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

Interim Report Summary

BWR

- Team H2O Project -

Revised on December, 21st, 2011

The biggest lesson is not the underestimation of the tsunami risk, but the lack of design philosophy to prevent any grave accidents from any threats.

Extracted from **Nuclear Safety Commission of Japan's Design Guidelines** (Supervised by Cabinet Office Nuclear Safety Commission Secretariat)

Part 1 Safety Review Guideline No 27: (Design) In case of power loss:

- **There is <u>no need to consider</u> 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 is deemed highly reliable**, then **there is <u>no need to take into account</u> any scenario of a complete AC power blackout** in the design of the plant.

Extracted from Additional **Report of Japanese Government to IAEA** (Second Report) September 2011 Nuclear Disaster Response Headquarters

- (First group of lessons learned) The tsunami damage to the plant which is **the cause of the accident,** occurred due to an **<u>underestimation</u> of the height and frequency of the tidal waves**, and that countermeasures against large scale tsunami impacts were insufficient.
- The Central Disaster Prevention Council, in regards to the **prevention plan for tsunami disaster**, proposed fundamental ideas such as to **pursue countermeasures against tsunami by <u>anticipating two categories</u>, the maximum size and the frequent size**.
  The Nuclear and Industrial Safety Agency started deliberating on design standards for <u>anticipating appropriate height</u> and taking into account the period and frequency of recurrence.

United Nations' comment on the Fukushima Dai-ichi nuclear accident (Mainichi Newspaper website, September 15, 2011)

- On September 14th, the UN presented a Summary Report on Nuclear Safety-Security regarding the impact of the Fukushima Dai-ichi Nuclear Plant Accident. The UN criticized Japan for being **<u>"too modest" in its assumptions of such a disaster and severe accidents,</u>** and commented that they were troubled by the safety standards and international emergency crisis response, which were at that point recognized as the international standard.
- In the report, it stated that "**Japan underestimated the possible threats**. And **<u>all nuclear power plants globally must review their risk assessments against severe accidents</u>**, and that risk of nuclear power plant accidents must be eliminated through experience and utilization of the latest technologies.

No matter how high we set the estimation, there will always be a possibility of an event that exceeds it.

Safety design for nuclear reactors in the world had shared common design philosophy – No fundamental question against it had ever been raised in the past.

- **72 Safety Regulations Defined by the United States Atomic Energy Commission**

  - Later became the foundation for NRC regulation.
  - Later adopted by other G5 countries.
  - Products introduced to Japan through full-turnkey projects.

- **Probability approach applied by Prof. Rasmussen et al. at MIT**

  - Severe accidents and natural phenomena with probability of occurrence lower than a specific value, have little effect and risk to the safety of the nuclear reactor and are insignificant enough to ignore.

- **No countermeasure exists for events out of scope.**

  - Large scale tsunami beyond expectation had hit.
  - Complete power loss was not assumed.
  - Almost all safety devices and ECCS's assumed that power supply is available.

- **Probability theory should not be brought to use on events that have an enormous impact to society.**

  - Even if the probability is insignificantly low, if the impact is enormous, the risk is also enormous.
  - Probability % (miniscule) × Impact (∞) = ∞

That is why we need to re-examine the design philosophy – the problem does not lay only in the design conditions such as the 'estimation of scale' or the 'height of the tsunami'.

Specifically, it's important for us to humbly accept the following two points.

1. The design philosophy itself was flawed.

- After what happened in the Fukushima Dai-ichi Plant, we should stop debating safety issues focusing on "assumptions on the scale of events" such as the height of the tsunami or the magnitude of the earthquake.
- The core design philosophy should be "to maintain power supply and cooling functions on the reactor core, no matter what happens, and how to achieve this."

2. The last strong hold "primary containment vessel myth" has been busted.

- Until now, there was a belief that "even in an unforeseen event to the reactor core, the containment vessel will contain the radioactive material and will be guaranteed to prevent it from leaking" (= containment vessel myth).
- However, in Fukushima Dai-ichi the core melted down and the molten nuclear fuel rods accumulated at the bottom of the pressure vessel. Then the molten fuel breached through the base of the pressure vessel, and melted through the bottom of the containment vessel, resulting in the leakage of a large amount of radioactively contaminated water and gas outside the containment vessel.
- Furthermore, we have to say that all the operating reactors in Fukushima Dai-ichi, reactor No.1, No.2, and No.3, suffered meltdown and significant damage to their primary containment vessels.
- This means that, in Fukushima Dai-ichi, the containment vessel failed as the "last line of defense."

The biggest concern in the design (recriticality and LOCA) did NOT occur. Instead, the reactor fell into an unexpected loop after meltdown, resulting in massive hydrogen explosion and leakage of radiation to the external environment.

- **The biggest concern in the design of the nuclear reactor was recriticality and pipeline rupture (LOCA: Loss of Coolant Accident).**
  - It was feared that a breach of the molten nuclear fuel rods into the containment vessel would result in power excursion followed by a huge explosion, spreading radiation across the environment.
  - It was also feared that an event, such as a major earthquake, would cause a pipeline rupture to the core reactor's coolant circulation loop.

- **In order to prevent this, the nuclear reactors were designed to "shutdown", "cool", and "contain".**
  - In case of emergency, the nuclear reactor will be scrammed (emergency shutdown).
  - After the scram, decay heat removal will be constantly implemented to achieve cold shutdown (cool).
  - Even if cold shutdown is failed, the containment vessel will prevent radioactive material from leaking outside with its 2 meter-thick concrete walls (contain).

- **All reactors that suffered meltdown in Fukushima Dai-ichi (reactors 1-3) did not result in nuclear excursion. Why?**
  - In the process of the meltdown, the boron carbide of the control rods, inserted during the scram, melted and mixed into the fuel. This alleviated the nuclear reaction. Furthermore, the fuel rods that melted through the reactor fell and spread out at the bottom of the wide container. Our theory is that this condition also contributed to the prevention of recriticality.

- **However, the meltdown caused a massive amount of hydrogen and fission gas to leak from the containment vessel out into the reactor building, resulting in a hydrogen explosion. This event was not considered in the design of containment vessel.**

- **Therefore, the containment vessel was not able to 'contain' hydrogen and radiation from leaking out.**

In Fukushima Dai-ichi reactor 1, not even one of the emergency devices worked during the incident (which mostly can be said also with reactors 2, 3 and 4).

Countermeasures in design

- **Major earthquake**

⇒ **Scram** (Emergency shutdown). **All scrammed successfully** in Fukushima Dai-ichi, Dai-ni, Onagawa, Tokai Dai-ni.

- **Countermeasures to prevent accidents**
  - Backup power (emergency generator, batteries)
  - Backup coolant
- **Countermeasures to mitigate accidents**
  - Emergency Core Cooling System (IC, RCIC, HPCI, boron injection, etc.).
  - Containment vessel vent.
- **In case of core meltdown (Last line of defense)**
  - Containment vessel (2m thick concrete, and 3cm thick metal plate. (100% guaranteed containment in any situation.)

		Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5 & 6
Power	External power supply	× All 6 lines lost from the earthquake				
Power	Emergency generator	× All lost from the tsunami				△ Only 1 / 5 good
Power	DC power supply	× All lost from the tsunami		○ 2 / 2 good	× All lost from the tsunami	○ 4 / 4 good
Power	Power supply vehicle	× Only unit lost in explosion during an attempt to connect it to No.1				○ Used to run sea water pump
High Pressure Cooling ECCS, etc	HPCI / HPCS	× Failed to function		× After DC power depleted	– Coolant was not in use	
High Pressure Cooling ECCS, etc	IC / RCIC	× Failed after operating (Reactor 2, failed after 3 days)		× After DC power depleted	– Coolant was not in use	
High Pressure Cooling ECCS, etc	SLC	× Due to power loss				× Reactor 5 ○ Reactor 6
High Pressure Cooling ECCS, etc	CRD	× Due to power loss				× Reactor 5 ○ Reactor 6
Low Pressure Cooling ECCS, etc	FP	× FP pump did not work			× Power loss	× Reactor 5 ○ Reactor 6
Low Pressure Cooling ECCS, etc	MUWC / MUWP	× Power supply and motor flooded				○ Power supplied
Low Pressure Cooling saline pump	CCSW / RSW / RHRS etc.	× Power supply and motors flooded by the tsunami				△ RHT type partially functioning. Later repaired.

None functioned

None functioned

None functioned

All leaked

- **Precondition: Power supply available**
- **Design: Hydrogen explosion out of scope**

Reactor No.1, 3, and 4 = Hydrogen explosion

No.2 = Damaged containment vessel

The reactor went into an unexpected loop (not part of the design), which probability theory neglected, making itself incapable of preventing the meltdown and hydrogen explosion.

Safety design of both the power supply and ultimate heat-sink was too focused on multiplicity, and lacked diversity.

In Fukushima Dai-ichi

- Reactor No. 1
  - All of the two DC power sources (batteries) were placed in the basement of the turbine building.
  - 2 emergency generators (DG) were:
    - both placed in the basement of the turbine building.
    - both seawater cooling type, so their cooling systems were all placed at the sea side.
- Similar (sets of) safety measures were implemented at the other reactors as well.

- **Placed in the same area**
- **Equipment with same specifications**
- **Operated from the same power source**
- **The same above applies to other plants**

- **All failed to function for the "same reason".**
- **Without diversification, it will be difficult to eliminate risks, even if the number of measures are increased.**

The fundamental safety philosophy should be that "power, cooling function, and water sources must be secured in any situation". The safety principles should have 3 layers, normal, emergency, and extreme emergency.

Example

Normal

- Power
  - External power supply
  - Backup generator (DG)
  - DC power supply (battery)
- Cooling function
  - High-pressure coolant system (RCIC, HPCI etc.)
  - Ventilation
  - Low-pressure coolant system (RHR etc.)

Emergency

- Secure water and power by creating seawater intake tunnel, and connecting it to a vertical pipeline from a power hub set on an elevated area (see page 9).
- In case the regular measures fail, on-site emergency power and cooling systems work.
  - Backup battery
  - Power supply vehicle (AC& DC)
  - Emergency DG vehicle
  - Cable, Power panel, etc.
  - Water pump, etc.
- Executed by the electric power company.

Extreme Emergency

- Supply power from off-site by helicopters etc.
- Supply water from a nearby water source such as a river, lake, pond, etc.
- Collaboration by different parties (power company, government, and Self Defense Forces, etc.)
  - Secure access route to the plant, etc.

Diversity and multiplicity

- Countermeasures with different principles (diversity)
- Increase number of countermeasures (multiplicity)
- Hot standby and cold standby (Speed)
- Regular / Backup (role)
- On-site and off-site (location)
- Electric power company and its alliance with government (Main responsibility)

Can use computer simulation ↔ Difficult to simulate — Characteristic

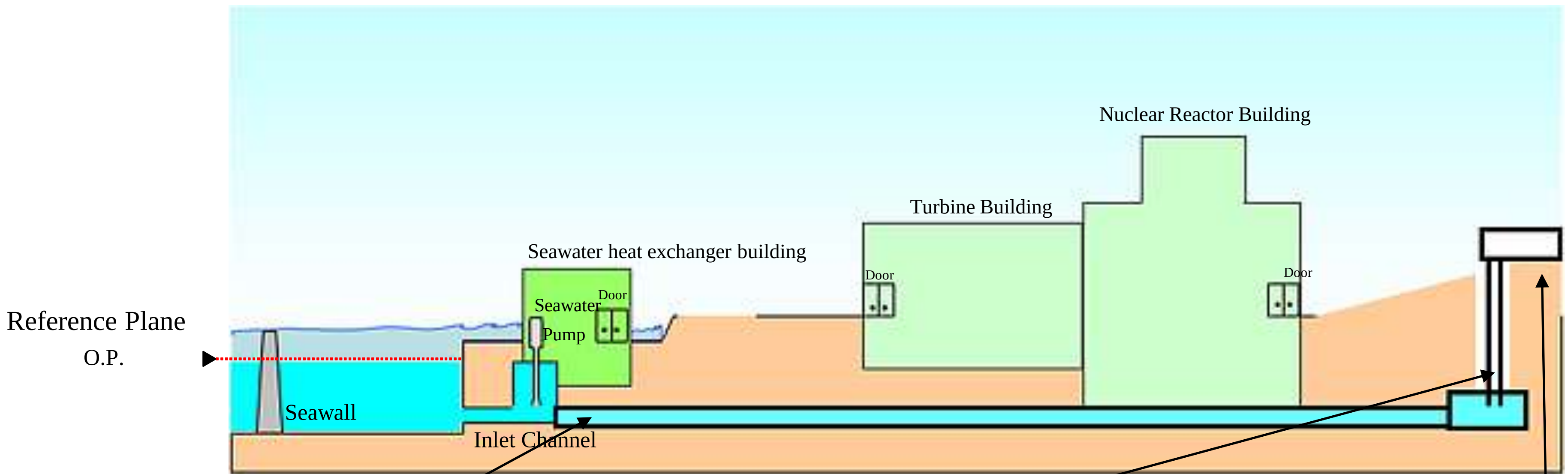
Hot standby ↔ Cold standby (on-site) ↔ Cold standby (off-site) — Speed

Built-in as permanent system ↔ Ready to be plugged in (on-site) ↔ Ready to be plugged in (off-site) — Built-in or not

On-site ↔ Off-site — Location

Power company ↔ Power company + Government, etc. — Main responsibility

Example of emergency countermeasure: Create seawater intake tunnel leading to the mountain for sufficient elevation. Plug in on-site emergency pumps and batteries to provide cooling function.



- Create a tunnel to draw in seawater.
- Build a vertical pipeline for drawing coolant water to a sufficiently high level.
- Connect pump, power hub, and power in case of emergency

If required, transport necessary equipment (power sources, pumps, etc.), by helicopter to the inlet (in case of extreme emergency)

Lessons learned from Fukushima Dai-ichi: Events overwhelmingly beyond the design philosophy had occurred.

- **Ordeals far beyond the design philosophy of the nuclear reactor**
  - Long-term power outage (AC&DC).
  - Without the cooling system, the core reactor started meltdown within an extremely short period of time.
  - Zirconium oxidation caused hydrogen buildup.
  - No system to vent the hydrogen resulted in a massive explosion.

- **None of the emergency safety devices functioned (all due to prolonged power loss)**
  - IC, ECCS, boric acid insertion, emergency gas treatment.

- **Even with such a strong earthquake and tsunami, cold-shutdown could have been achieved if just one emergency power supply was secured**
  - Fukushima Dai-ichi Reactors 5 and 6 (only one backup generator for the cooling system was working)
  - Fukushima Dai-ni Reactors 1 – 4 (2 units for Reactor 3, and 1 unit backup generator for Reactor 4 were working)

- **Major events that hindered recovery action on site, or significantly damaged functions of the reactor**
  - Critical devices were stored in the basements and completely flooded.
    - ‥ Emergency generators (AC)
    - ‥ Batteries (DC)
  - Cooling system pumps and motors at the shoreline were damaged or submerged by the tsunami.
  - Unable to secure coolant for the water cooling emergency generators.
  - Unable to control ventilation from the outside.
  - Power panels for connecting external power were flooded.
  - Difficulty in connecting power vehicles to the panels, most of which were submerged and not functioning.

Ordeal far beyond the design philosophy of the nuclear reactor – Events totally unexpected in the original design, or events expected but on an unforeseeable scale have occurred.

Crucial Events at Fukushima Dai-ichi No. 1 – 4	Design Philosophy	Reality	Implications
Prolonged outage of all DC and AC power	• Even if station-blackout occurs, power can be quickly restored before causing any serious problems. • The emergency DG can be used as backup until external power is restored. • DC power will last for at least 8 hours. • Even if DC power drains down, it can be extended by recharging from AC power source.	• External AC power supply and emergency DG were not restored before the hydrogen explosion. • Almost all DC power was submerged by the tsunami. • The flooded DC batteries were un-rechargeable.	**▪ AC power shortage lasted longer than what was estimated in the design.** **▪ Instant loss of all DC power supply from the flood was not expected.**
With complete loss of cooling functions, core meltdown occurred within a very short period of time.	• The core reactor's high pressure cooling function is run by DC power. • DC power will not drain right away. • Thus, even if station-blackout occurs, the reactor's water level, temperature, and pressure can be controlled with the high pressure cooling system until AC power is restored.	• DC power supply drained instantly, and the high pressure cooling system stopped working simultaneously (Reactor 1). • Water level of the nuclear reactor dropped, and core meltdown occurred in a very short time. • Although the timing of the fuel damage was predicted, power and pumps were not restored in time.	**▪ Loss of power and cooling function lasted longer than anticipated in the design.** **▪ No manual to restore power and cooling function under harsh conditions, such as in complete darkness and amid rubble.**
Zirconium oxidation built up massive hydrogen.	• Hydrogen can be brought down below the inflammable level by injecting nitrogen in the containment vessel and activating the flammability control system. • Radioactive materials can be contained within the vessel even while operating ventilation.	• Core damage caused hydrogen buildup. • Hydrogen leaked into the containment vessel through the Safety Relief Valve (SRV). • Increased pressure and temperature in the containment vessel caused the hydrogen to leak into the reactor building through the vent line, and accumulated in the upper floor. Flammability control system did not work. • The hydrogen level reached the combustion threshold and resulted in a massive explosion. • On-site personnel were not aware of the risks of hydrogen explosion.	**▪ Hydrogen leak to the reactor building and explosion were not considered in the design.** **▪ Thus, no hydrogen detection system in the building.** **▪ No system to release the hydrogen outside.** **▪ No manual to deal with this type of hydrogen explosion.**
No system to release the hydrogen, which resulted in a massive explosion.	• Therefore, hydrogen will not leak into the reactor building nor accumulate. If ever there is a leak, flammability control system can be applied. • This prevents hydrogen explosion caused by leak to the reactor building.		

Long-term power outage (DC&AC) 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 coolant 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.

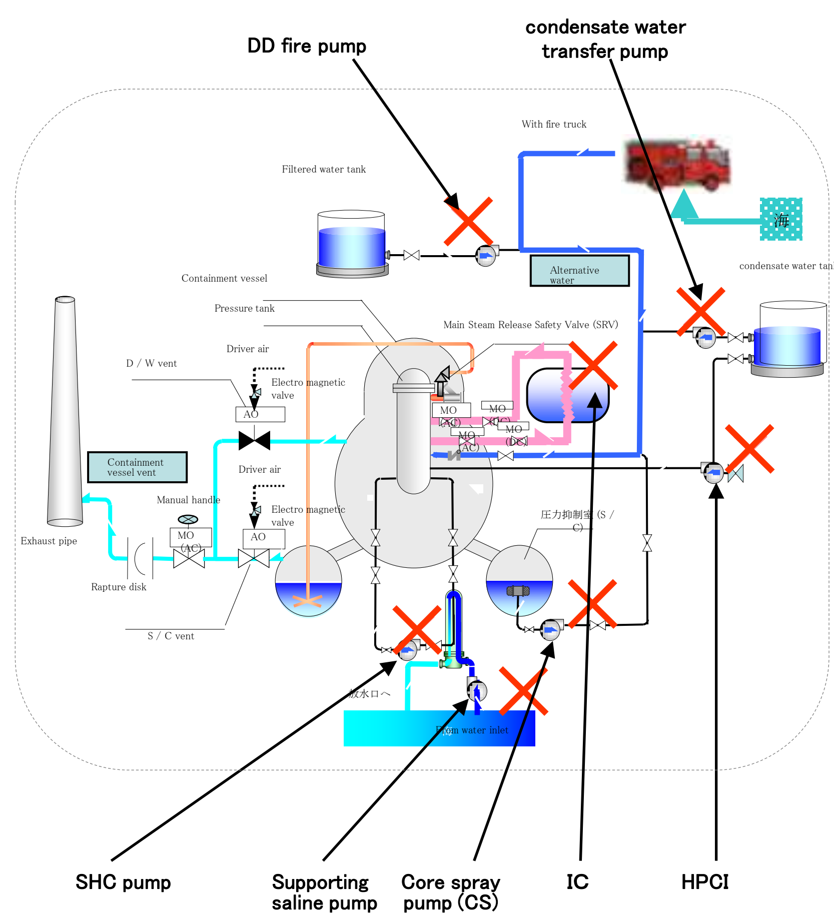
Loss of cooling system and occurrence of core meltdown

		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	○
High Pressure Cooling	IC / RCIC	× Worked but later malfunctioned (Reactor 2: 3 days after)		× After DC power drained	– In cold shutdown		○	○ (to be verified)	
High Pressure Cooling	SLC System	× Due to power loss				× Rctr 5 ○Rctr 6	○	○ (to be verified)	
High Pressure Cooling	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)	
Low Pressure Cooling	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.

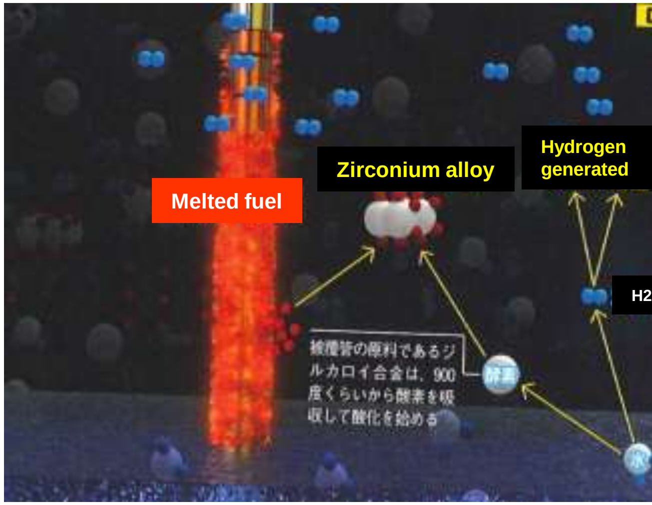
Fukushima Dai-ichi Reactor 1: Total loss of cooling function



- **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.**

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)

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

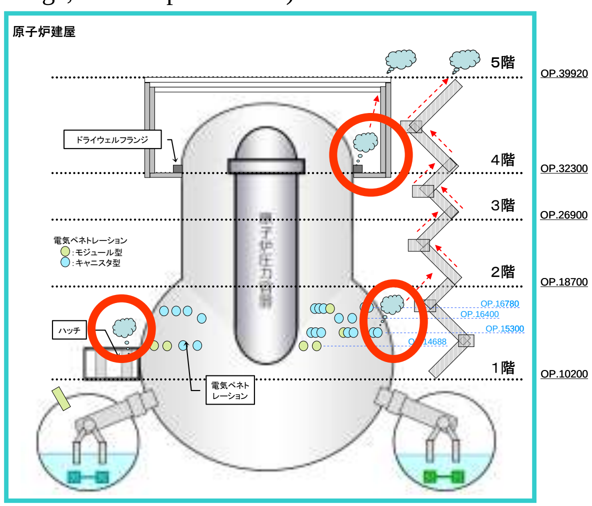
Reactor No. 3 (East side)

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

Reactor No. 4 (East side)

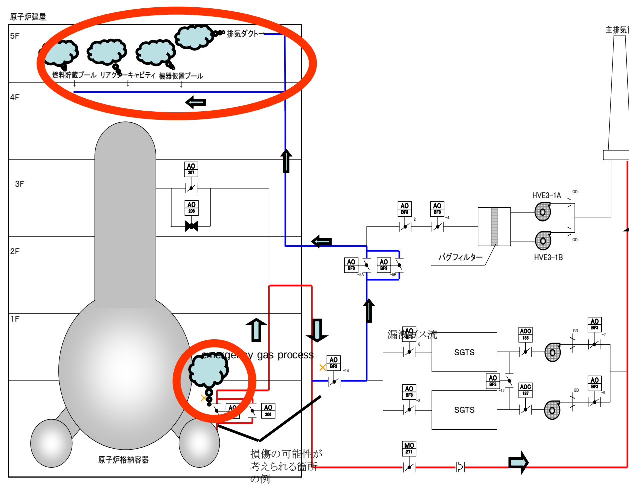
Hydrogen built up in the 5th & partially in the 4th, floor (east west)

- 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).

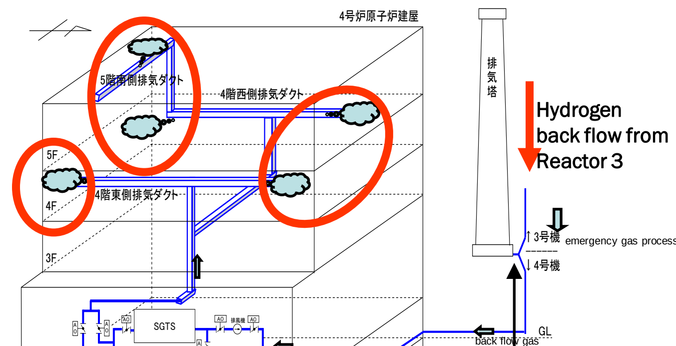


< Leak path from containment vessel (estimated) >

- 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.



- 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.



Extremely Confidential

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)

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

(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)
External AC power	×	×	×	×	×	×
DC power (A),(B)	×	×	○(2 systems)	×	○(2 systems)	○(2 systems)
Emergency DG	×	×	×	×	×	○(1/3 units)
Sea water system	×	×	×	×	×	×
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)
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)
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)
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)	
2011/3/15		Pressure in containment vessel S/C indicated 0MPa (abs) (6:00-6:10)		Hydrogen explosion (6:12)		
2011/3/16						
2011/3/17						
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)

Form	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
External AC power	○(1/4 lines)	○(1/4 lines)	○(1/4 lines)	○(1/4 lines)
DC power (A),(B)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)
Emergency DG	×	×	○(2/3 units)	○(1/3 units)
Sea water system	×	×	○(2/3 systems)	○(1/3 systems)
2011/3/11	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)
2011/3/12	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)
2011/3/13	RHRS, RHRC pump activated (incoming power from makeshift cable 20:17/21:03)			
2011/3/14	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)
2011/3/15				Cold shutdown (7:15)

Form	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	○(1/5 lines)	○(1/5 lines)	○(1/5 lines)	×
DC power (A),(B)	○(2 systems)	○(2 systems)	○(2 systems)	○(2 systems)
Emergency DG	○(2/2 units)	○(1/3 units)	○(3/3 units)	○(2/3 units)
Sea water system	○(2/2 systems)	○(1/3 systems)	○(3/3 systems)	○(2/3 systems)
2011/3/11	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	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				Supplemental external power recovered (19:37)
2011/3/14				RHR pump activated (S/C pool cooling begun 3:50) RHR pump activated (Shutdown cooling mode 23:43)
2011/3/15				Cold shutdown (0:40)
2011/3/16				Switched to normal external power (15:47)

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)	×(※[illegible])	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)						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-load 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	○

(Legend)○: Working ×: Malfunctioned

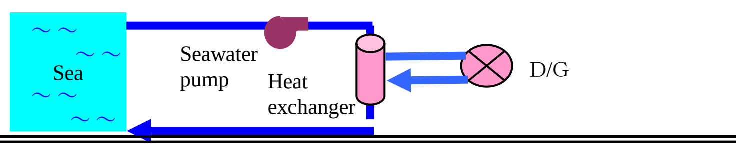
*1 Power panel malfunction from flood

*2 Malfunction from loss of cooling system

Emergency diesel generators at Fukushima Dai-ichi

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

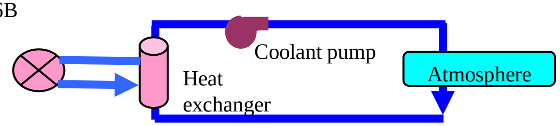
Reactor 1A・B, Reactor 2A, Reactor 3A・B, Reactor 4A, Reactor 5A&B, Reactor 6A&H



All malfunctioned from tsunami

Air cooling type D/G (3 units)

Reactor 2B, Reactor 4B, Reactor 6B

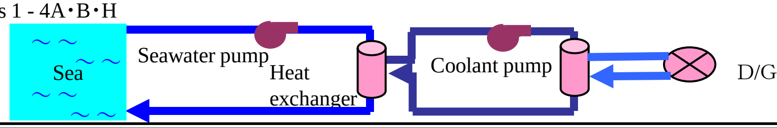


Only reactor 6 was working

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 type 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

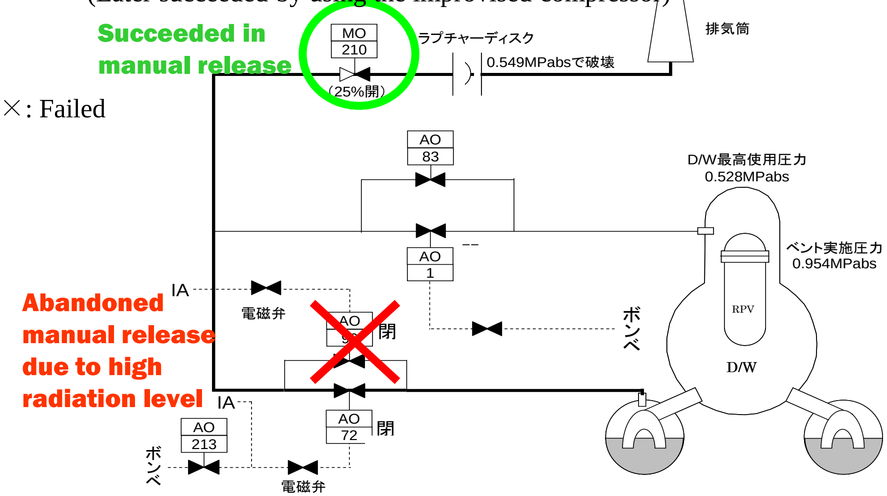
- Was not able to operate the ventilation appropriately. On top of power outage, multiple obstacles such as darkness, transmission problems, parameter loss, frequent aftershocks, increasing radiation, rubble, etc., made it impossible. Manual operation of ventilation was also extremely difficult.
- As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



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 Electrical panel	Usability	Unit 2 Electrical panel	Usability	Unit 3 Electrical panel	Usability	Unit 4 Electrical panel	Usability	Unit 5 Electrical panel	Usability	Unit 6 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 Electrical panel	Usability	Unit 2 Electrical panel	Usability	Unit 3 Electrical panel	Usability	Unit 4 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)							

Information on DC power of system-H was omitted.

Onagawa (Tohoku Electric Power Co)

		Unit 1 Electrical panel	Usability	Unit 2 Electrical panel	Usability	Unit 3 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	○
	Normal	P/C 2A	×
		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

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 to, 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.

Summary of countermeasures - 1

Power Supply

Cooling function

Control Room function

Ventilation function

Prevention against hydrogen explosion

Disaster and accident manual/infrastructure

Specific measures/ Guidelines

Secure power (Without power supplies, cooling function to the reactor will instantly stop)

Secure external AC power supply

- Ensure water seal and pressure resistance, or place in elevated areas.
- Improve earthquake resistance of external power supply and multiplicity of power supply routes. Allow versatility of power within the wider region.

Secure emergency diesel generator (DG)

- Ensure water seal and pressure resistance, or place in elevated areas.
- Reinforce the capability to share DG power supplies: All DG to be shared by all reactors (i.e. multiplexing). DG at Reactor 6 was shared with Reactor 5, but not so with Reactors 1- 4.
- Add more air-cooling and gas turbine types of DG (Only the air cool type survived as it did not need seawater pump and circulation.)
- Place gasoline and diesel tanks on elevated areas.
- Activate DG automatically during earthquake scram.

Secure AC power

- Ensure water seal and pressure resistance, or place in elevated area.
- Versatile AC power supply (versatility between M/C and P/C)
- Reinforcement of power supply vehicles
  - Add on-site units, add more units, review locations
  - Add different types of vehicles: DC, AC, AC & DC mixed, with generator, with DG, etc.
- Enable air transport of power supply vehicles and other backup power supplies (set up helipad on the premises or rooftop)
- Store power cables and tools for working on terminals in appropriate places.
- Set up multiple hubs for connecting power supply vehicles to power panels, and improve water resistance.

Secure DC power supply

- Ensure water seal and pressure resistance, or place in elevated area.
- Upgrade DC power capacity (from 8 hours to 24 hours or above).
- Designate mobile battery vehicles in case a disaster renders the DC power supplies useless.

Note) Compared with instructions from NISA

- Black text = exists
- Red text = does not exist

Summary of countermeasures - 2

Specific measures/ Guidelines

Power Supply

Cooling function

Control Room function

Ventilation function

Prevention against hydrogen explosion

Disaster and accident manual/infrastructure

Secure cooling functions (Without the cooling function, core will melt down in a matter of hours. Meltdown triggers hydrogen buildup.)

- Ensure water source: secure source and means of water supply from multiple sources such as water tanks, water reservoir, lakes, rivers, sea, etc.
- Secure the necessary number of fire trucks and fire hoses. Set in elevated areas.
- Install multiple hubs for fire truck hoses.
- Secure water seal and pressure resistance of high- and low-pressure cooling systems, or place in elevated areas.
- Secure water seal and pressure resistance of facilities and buildings near the sea.
- Prepare motor cleaning devices and parts.
- Must have alternative core cooling system, which drives on an independent set of coolant, power, and water-injection systems.
- Implement feed-and-breed systems via wet-well vent (to secure heat sink until cold shutdown).
- Prepare portable underwater pumps.

Monitoring of spent fuel pool

- Strengthen the system to thoroughly monitor temperature and water level (both hard and soft).

Secure control room functions

- It is important to secure monitoring systems. Prepare backup batteries so that measuring instruments can be monitored during power outage.
- Maintenance and upgrade of central control room.
- Proper storage of protective suits, masks, dosimeters, etc for workers.

Secure ventilation

- Reexamine the logic of the ventilation system (its effectiveness was unclear) and design philosophy of rupture disc.
- Reconsider the location of the vent line valve (focus on operability).
- Considering the rupture disc didn't open, review the method for opening/closing its valve (change the method).
- Consider installing multiple measures to reduce pressure within the core (consider a system that doesn't rely on SR valve which is run by DC power).
- Prepare temporary power source and gas tanks so that vent line can be set up swiftly during power outage.
- Prepare batteries near/in the central control room to open and close SR valve to relieve core-pressure.

Note) Compared with instructions from NISA

- Black text = exists
- Red text = does not exist

Summary of countermeasures - 3

Power Supply

Cooling function

Control Room function

Ventilation function

Prevention against hydrogen explosion

Disaster and accident manual/infrastructure

Note) Compared with instructions from NISA

- Black text = exists
- Red text = does not exist

Specific measures/ Guidelines

To prevent a hydrogen explosion

- Reinforce the containment vessel's sealing functions: Reevaluate the sealing materials used for PCV head flanges, electric cable routing, hatches, etc, and improve the resistance against high temperature and pressure.
- In case of massive hydrogen buildup, install measures to reduce its density in an enclosed space;
- ・ Install hydrogen detectors in the enclosed space (transmit signal using own power source or by RF).
- ・ Ensure filling of nitrogen into the containment vessel during ventilation.
- Install canopy to ventilate hydrogen (remote control＋manual operation＋absorption filter for fission gas)

Enrich disaster and accident manual (AM)

- Redesign of AM: How long (hours) should the water and power supply last? How to arrange off-site support while supplies last? In order to achieve this, perform the following:
- ・ Set quantitative values on how long water and power supplies will last, and create corresponding manuals.
- ・ Define operational manual to supply alternative power/water and equipment, and to set them up on-site in order to ensure completion within specified life expectancy.
- ・ Implement periodic training to verify that the above tasks can be executed within the necessary period of time. (including extreme conditions such as night time, holidays, simultaneous accidents on all reactor units, etc.)

Reinforcement of infrastructure

- Assemble operators to the power plant after an earthquake, assign emergency supporting staff. (Assemble within a specified time. Set an alternative assembly location in case of large scale disaster (i.e. - beyond 100 yd in US))
- Secure access to the plant (reinforce roads, bridges, etc.)
- Improve accessibility to and from the plant in case of earthquake and tsunami:
  - ・ Reinforce the main road (include measures against liquefaction).
  - ・ Secure appropriate amount of heavy machinery, and drivers for clearing up rubble.
  - ・ Secure routes suitable for earthquake and tsunami situation (Construct passage or path that will not crack or liquefy, and has no manholes.)
  - ・ Set up gasoline tanks.
- Communication among operators, restoration team, emergency response office, and central control room were cut off. This made it impossible to report in a timely manner. Means and equipment for communication during an emergency must be secured.

"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

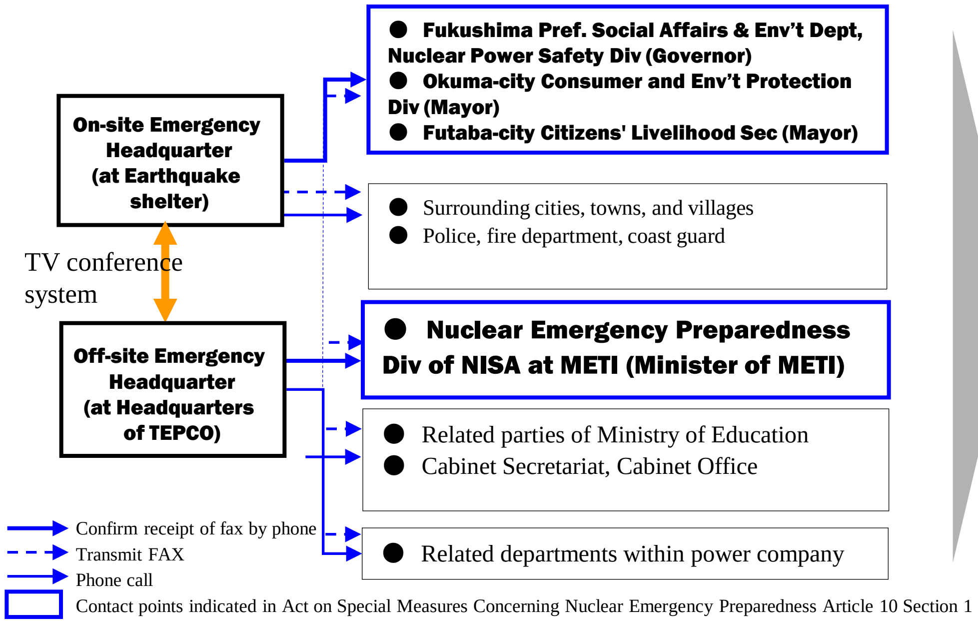
- Design an organization and authority where proper and transparent governance works.
  - Plant safety: The site (plant head or shift manager) is the chief decision maker.
  - Local safety: The local government can share information from the plant in real-time to make final decisions.
  - Decision-making process should be transparent and should not be delayed or diverted due to external influences.

Proper training to secure safety

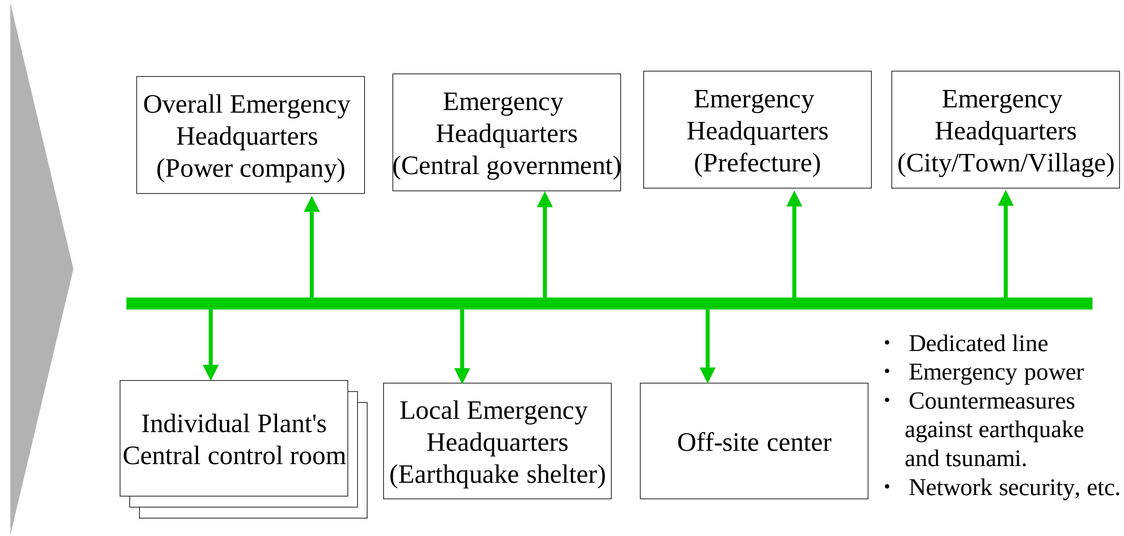
- To guarantee the items above, AM (accident management) procedure manual and countermeasures have been defined appropriately.
- Select qualified personnel for executing the manual.
- Selected personnel will undergo necessary training.
- Periodic evaluation on these procedures, personnel, and training 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)



Future

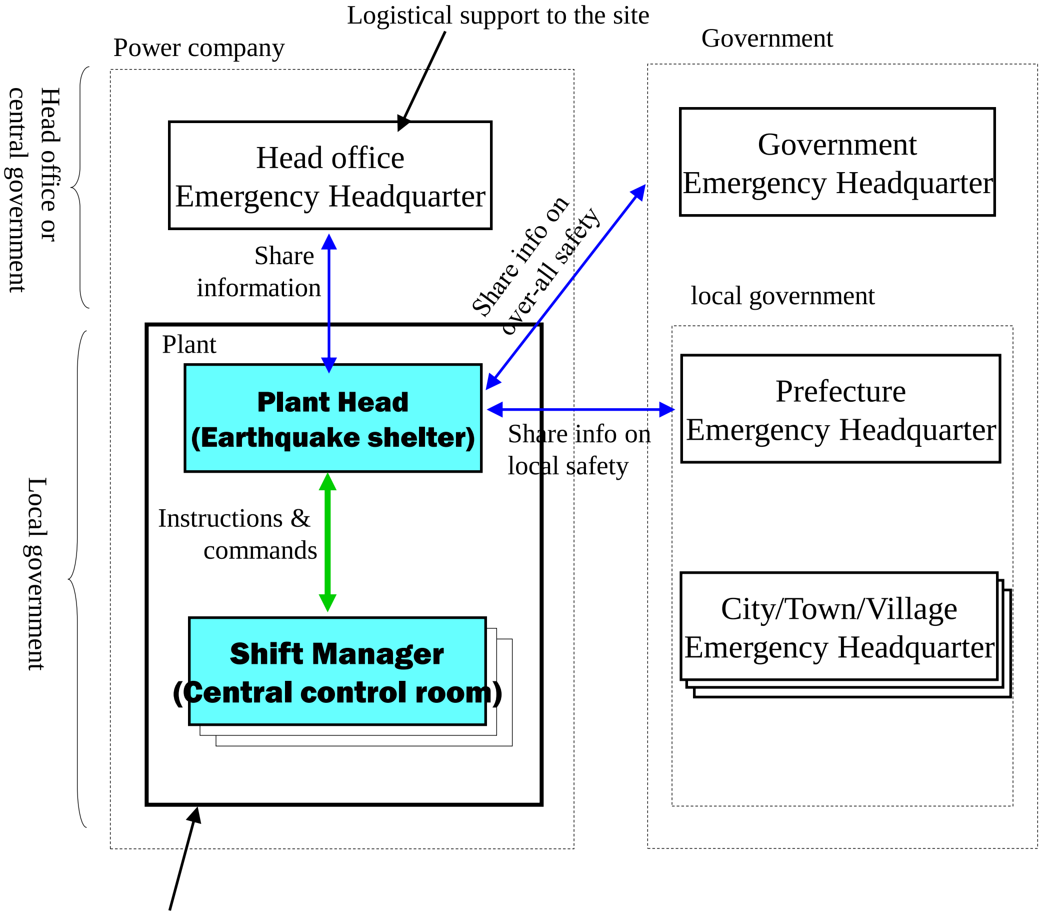


- **Real-time (limited):** Real-time TV conference available between the power plan and Head Office.
- **Bi-directional (partial):** Communication other than with government bodies are mainly one-directional through phone, FAX and mail.
- **Limited information sharing:**
  - Communication difficulties 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".



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

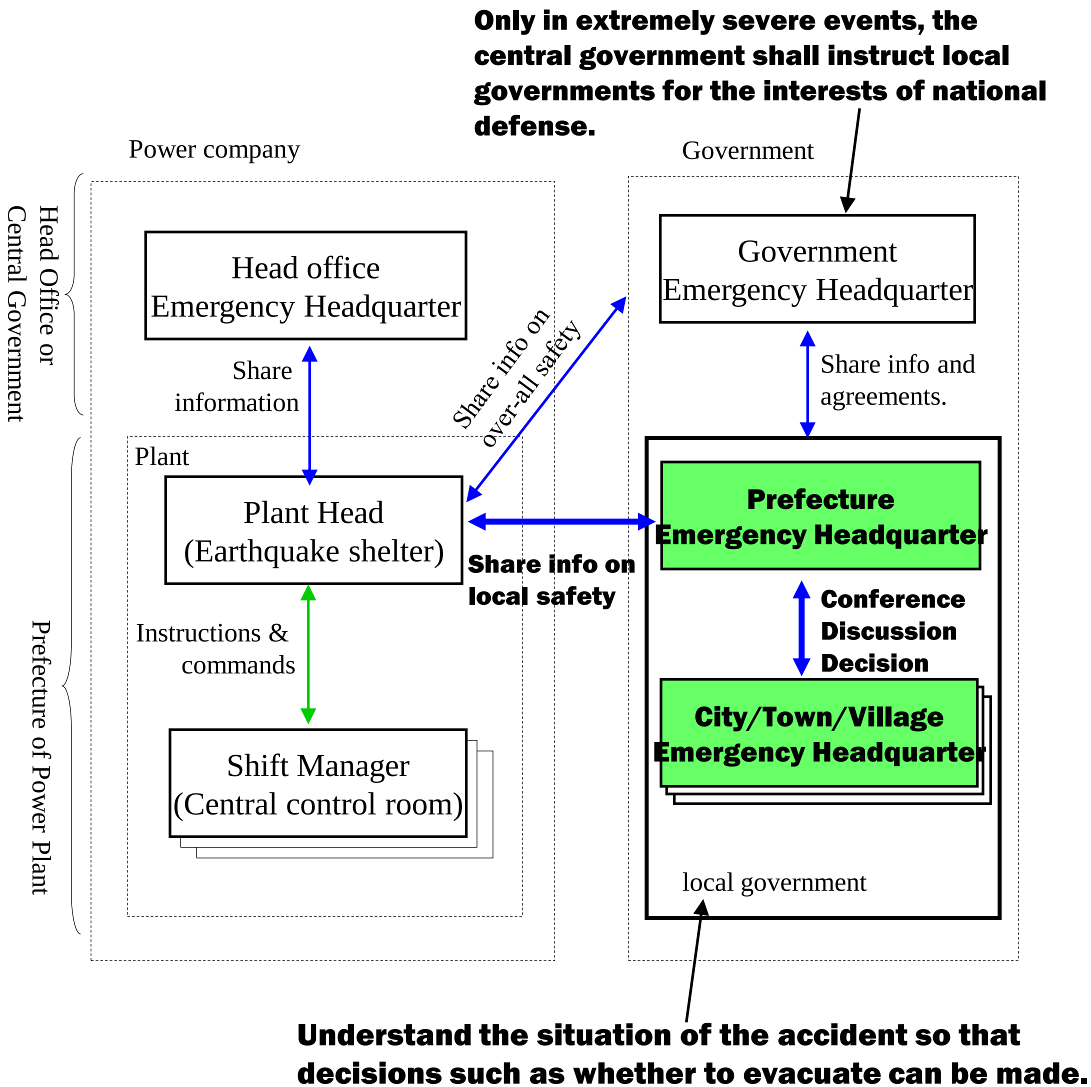
- Power plant: **Decisions and actions with top priorities on accident prevention and safety.** On this issue, it should be **independent from management**.
- Head office: Entrust the site to "plant safety". Provides **logistical support** to the plant.

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.



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

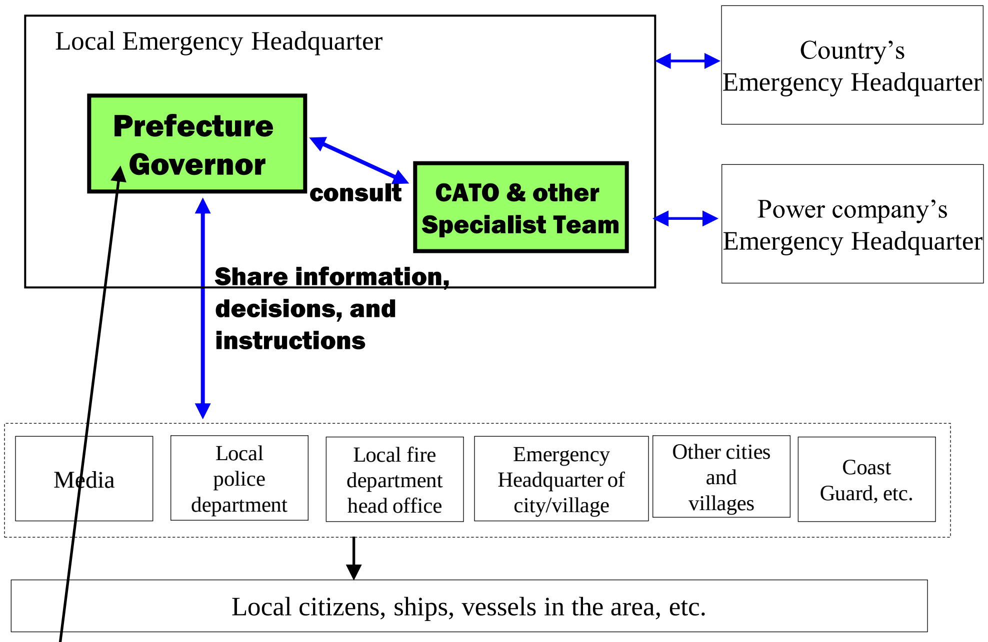
- **Decision-making**: On local safety and evacuation, the head of local government should have full understanding of the situation and discuss with plant's head before making any final decision.
- **Training**: Head of local government should receive constant training to develop good judgment skills.
- **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)



- **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.

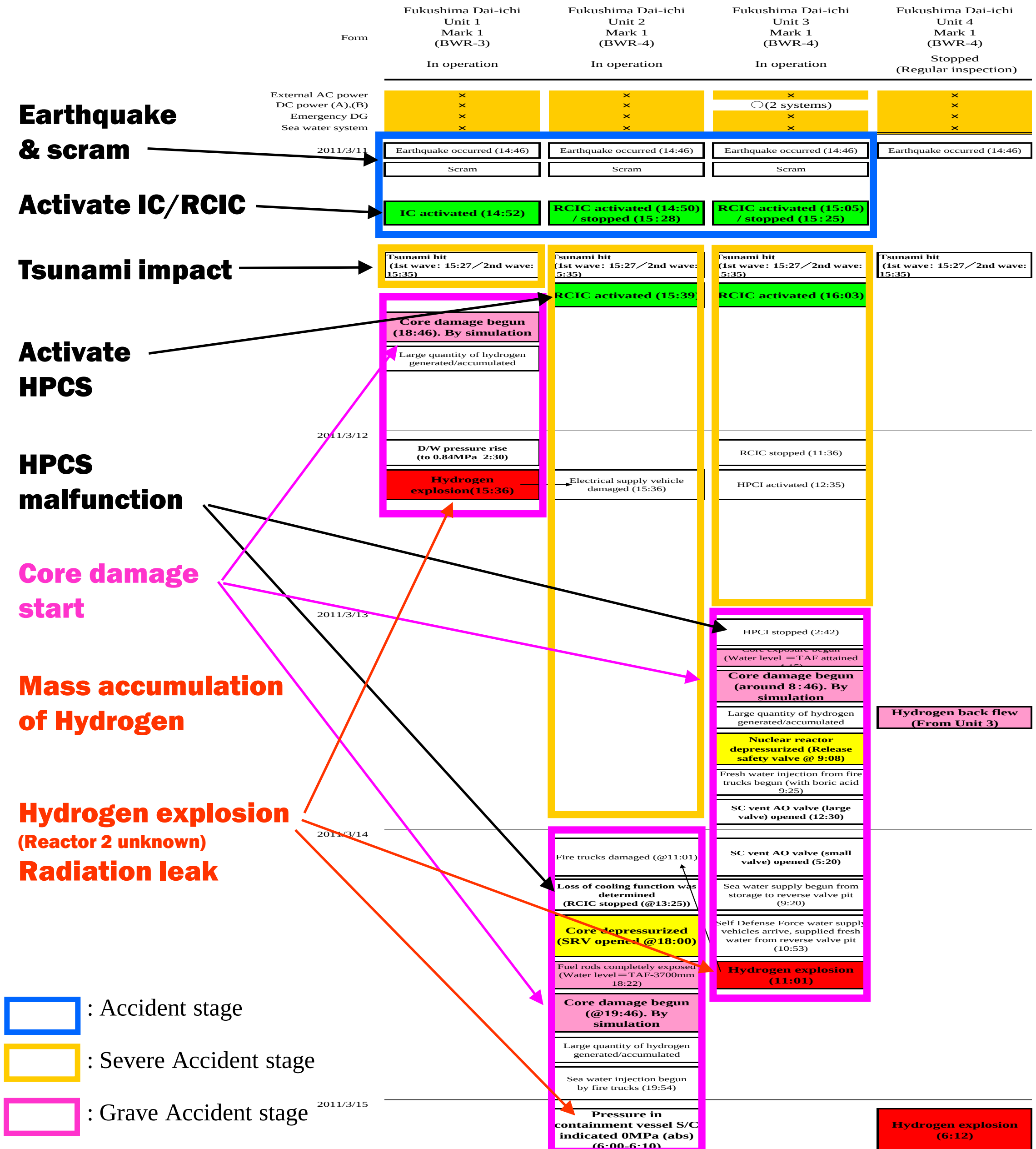
From now on, we need to manage accidents in 3 categories and establish its own AM structure.

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.

Extremely Confidential

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?



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?

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 <u>restoration of the transmission line</u>** or **restoration of power through <u>the emergency AC power supply</u>** 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.**

List of the main sources and references

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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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