure water tank, fire extinguishing water etc).
* Flexible emergency equipments (power supply vehicle etc).
* Setting underground cable for external power supply in mid to long term (for earthquake countermeasures).

- **Enhancement of diversification and multiplexing in seawater intake and discharge route for its geographic advantage of facing the bay.**

* E.g.: Enable water intake from both intake/discharge sides via under-water pumps.
* Secure makeshift resources and machines such as portable booster pump with permanent connection stations.
* Secure makeshift power source panels, power supply vehicles, cables, under-water pumps, booster pumps, bellows plumbing etc.

- **More diversification and multiplexing of Auxiliary Feed Water Pump and DC power source, which are the life lines of the plant.**

* Turbine Driven Auxiliary Feed Water Pump: Water-proof processing as prevention. Preparing standing stocks of back-up systems and equipments as mitigation.
* DC Battery: Same as above. Essential to secure back-up DC power considering the case of power panels being submerged.
* DC Power Source Panel System: Same as above.

(Continued)

- **Is it essential to examine the issues below to prevent hydrogen explosion?**

* It is effective to prepare and train safety measures to reduce hydrogen in the containment vessel with its operation procedure defined, even though it will not attain detonation level according to preliminary calculations.

* It is also the same for the hydrogen explosion in the annulus section in case of H_2 leakage.
(E.g.: What should be done when the motor is disabled?)

- **Diversification and Multiplexing of off-site support. (Must be prepared with operating procedures and practical training).**

* Prepare and train to use the second or third heliport in case the primary heliport (= closer to the ocean than reactor No.1) is lost by Tsunami.

* Secure transportation routes from heliport smoothly. (For heavy machineries to remove rubble, and to strengthen pathways)

- **Ensure living environment such as drinkable water, etc.**

* Some nuclear plants use the seawater desalination unit for drinking water.

* Secure alternative means to avoid any disturbance in plant operation by loss of power or of sea water system, causing degradation of living environment.

- **This case study was conducted only under one assumption of earthquake and tsunami, that is the same level as the one in the Fukushima Dai-ichi. There are various possibilities which can cause Severe Nuclear Accidents, such as Terrorist Attacks, Crash of Jet Airplanes, etc. Verifications under various other assumptions are absolutely necessary.**

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The First Stress Test
by the Nuclear and Industrial Safety Agency
at the Ministry of Economy, Trade and Industry

In this chapter the following 4 points are overviewed on the First Stress Test directed by NISA

- Current situation of the stress test (ST) in Japan
- Current situation of the stress test (ST) in EU
- Issues
- Points to be considered or modified

The following pages will discuss these points.

Stress Tests in Japan: No specific judgmental criteria is defined even though it is the prerequisite for reactivation of the nuclear power plant.

- After implementing various countermeasures in response to the accident in Fukushima, the Nuclear and Industrial Safety Agency (NISA) recognized it is not enough to obtain public acceptance, and it instructed the operation of the comprehensive endurance test (= stress test).

- The Stress Test consists of the Primary Test and the Secondary Test.
  - Primary Test: Prerequisite for judgment of reactivation for reactors undergoing periodic inspection.
  - Secondary Test: Requirement for judgment of continuous operation or halt for all the existing nuclear plants and nuclear-related facilities.

- By December 20, 2011, the test results have been submitted from 7 plants, and 4 power companies, such as for Ooi No. 3 and 4, and Ikata No. 3. NISA is deliberating these results.

- The Nuclear Safety Commission of Japan (NSC) has requested the comprehensive safety test, including assumptions beyond its design concepts, and the report on the assessment method and implementation plan based on the article 25 in Establishment Act of Japan Atomic Energy Commission (AEC), and Nuclear Safety Commission.

- The Stress Test examines mainly the safety allowance against each reactor's design assumptions to an earthquake, tsunami, loss of all AC power source, loss of ultimate heat sink, and combinations of these events.

- No specific judgmental criteria is defined in this test even though it is the prerequisite for reactivation of each nuclear power plant.

Comprehensive Safety Assessment (Stress Test): Summary of primary tests which have been submitted so far (as of the end of December, 2011)

Item	Assessment Index	**Cliff Edge Effect (After Emergency Safety Measure Operations)**						
		Tomari No.1	Ooi No.3	Ooi No.4	Ikata No.3	Genkai No.2	Sendai No.1	Sendai No.2
Earthquake (Reactor)	Comparison with Standard Ground Motion (Ss)	**1.86 Times** **(Power Distribution Board)** **Ss:550gal**	**1.80 Times** **(High-Voltage Switchgear)** **Ss:700gal**	**1.80 Times** **(High-Voltage Switchgear)** **Ss:700gal**	**1.86 Times** **(DC Power Source System)** **Ss:570gal**	**1.75 Times** **(Condensate Water Tank)** **Ss:540gal**	**1.86 Times** **(Low-Voltage Circuit Breakers)** **Ss:540gal**	**1.89 Times** **(Low-Voltage Circuit Breakers)** **Ss:540gal**
Tsunami (Reactor)	Comparison with Supposed Tsunami Height	**1.53 Times** **(Power Distribution Board, etc.)** **Supposed Tsunami Height9.8m**	**4.0 Times** **(Turbine Driven Auxiliary Feed Water Pump)** **Supposed Tsunami Height2.85m**	**4.0 Times** **(Turbine Driven Auxiliary Feed Water Pump)** **Supposed Tsunami Height2.85m**	**4.06 Times** **(Turbine Driven Auxiliary Feed Water Pump)** **Supposed Tsunami Height3.49m**	**6.19 Times** **(Turbine Driven Auxiliary Feed Water Pump)** **Supposed Tsunami Height2.1m**	**4.05 Times** **(Turbine Driven Auxiliary Feed Water Pump)** **Supposed Tsunami Height3.7m**	**4.05 Times** **(Turbine Driven Auxiliary Feed Water Pump)** **Supposed Tsunami Height3.7m**
Superposition of Earthquake and Tsunami	Superposition of 2 Events Above	**Same as Above**	**Same as Above**	**Same as Above**	**Same as Above**	**Same as Above**	**Same as Above**	**Same as Above**
Loss of All AC Power Source (Core)	Cooling Time without Off-Site Support	**Approx.20 Days** **(Fuel for Alternative Power/Water Feeding (Light Oil))**	**Approx.16 Days** **(Fuel for Make-up Water Pump (Gasoline))**	**Approx.16 Days** **(Fuel for Make-up Water Pump (Gasoline))**	**Approx.10.7 Days** **(Fuel for Power Source Car (Heavy Oil))**	**Approx.65 Days** **(Fuel for High-Voltage Generator Car (Heavy Oil))**	**Approx.104 Days** **(Fuel for High-Voltage Generator Car (Heavy Oil))**	**Approx.104 Days** **(Fuel for High-Voltage Generator Car (Heavy Oil))**
Loss of All AC Power Source (Spent Fuel)			**Approx.10 Days** **(Fuel for Make-up Pit Water Pump (Gasoline))**	**Approx.10 Days** **(Fuel for Make-up Pit Water Pump (Gasoline))**	**Approx.8.2 Days** **(Fuel for Fire-Extinguishing Vehicle (Light Oil))**	**Approx.65 Days** **(Generator Fuel for Makeshift Pump (Gasoline and Heavy Oil))**	**Approx.104 Days** **(Generator Fuel for Makeshift Pump (Heavy Oil))**	**Approx.104 Days** **(Generator Fuel for Makeshift Pump (Heavy Oil))**
Loss of Ultimate Heat Sink (Core)		**Approx.142 Days** **(Fuel for Alternative Feed Water (Light Oil))**	**Approx.16 Days** **(Fuel for Make-up Water Pump (Gasoline))**	**Approx.16 Days** **(Fuel for Make-up Water Pump (Gasoline))**	**Not Causing Fuel Rod Damage**	**Approx.378 Days** **(Generator Fuel for Makeshift Pump (Gasoline and Heavy Oil))**	**Approx.939 Days** **(Generator Fuel for Makeshift Pump (Heavy Oil))**	**Approx.939 Days** **(Generator Fuel for Makeshift Pump (Heavy Oil))**
Loss of Ultimate Heat Sink (Spent Fuel)			**Approx.10 Days** **(Fuel for Make-up Pit Water Pump (Gasoline))**	**Approx.10 Days** **(Fuel for Make-up Pit Water Pump (Gasoline))**	**Approx.28 Days** **(Fuel for Sea Water Make-up Pump to Plain Water Tank (Gasoline))**			

Current Stress Test in EU: Stress tests in EU consist of two layers, EU-common and nation specific. Neither are requirements for plant reactivation. The purposes are to recognize strengths and weaknesses of each plant and to develop safety measures.

- On March 25, 2011, responding to the Fukushima Dai-ichi Nuclear Power Plant accident, the European Council requested the European Commission (EC) and the European Nuclear Safety Regulatory Group (ENSREG) to define the stress test specifications to retest the safety allowance of the nuclear power plants.

- Based on the specifications, the electric power providers in EU will report the test result to the regulatory authorities in each country. Each country will summarize them and report to the EC which in turn will report to the European Council. After all the phased reports, the final report to the European Council will be submitted in June, 2012.

- All regulatory authorities across all countries are preparing the results to the EC by December 31, 2011, to recognize the safety allowance of the plant.

- With the earthquake and tsunami set as initiating events, the test assesses the cliff-edge effects of subsequent events such as the loss of external power, the loss of ultimate heat sink, and events combined. Based on the test results, the EU will develop and implement further countermeasures.

- The differences from the Japanese Stress Tests are: (1) initiating events include not tsunami but flood, and (2) the purpose is not a precondition for plant reactivation but the development of further safety measures.

- Stress Tests in the EU consist of two layers, EU-common tests and and tests in each nation. The former is applies commonly in all EU nations and all the reports are made available to the public. On the other hand, the latter includes not only safety measures but also security, and is not required to submit the results to the European Council, or to make it available to the public.

Issues of Stress Tests in Japan: Current stress test does not consider uncertain elements such as a human error, or inefficient performance caused by lack of training.

● **As the stress test applies the deterministic approach, uncertainties such as human errors are not considered.**

- Human error: Effectiveness and reliability of manual operations such as to connect cables or open valves.
- Proficiency of operators on technology and accident management gained through training. (Can staff operate the systems appropriately?)
- Risk of simultaneous accidents in multiple plants.
- Effectiveness of supports and safety measures from off-sites.

● **In other words, doesn't the current stress test stand on the following unspoken assumptions?**

- Examples-1：Once they carry in the cables, they can always connect them by hands.
- 2：Once installed, devices which require complicated operations will function, regardless of the proficiencies of operating staff.
- 3：Once implemented, safety measures will always work equally whether an accident occurs in a single plant or several plants simultaneously.
- 4：Effectiveness of off-site support does not affect the safety allowance and cliff-edge of the plant.

(On the other hand, if a 10-meter waterproof door is installed, a complete loss of function due to flooding will occur once the level of water goes even slightly beyond 10m.)

● **The stress test is effective for technical assessment such as the safety margin of the plants and functions to enhance or improve. However, it does not cover all the issues necessary to consider for the prevention of severe accidents as Fukushima Dai-ichi.**

In order to secure “enough power and core cooling under any severe circumstance”, it is necessary to examine the following issues at the corporate, government and municipality levels.

- Can staff necessary for accident management (both in plant and headquarters) be assembled within the specified time even on holidays or at night?
- Can staff respond to an accident in sufficient numbers and in each professional role even if accidents happen simultaneously in several or all plants?
- For securement of power sources, are they prepared to protect and supply enough fuel no matter how severe the accident is?
- For securement of the ultimate heat sink, are they prepared to protect and supply enough fuel no matter how severe the accident is?
- Can they recover or prepare power source as well as ultimate heat sink within the specified time?
- Are periodic trainings conducted to achieve the agenda above, and managed in PDCA cycle method for further enhancement?
- Can government and municipalities work together to establish emergency organization to procure and transport necessary supplies to the accident site within the specified time limit?

Conclusion

Conclusion

- **The biggest lesson learned from the Fukushima Dai-ichi Nuclear disaster is <u>not that we had underestimated the risk of Tsunami, but that we had lacked the design philosophy stating "we have to prevent severe nuclear accidents</u> no matter how extreme the circumstances". However high we set our assumptions, there will always be a possibility of an event that exceeds them.**

- **Having clarified what happened in Fukushima Dai-ichi, we should stop relying so much on "Probability Theory" and "assumptions on the scale of events", such as for the height of the tsunami when designing the safety measures. This is especially so concerning an accident that causes irreparable damage to society or our daily lives.**

- **In order to prevent a disaster like Fukushima Dai-ichi from ever happening again, we should redefine the design philosophy and fundamental safety principle of nuclear power plants to: "Power sources and cooling functions have to be secured under any severe circumstance". In other words, "severe accidents must be prevented no matter how severe the event that occurs". Any nuclear plant which can not fulfill this condition should not be reactivated.**

- **We have to immediately examine the "diversity and multiplicity" (= multiplicity of safety measures using different principles) of all of the nuclear plants. Based on that, we should establish three stages of accident management, "During Normal Use", "During Emergency", and "During Extreme Emergency".**
- For an Extreme Emergency, accident management should include off-site support by not only the electric power providers but also the central government and local municipalities.
- We should establish a real-time network system which enables all of the stakeholders above to share information and co-conduct decision-making. The network must be available immediately after entering Accident Management (AM) mode.

Conclusion

- **The direct cause of the nuclear accident in Fukushima Dai-ichi is the basic design concept created by the Nuclear Safety Commission of Japan, that states, "It is not necessary to consider the case of long-term loss of all AC power sources". When was it decided, and how was it accepted and allowed to be applied for decades? Its responsible stakeholders, the mechanism of decision making and governance, its cause and prevention should be uncovered.**

- **Staff in the field (such as the nuclear plants, power providers, and manufacturers) could have made greater efforts to enhance the safety measures before March 11. Since they "assumed" too much regarding the earthquake and tsunami, they could not have had a realistic grasp of what a "Real Emergency" is. Of the several cases introduced previously in this report, this is one of the most regrettable.**

- All outside uptake power supplies went under water. => They should have been set at higher positions, and some should have been waterproofed.

- At Fukushima Dai-ichi, even though reactor No.1 had a different valve system in IC/RCIC (fail-close) from the rest of the reactors (No.2 – 6, fail-open), staff in the plant believed that the IC of reactor No.1 would have been working (with its internal valves opened). Therefore, they might have prioritized the rescue of reactor No.2. => They should have unified the system of all reactors as 'fail-open'.

- All of the water-cooling emergency diesel generators (DG) were of one kind and in one place. They were too focused on multiplicity. => They should have diversified.

Conclusion

- **Including the originator, the EU, there is no nation which utilizes computer simulation-type stress tests as a precondition for restarting a nuclear power plant. The Japanese Government should reconsider using it as one of its technological verifications.**

- Stress Testing is effective for identifying technical items to be improved in a plant.
- However, unpredictable elements such as human error, proficiency level from training, simultaneous accidents in several plants and support from off-site, are out of the scope of its simulation algorithm. (It applies a deterministic approach, inputs of which only consist of on-site measurements in a single plant.)

- **The currently implemented First Stress Test includes almost all of the emergency safety measures directed by the government since March 11, 2011. Therefore, they are highly likely to get almost exactly the same results in the Second Stress Test. Is there any essential meaning in conducting the Second Stress Test after the first test? The government should integrate the second test into the first one.**

- **Lessons-learned from this research are applicable universally, not only for BWR plants but also PWR plants.**

- **There are many nuclear plants with a similar design philosophy, technical specifications, and accident management measures globally. In order to prevent an accident like the one in Fukushima Dai-ichi from ever happening again, the government should share the facts and lessons-learned in this report with the rest of the world as quickly and accurately as possible.**

Conclusion

- **Related parties, such as various local governments, are now waiting for the so-called "Official" research reports currently ongoing, one by the central government and the other by the national diet. There are an increasing number of voices saying "Without official reports, we can not explain the details of this accident well enough to local residents based on lessons-learned in the Fukushima Dai-ichi accident," or "We want to postpone any discussion or decision on whether the nuclear power plant in our municipality should be reactivated until the official reports are submitted." By Spring, 2012, the central government should make a decision on de/reactivation of the nuclear power plants, along with plans for accident prevention and policies for future energy supply.**

- If the situation above continues, there will be a greater possibility of procrastination in even starting discussions until Spring (or Summer), 2012, by which time the official research reports and Secondary Stress Test will be produced.
- If public opinion recognizes those official reports as insufficient, the decision-making will be postponed even longer.
- In this case, the risk to life and to the domestic economy will increase further.

- **There is sufficient accident data already reported which includes enough analyses of the facts, causes, and safety measures. What must be done now is to "explain, publicize, and take actions" based on these findings.**

Appendix

Abbreviations of Nuclear Power Plant Terminology

AM: Accident Management

AO Valve: Air-Operated Valve

BWR: Boiling Water Reactor

CRD: Control Rod Drive

CUW：Reactor Water Cleanup System

CCSW: Containment Cooling Service Water System

CS: Core Spray System

D/G，DG：Diesel Generator

DGSW：Diesel Generator Sea Water System

D/W：Dry-Well

DS Pit：Dryer Separator Pit

D/D FP：Diesel/Driven Fire Protection Pump

ECCS：Emergency Core Cooling System

EECW：Emergency Equipment Cooling Water System

FCS: Flammability Control System

FDW: Reactor Feed Water System

FPC: Fuel Pool Cooling and Filtering System

FPMUW: Fuel Pool Make-up Water System

Gal: CGS unit of acceleration

HPCI: High Pressure Coolant Injection System

HPCP: High Pressure Condensate Pump

HPCS: High Pressure Core Spray System

HPCSS: HPCS D/G Sea Water System

HPCW: HPCS D/G Cooling Water System

HPSW: HPCS D/G Sea Water System

HVE: Heating Ventilating Exhaust System

IAEA: International Atomic Energy Agency

IC: Isolation Condenser

INES: International Nuclear Event Scale

kPa abs: kilo Pascal Absolute Pressure

LPCS: Low Pressure Coolant Injection System

M/D RFP: Motor Driven Reactor Feed Water Pump

M/C: Metal-Clad Switch Gear

MO Valve: Motor Operated Valve

MUWP: Make-Up Water System (Purified)

MUWC: Make-Up Water System (Condensate)

MSIV: Main Steam Isolation Valve

P/C: Power Center

PCV: Primary Containment Vessel

PWR: Pressurized Water Reactor

R/B: Reactor Building

RCIC: Reactor Core Isolation Cooling System

RCW: Reactor Building Closed Water System

RD, R/D: Rupture Disk

RHR: Residual Heat Removal System

RHRC: RHR Cooling Water System

RHR LPCI mode: RHR Low Pressure Cooling Injection Mode

RHRS: RH Sea Water System

RPV: Reactor Pressure Vessel

RSW: Reactor Building Closed Cooling Sea Water System

RW/B: Rad-Waste Building

SBO: Station Black out

S/C: Suppression Chamber

SFP: Spent Fuel Pool

SGTS: Stand-by Gas Treatment System

SHC Mode: Shut Down Cooling Mode

SLC: Stand-By Liquid Control System

SRV: Safety Relief Valve

Ss: Basic earthquake ground motion

TAF: Top of Active Fuel

T/B: Turbine Building

TCW: Turbine Building Closed Cooling Water System

W/W: Wet Well

Outer: Support buildings surrounding nuclear power plant for auxiliary machines such as DG and power panels.

Ultimate Heat Sink: Substances releasing heat ultimately such as the ocean or the open air, in order to remove decay heat in the core.

Self Air Set: Air mask to prevent internal exposure during severe work in high dosage level. A set of equipment with oxygen tank.

Electric Penetration: Areas penetrating through walls for routing electric cables to the nuclear reactor containment.

Sloshing: Spilling and splashing of pooled water caused by long period oscillation such as earthquake.

Bag Filter: Filter to eliminate radioactive particulate matter.

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- Regarding Comprehensive Safety Assessment on Ooi Nuclear Power Plant No.4 (November 17, 2011)
- Regarding Operation of Safety Measures of Software Side Considering the Accidents in Fukushima Dai-ichi Nuclear Power Plant (November 28, 2011)

Note) The translation of this report has been done by a limited number of staff and within a limited period of time. If there are any discrepancies between this translation and the original Japanese report, please refer to the Japanese report for clarifications.

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