Severe Accident in Fukushima Dai-ichi Nuclear Power Plant and Lessons-Learned

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The Beginning

- The first tsunami attack at 15:27
- The second at 15:35, which exceeded the site elevation
  - Diesel Generators failed from 15:37-15:41
    - Station Blackout without power recovery
  - Seawater system failed
    - Loss of ultimate heat sink
  - DC Batteries failed
    - No plant parameter information(pressure, water level, injection rate)
    - Loss of AC power followed batteries failure

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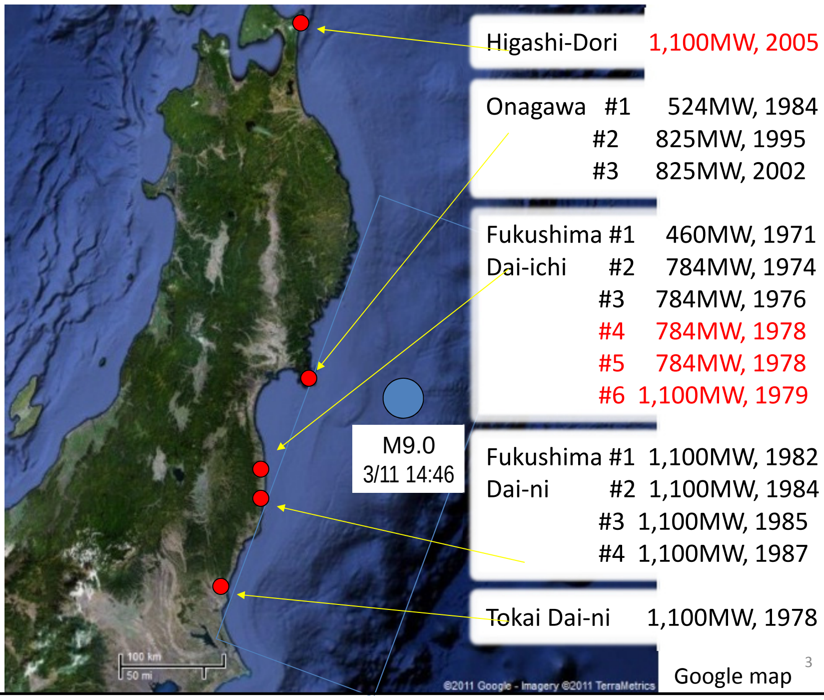
Earthquake Source and NPPs



Google map

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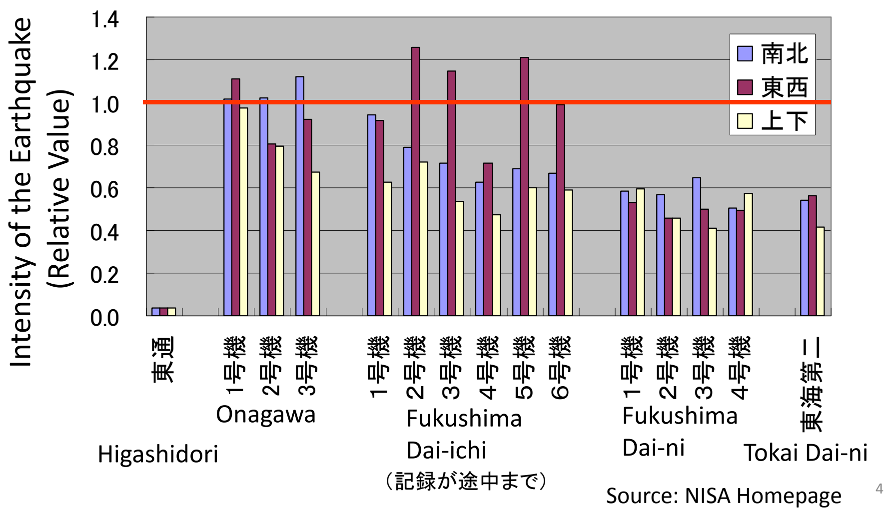
Earthquake
(Observed PGA/Design Ss ground motion）



Source: NISA Homepage

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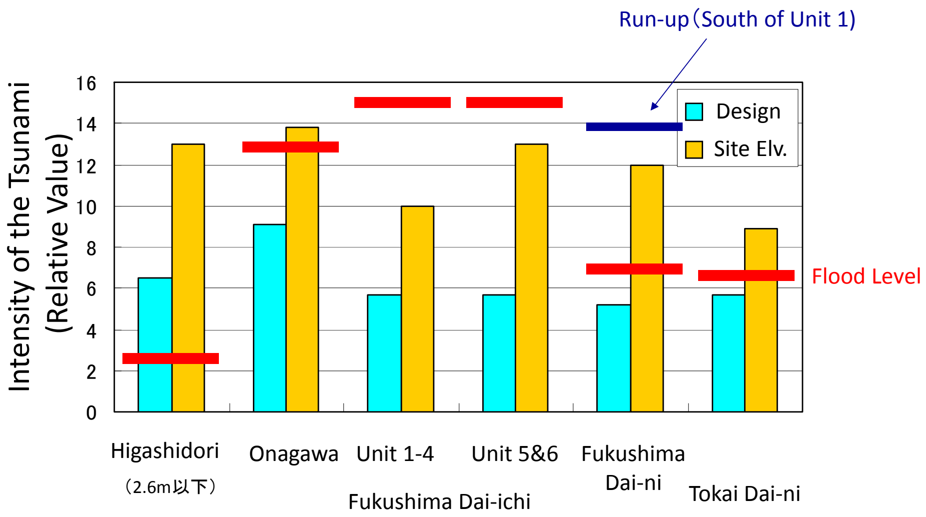
Tsunami Flood Level



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15:42, Mar.11
15:43, Mar.11
15:46, Mar.11
15:57, Mar.11
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Crew decision: A tanker feeding heavy oil at the port escaped narrowly in emergency

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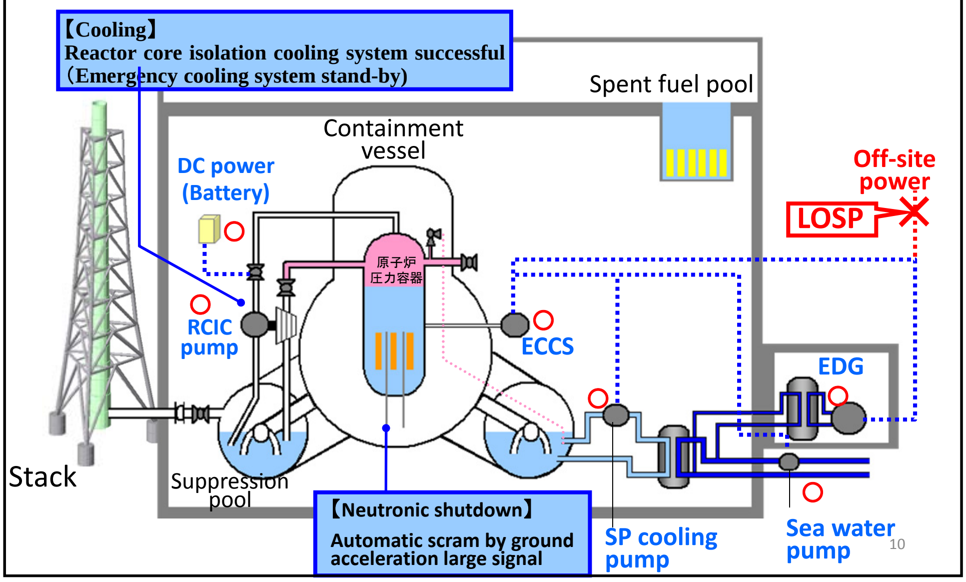
After Earthquake: Safety Functions Successful
March 11, 14:47pm



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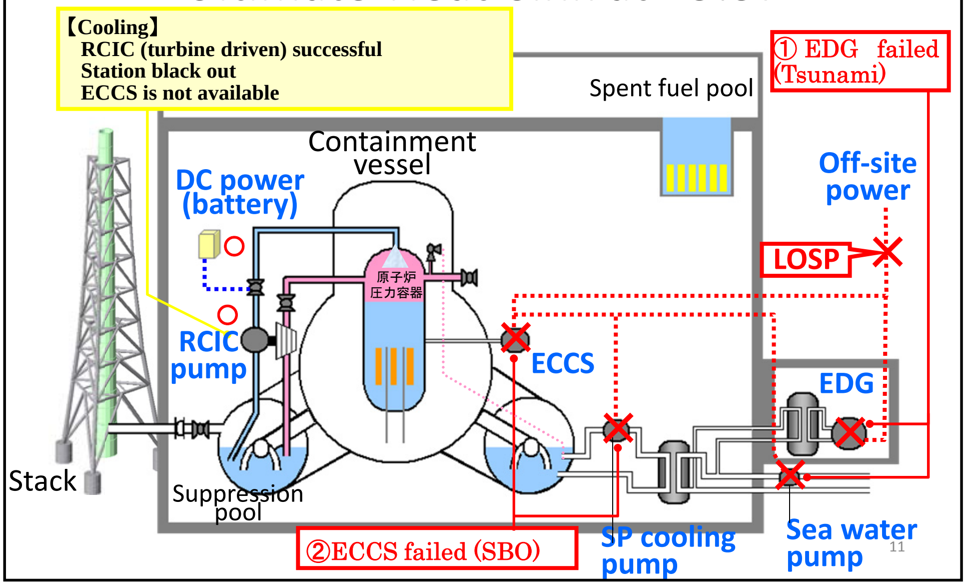
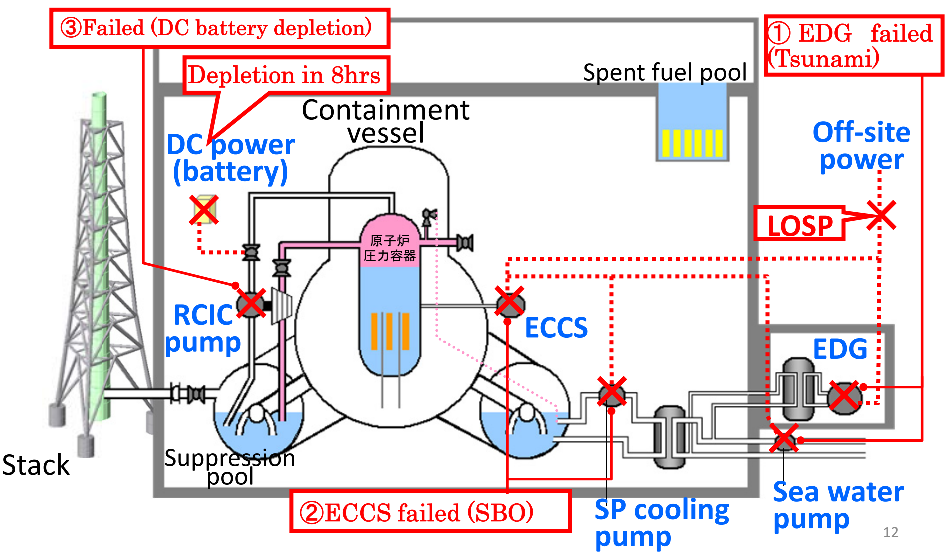
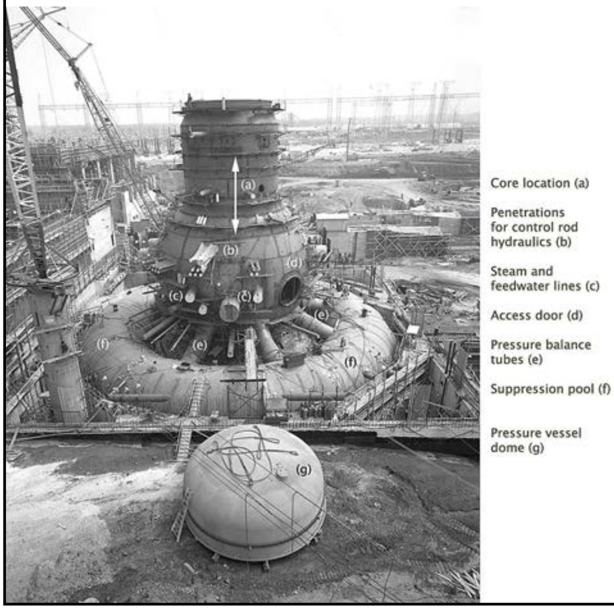
After Tsunami: SBO and Loss-of-Ultimate-Heat-Sink at 15:37

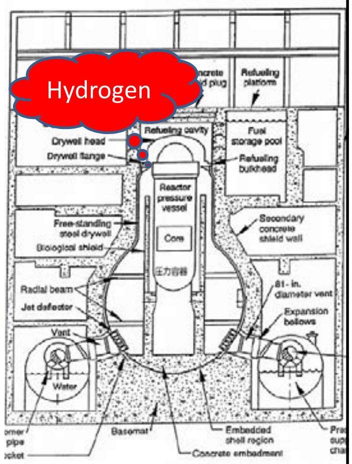


After DC Battery Depletion (8 hours at least): It Depends on Units



Boiling Water Reactor Mk-I Type (Browns Ferry)





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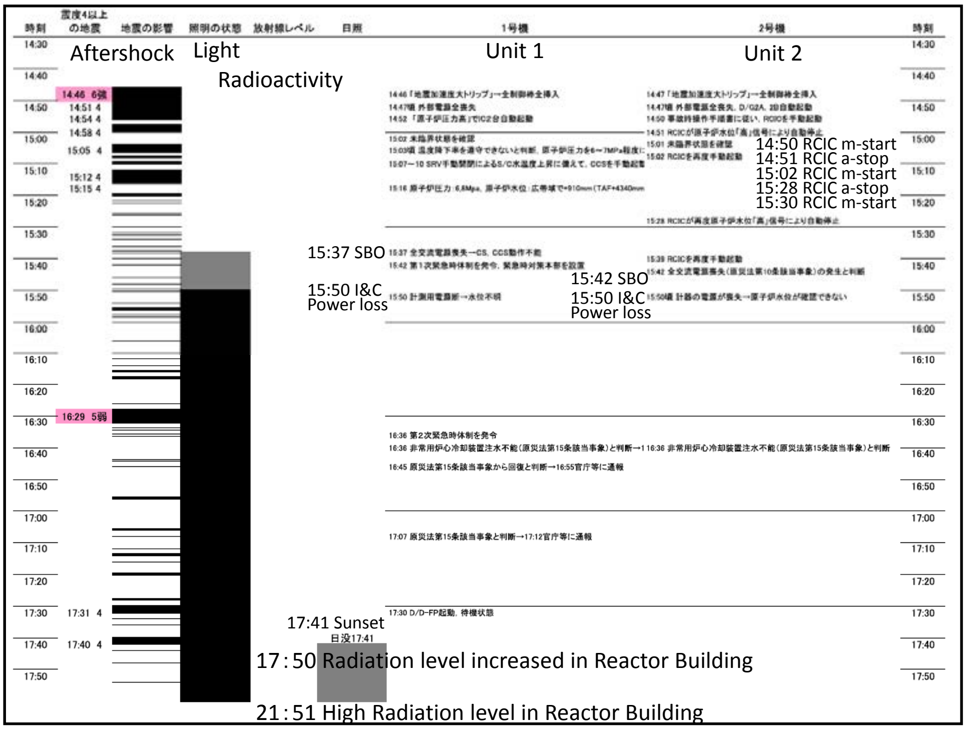
Air Photo Service（March 20）

Witness of the Accident

- "After this (around when the tsunami arrived), power lights began to flick, and then I saw they all turned off.
  The emergency power was shut off, and all of the lights on the MCR panel started to turn off. I did not know what happened however I couldn't figure out that it was caused by a tsunami.
  My fears were confirmed when operator was running into the MCR and yelling we're being flooded with seawater".

- "As the tsunami engulfed us, the emergency power became unusable and lights in the MCR were reduced to one emergency light (making it possible to just barely see within the darkness)."

- **"<u>We lost the power, and I felt that we could not do anything. The other operators looked nervous. They yelled, "we can't do anything, why are we still here!?" However I bowed my head and asked them to remain and they did.</u>"**



[Confirming reactor building equipment in the darkness]

- "The ERC at the power station asked me in the MCR to confirm the operating of RCIC, **however that was not easy. Normally it only takes a few minutes, however it required 45 minutes to an hour, because fastening a self-contained air unit took 10 to 15 minutes. Performing in the field took 30 minutes, returning to the MCR, taking off all the equipment, and going back to the MCR for the report.**
  It would not have taken as long if we had **some communication measure.** Aftershocks were continued, and there was still the possibility of another tsunami would arrive."

<Self-contained air unit>

Taken the Service Building entrance from the inside.
The floor was cluttered with objects.

<Working in the darkness>

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Major Events

Unit 1 has Isolation Condenser (IC); Units 2-6 have Reactor Isolation Cooling System (RCIC)

- Unit 1
  - March 11, 15:37pm IC stopped operation
  - March 12, 15:36pm H_2 explosion
- Unit 2
  - March 14, 13:25pm RCIC stopped operation
  - March 15, 6:10am FP large release
- Unit 3
  - March 13, 2:42am HPCI intentionally stopped
  - March 14, 11:01am H_2 explosion

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Monitored by the Assistant Shift Supervisor

The Assistant Shift Supervisor at the desk monitored plant data and information wearing a full face mask in the total darkness.

Checking Instrument Gauges

Checking instrument gauges in the total darkness with only a flashlight to depend on.

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Availability of Electrical Equipment Operator Identified in Evening of March 11

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Offsite Power	X (0/6/7)	X (0/6/7)	X (0/6/7)	X (0/6/7)	X (0/6/7)	X (0/6/7)
Metal Clad	X	X	X	X	X	Δ
	X	X	X	X	X	O
	NA	X	NA	X	NA	Δ
Power Center	X	Δ	X	-	X	Δ
	X	Δ	X	Δ	X	O
	NA	X	NA	X	NA	O
Emergency DG	X	X	X	X	X	X
	X	X	X	X	X	O
	NA	NA	NA	NA	NA	X
DC Battery	X	X	O	X	O	O
	X	X	O	X	O	O

X: Not available (submerged/spray)　　Δ: Not available (no power feed)
O: Available　　NA: Not applicable

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Temporary Instrument Power

Temporary batteries were connected to power control room instruments due to loss of power.

Installing Temporary Power

Workers who are not working for electrical system were called out to manually lay the power cables

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[Others]

- "Some large aftershocks caused us to **flee to high level ground many times out of fear of dying while still wearing the full face mask."**

- "That was only way to restore the instruments at that time due to loss of time. Car batteries were begun to gather.
  However, carrying the batteries was difficult due to their weight. **It was the worst situation ever."**

- "Normally, laying cables requires one to two months; however, it was completed in only a couple of hours. **Also, we had to find the penetration seals in the darkness and splice the ends. With the puddles of water around, we thought we were going to get electrocuted."**

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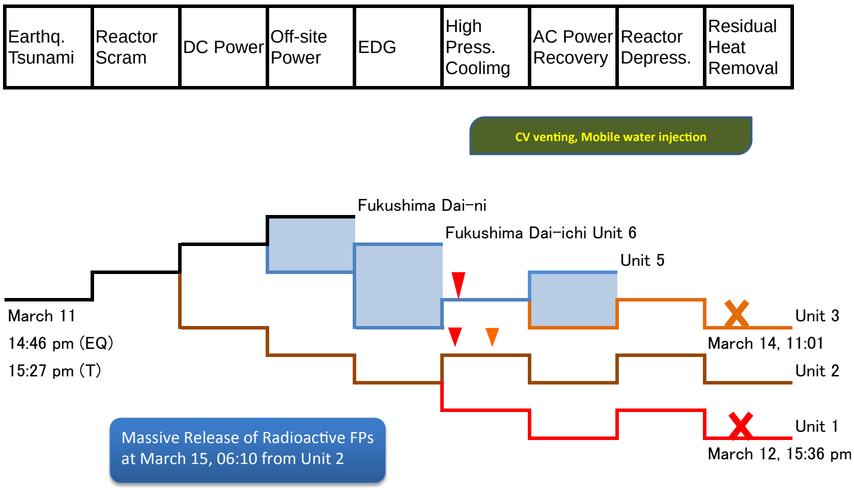
Accident Progression at Fukushima #1 and #2 Sites



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[The difficulty of venting]

- "Because the power was lost, we had to vent by manually opening the valves. However, due to high radiation exposure in the field we had to gather who could engage in venting work, and the Shift Supervisor allocated each team . Even though we had full protective gear, **the radiation levels were quite high therefore we did not let young operator go."**

- "We went into the field in order to open the vent valves. When we were at the near the torus room, we heard a large, weird popping sound. The valve is at up high, so I put my foot on the torus to lift myself up. Then, **my black rubber boot was melted like butter."**

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Power Recovery of Unit 2 and Alternative Cooling of Unit 1 & 2

Obstacles on access routes

Fire hoses caused detour for access. After the explosion, debris and damaged fire engines become additional obstacles.

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Issus Criticized as Inadequate in Accident Investigation Reports

- Isolation Condenser (IC) in Unit 1
  - Manual stop of IC before tsunami arrival, although it is in conformity to operating procedure
  - Design of isolation valve (isolation or cooling?)
  - TEPCO’ knowledge and training on IC
  - Information sharing among HQ, MCR and operators
- Wrong procedure of alternative cooling in Unit 3
  - Operator did not follow the EOP
  - Operator stopped HPCI; tried depressurization in fail; failed to restart HPCI nor RCIC.

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Isolation Condenser of Unit 1

Operators stopped B-system, controlled A-System

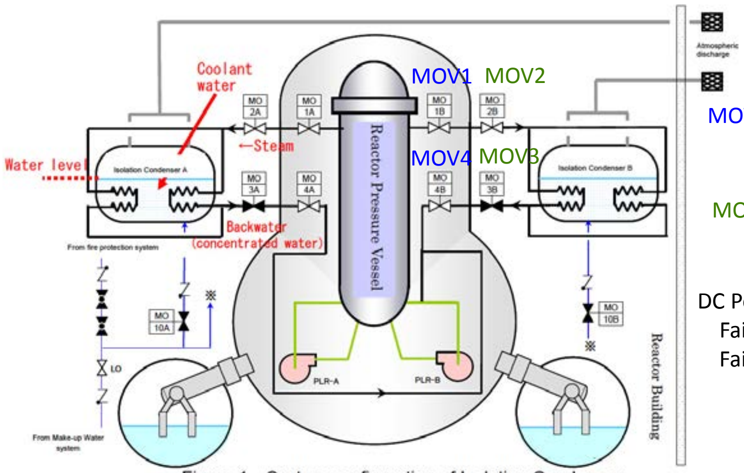

Figure 1 : System configuration of Isolation Condenser

MOV1 , MOV4
AC powered

MOV2 , MOV3
DC powered

DC Power loss
Fail safe in unit 1
Fail as is in units 2-6

http://www.tepco.co.jp/en/nu/fukushima-np/info/12051001-e.html

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IC Issue in Unit 1 (1/3)
Design and Operating Procedure

- Operator stopped IC because temperature decreases too fast (55C/h) which observes the procedures.
- IC valves are fail-safe (closed) while RCIC in other units isolation valves are fail-as-is for LOCA or loss of DC power. IC is used in Unit 1 only (CV function concept).
- DC power loss results in CV isolation in unit 1 while fail as is in SBO situation.
- DC power is lost earlier than AC power. Then the valves closed first and AC power loss followed.
- Valves inside containment are AC powered. Then, the recovery open is difficult.

Notes:
SBO: Station Blackout CV: Containment Vessel LOCA: Loss of Coolant Accident

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IC Issue in Unit 1 (2/3)
Operation in Main Control Room

- No IC operation status alarm (probably because of SBO). MCR lost lights at the same time and operators did not identify valve status indicator. Then the MCR did not notice IC valves closed and operation stopped.
- The operator closed MOV-3A manually but the fact was not shared in the MCR and HQ. The operation was almost at the same time as the Tsunami attack. No time to report and MCR was in absolute chaos.
- Because of aftershocks and tsunami alarms, no other batteries, electrical panel water-sprayed, early recovery of MOV-3A is difficult even if other valves are open.
- However early alternative water injection may be possible using DG-driven fire pump if IC status was known.
- No experience of IC operation in Unit 1. The plant simulator does not model the IC and the operators are not familiar with the system.

Notes:
MCR: Main Control Room MOV: Motor-operated Valve HQ: Headquarters

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IC Issue in Unit 1 (3/3)
Site Head Quarter (Seismic Isolation Bldg.)

- IC started automatically (14:52)
- No information on manual control of IC (stop at 15:37)
- No reporting of IC status after tsunami
- SBO and loss of DC power
- Reactor water level TAF+250mm (16:45)
- Started to prepare for alternative cooling (17:12) and started DG-driven FP (20:50)
- Serious chaotic situation
- Radioactivity high in site and drywell pressure 600kPa. HQ started to doubt IC does not work (23:50)
- DG-driven FP stopped and could not restart (1:48)
- Fire engine was used after preparation long time (5:46)

Notes:
TAF: Top of Fuel DG: Diesel Generator FP: Fire Pump

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Alternative Cooling in Unit 3 Actual Sequence and EOP

- EOP requires:
  - If the water level is unknown, activate low pressure injection system. If it does not work, start HPCI and RCIC and prepare for alternative cooling.
  - After it is ready, depressurize the system rapidly and switch to low pressure injection start.
- Operator started RCIC. It automatically stopped on March 12, 11:36. HPCI automatically started by water level low signal. Operator controlled the flow rate to save battery load, which follows the AOP.
- DC power for water level depleted. No information on water level. (20:36) Operator continued HPCI operation.
- Operator observed the reactor pressure, that decreased to the value at which the HPCI is supposed to stop automatically.
- Operator is not sure if HPCI works and afraid that HPCI components are damaged. Then stopped HPCI (2:42) but depressurization failed.

Notes:
EOP: Emergency Operation Procedure RCIC: Reactor Isolation Cooling System
HPCI: High Pressure Coolant Injection

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Lessons from the 1F Accident

The National Diet of Fukushima Nuclear Accident Independent Investigation Commission (NAIIC)

- The root causes of the accident were in the organizational and regulatory systems that supported faulty rationales for decisions and actions. The accident was "manmade";
- There were organizational problems that limited an effective emergency response in the utility such as insufficient level of knowledge, training, equipment inspection and emergency procedures related to severe accidents;
- The nuclear regulators lacked the expertise commitment to assure the safety of nuclear power. They were in the state of regulatory capture, in which the industry had too great an influence over the regulator.
- The nuclear power plant operator did not fulfill its ultimate responsibility for the safety of his facility, relying on the regulators taking final responsibility. This relationship weakened the pursuance of minimizing risk in line with the principle of as low as reasonably practicable (ALARP);
- Laws and regulations related to nuclear safety have only been revised as stopgap measures when an accident happened: the latest technological findings from international sources have not been reflected in existing nuclear energy laws and regulations. What must be admitted is that this disaster was 'Made in Japan';
- Recommended fundamental reforms of both the structure of the electric power industry and the structure of the related government and regulatory agencies as well as their operation processes, the elimination of insular attitude, in particular.

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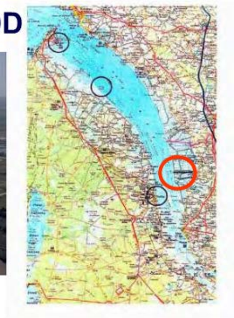
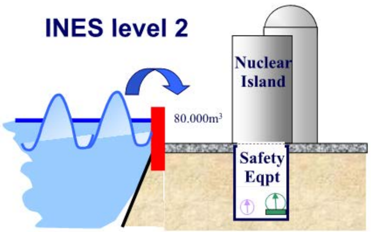
French Experience: Flooding

2. DECEMBER 1999 BLAYAIS FLOOD

1999 Storm
⬇
« Le Blayais » NPP partial flooding



INES level 2



High water level in the river Gironde : high tide + storm surge (+2m) and waves (2m) generated by the wind on the estuary (200 km/h)

➡Waves came over the dyke and caused flooding on site and in units 1 and 2
➡On-site Emergency plan (36 hours)

Eric de Fraguier, Lessons learned from 1999 Blayais flood : Overview of EDF flood risk management plan, NRC – Regulatory Information Cong, 2010

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Similarity to Fukushima Dai-ichi Event

- Flooding hazard is escalated by multiple events combination that resulted in beyond-design basis
  - Severe storm-driven waves coinciding with high estuary level
- Insufficient protection
  - Protection at site boundary (invasion of water) inadequate dykes
  - Water tightness of building and structure: underground rooms
  - Robustness of instrumentation and control capability: detect water in affected rooms and warning system
  - Multiple units had common cause influence: 4 units concerned organizational difficulties
- Inadequate environment
  - Communication and accessibility are failed and management environment is seriously deteriorated: blocked roadways, phone communication
  - Off-site support is not enough because of storm
  - Off site power supply is not available: partial temporary LOSP
  - Sand and garbage carried by water: clogging-up of filters of water intake

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Accident Sequence Precursor Study for Le Blayais NPS by JNES in 2007

- Blayais event is postulated, and the sequences that follow and conditional core damage probabilities (CCDP) were evaluated
- Assumptions
  - Flooding inside reactor building (RB) and every equipment in B2 floor of RB fails
  - Offsite power is not recovered within 8 hours
- Application
  - BWR3 (Unit 1) CCDP=1.5×10^{-3}
    - LOSP; HPCS failure; Core spray pump and containment spray pump failures
    - EDG is available, LPCI is available
  - BWR4 (Units 2-5) CCDP=3.5×10^{-2}
    - LOSP; Core spray pump, RHR pump, HPCI pump and RCIC pump failure
    - EDG is available, LPCI is available
  - BWR5 (Unit 6) CCDP=2.4×10^{-2}
    - LOSP; EDG failure; HPCS failure
  - PWR CCDP=7.8×10^{-5}
    - LOSP; LPCI pump, Containment spray pump and turbine-driven AFW pump failure

Flooding inside turbine building and most equipment in basement floors failed

Source: Accident Sequence Precursor Assessment, JNES/SAE07-058, JNES Report, April 2007
JNES: Japan Nuclear Energy Safety Organization

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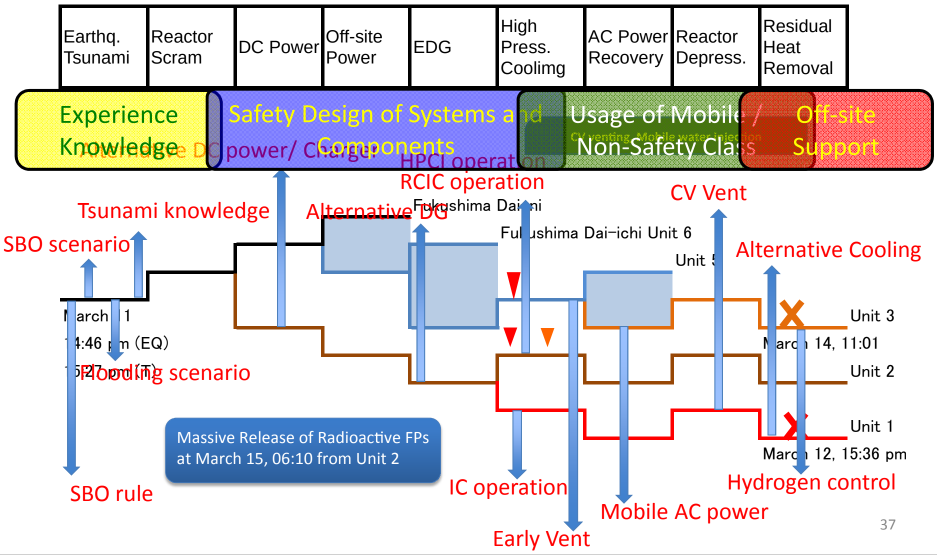
Fukushima Dai-ichi and Dai-ni Tsunami Evaluation: It took Too Long a Time

- JSCE report publication for tsunami evaluation methodology in 2002
- Regulatory Guide for Reviewing Seismic Design was revised in 2006
  - Accompanying event, tsunami and landslide
  - Exceedance risk assessment (Possibility of an earthquake exceeds design basis level)
- Seismic PRA standard was issued by AESJ in 2007
- Niigata- Chuetsu-Oki Earthquake in 2007
  - Seismic isolated building for on site emergency response center
  - Fire engines and inlets for alternate water injection
- Tsunami experts warned tsunami risk in 2008

Unit	Tsunami Height〔m〕			
	Design Basis (Chile tsunami)	2002 Tsunami source located off the coast of Miyagi Pref.	2008 Tsunami source located off the coast of Fukushima Pref.	Record of March 11th, 2011
1F 1-6	3.1	5.7	10.2 (15.7) (Maximum run up)	13.1 (15.5) (Maximum run up)
2F1-4	3.7	5.2	–	9.1

Accident Scenario and Chance of Recovery (Avoidance of Large FP Release)



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Crossroad Exists Everywhere, Every Phase of Event Sequences

- Knowledge and experience
  - Operational experiences in domestic and overseas
  - Contemporary research/knowledge
- Safety design and training
  - Review and revise of postulated event set and design basis event
- Accident management
  - Robust, independent, resilient, credible measures
- Emergency readiness
  - Risk-reduction or crisis prevention (off-site response)
- Success elements common to every phase
  - Risk-informed defense-in-depth protection
  - Knowledge and Operation based Resource Management by Staff

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