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International Atomic Energy Agency

2291-31

Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors

27 June - 1 July, 2011

FUKUSHIMA ACCIDENT

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Division of Nuclear Power
Department of Nuclear Energy
International Atomic Energy Agency
Vienna
Austria

The Accident at Fukushima Nuclear Power Stations and Lessons Learned

Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy, 27 June - 1 July 2011

Katsumi Yamada

Division of Nuclear Power

IAEA

International Atomic Energy Agency

Notes

- The information included here is considered most reliable at present but is subject to change according to results of the Investigation Commission set up by the Japanese Government.
- The views expressed here does not necessarily represent the official view of the IAEA.

OUTLINE

- Overview of Fukushima Daiichi and Daini Nuclear Power Stations
- The Earthquake and Tsunami
- BWR Technologies and Safety Systems
- Event Sequence at Fukushima Daiichi
  - Plant Responses and Operators Actions
- Preliminary Lessons Learned
- Current Status and Recovery Plan
- Summary

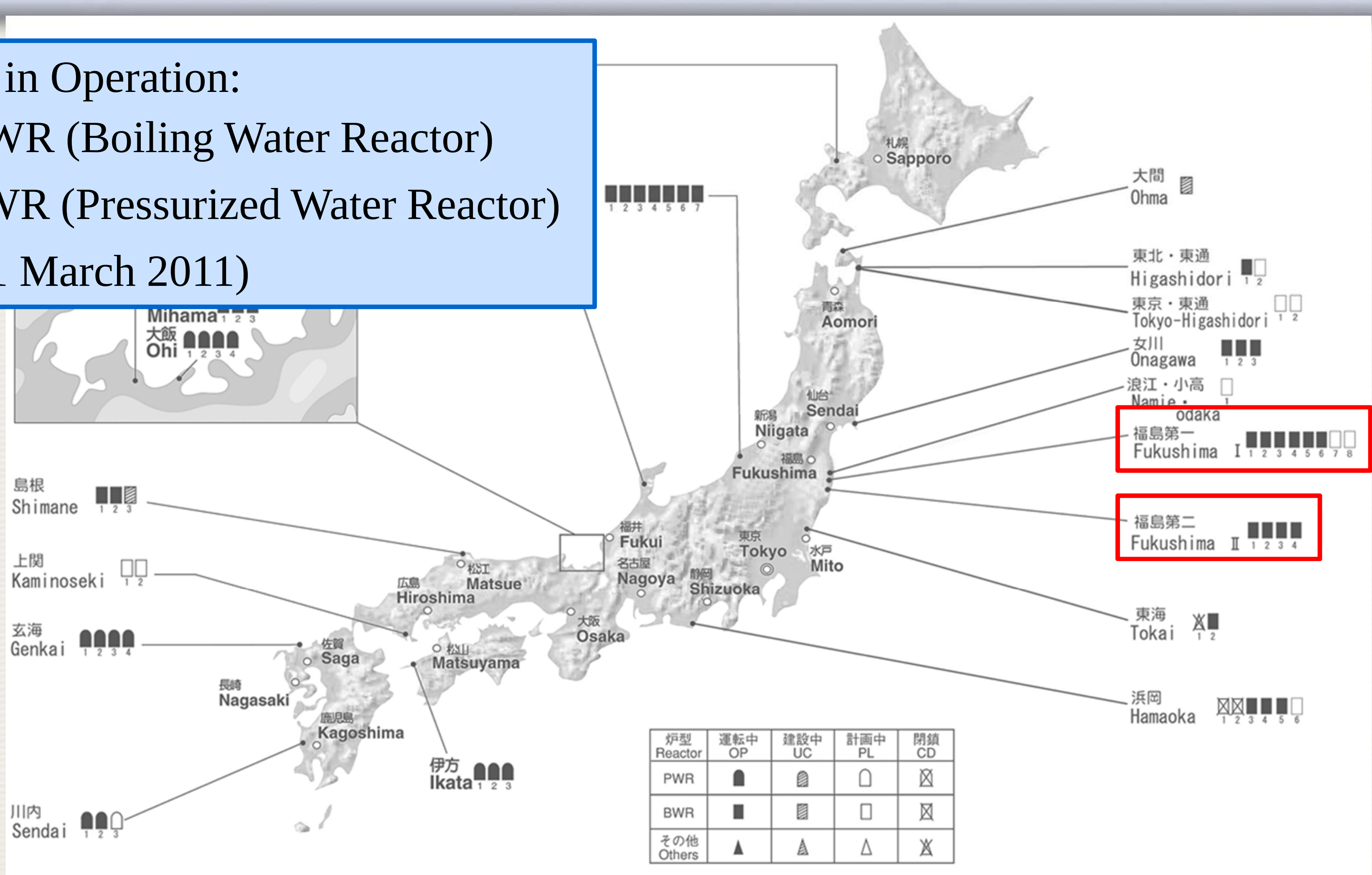
Overview of Fukushima Daiichi and Daini Nuclear Power Stations

Nuclear Power Stations (NPSs) in Japan

54 Units in Operation:

- 30 BWR (Boiling Water Reactor)
- 24 PWR (Pressurized Water Reactor)

(as of 31 March 2011)



http://www.jaif.or.jp/ja/nuclear_world/data/image/jp_npp-location.jpg

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Fukushima Daiichi and Daini NPSs

Fukushima Daiichi NPS

Fukushima Daiichi NPS

http://www.pref.fukushima.jp/nuclear/hatsudensyo/index.html

Owned and operated by the Tokyo Electric Power Company, Incorporated (TEPCO).

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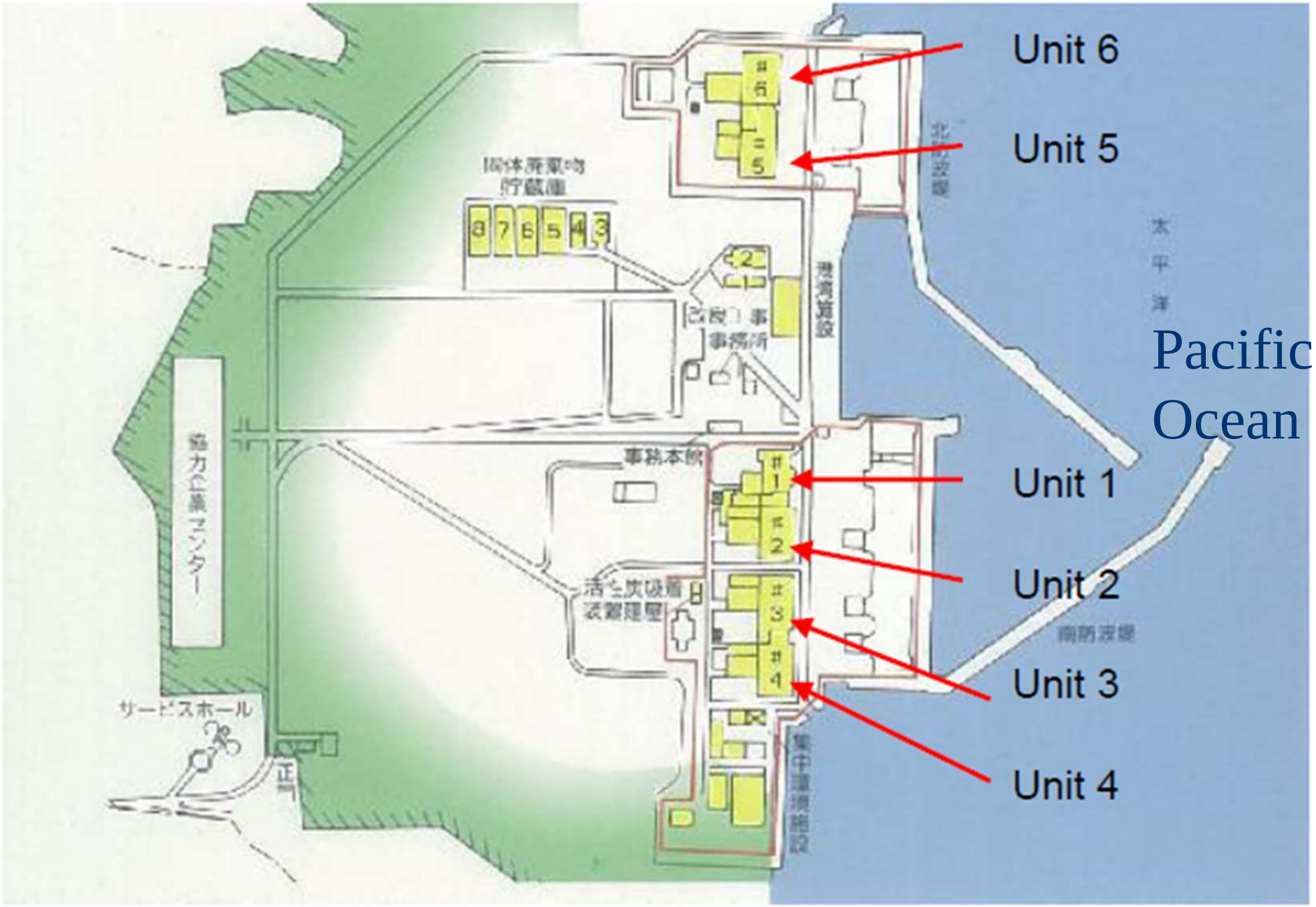
Fukushima Daiichi NPS



Fukushima Daiichi Nuclear Power Station

Unit #	Reactor Type	Containment Type	Electric Output (Gross)	Start of Construction	Commercial Operation	Status at Earthquake
Unit-1	BWR/3		460 MWe	1967	1971	Operation
Unit-2				1969	1974	Operation
Unit-3	BWR/4	MARK-I	784 MWe	1970	1976	Operation
Unit-4				1972	1978	Refueling Outage
Unit-5				1971	1978	Refueling Outage
Unit-6	BWR/5	MARK-II	1100 MWe	1973	1979	Refueling Outage

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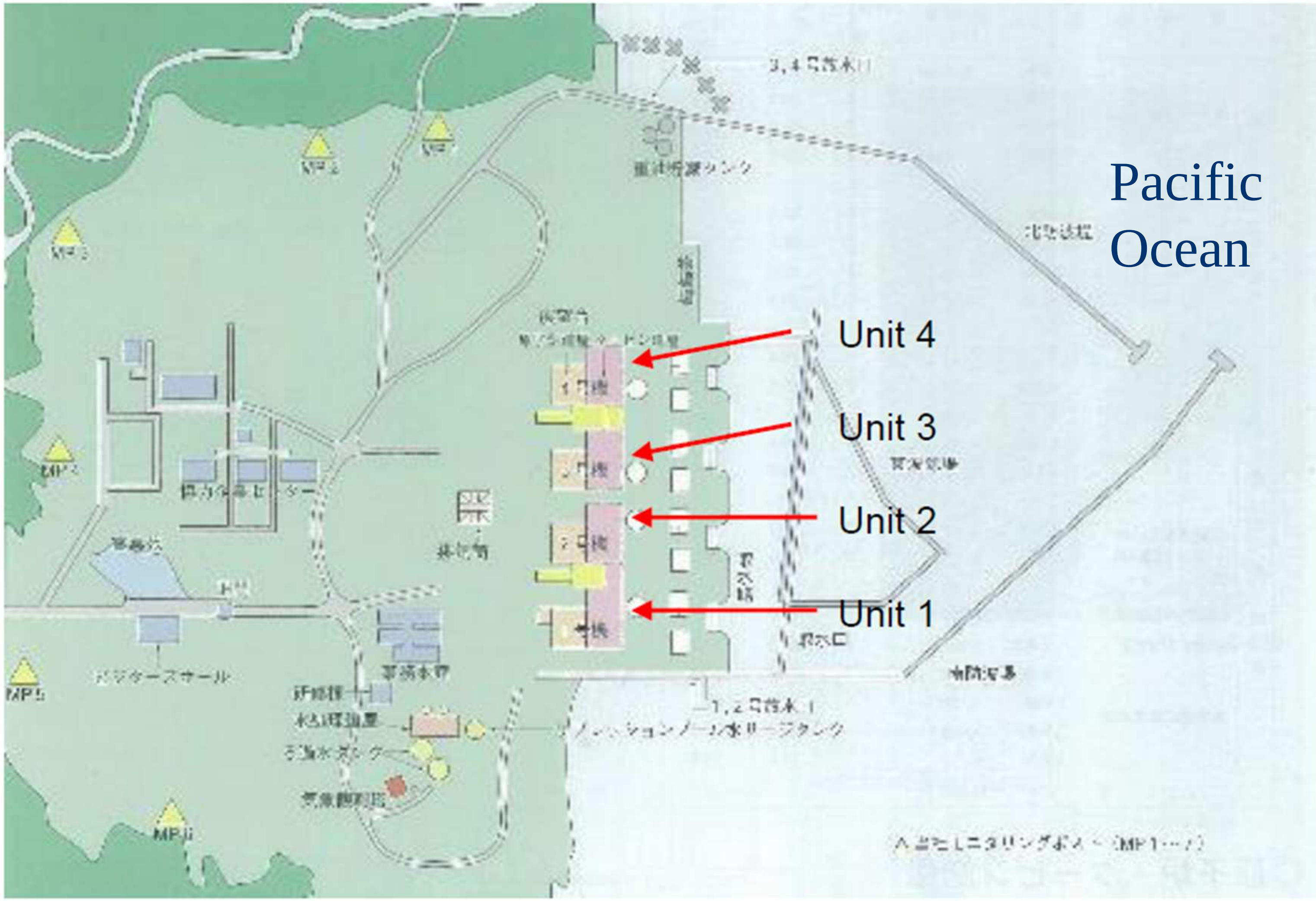
Fukushima Daini NPS



Fukushima Daini Nuclear Power Station

Unit #	Reactor Type	Containment Type	Electric Output (Gross)	Start of Construction	Commercial Operation	Status at Earthquake
Unit-1	BWR/5	MARK-II	1100 MWe	1975	1982	Operation
Unit-2		Improved MARK-II		1979	1984	
Unit-3				1980	1985	
Unit-4				1980	1987	

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The Earthquake and Tsunami

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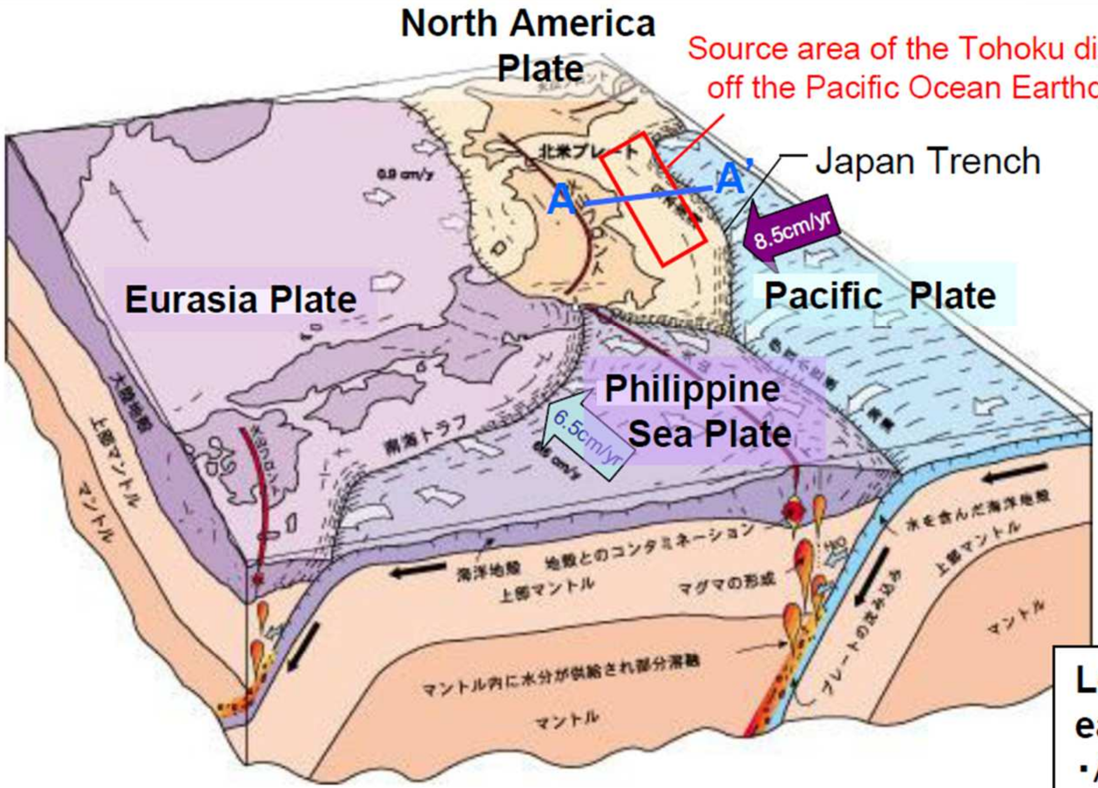
Plate Tectonics around Japan



Plates structure around Japan

- Pacific Plate
- North America Plate
- Philippine Sea Plate
- Eurasia Plate

Plate Motion

- Pacific plate subducting under North America plate of 8.5 cm/yr in west direction
- Phillipine sea plate subducting under Eurasia plate of 6.5 cm/yr in north-west direction

Locations of principal interplate earthquakes

- Along Japan trench: Plate boundary of pacific plate and north America one
- Along Nankai trough: Plate boundary of Philippine sea plate and Eurasia one

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Tohoku District – Off the Pacific Ocean Earthquake

- Occurred on the boundary of the North American plate along the Japan Trench and the Pacific plate at 14:46 on 11 March 2011.
- The hypocenter was approximately 130 km off the coast of northeast Japan, and the depth was 24 km.
- Moment Magnitude Mw: 9.0

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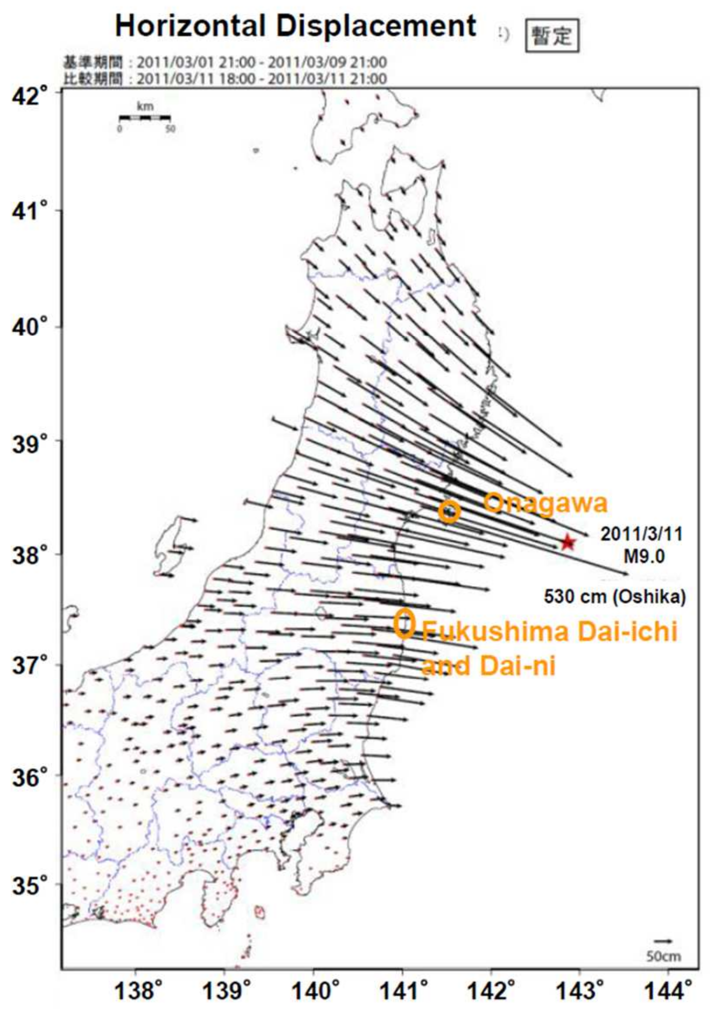
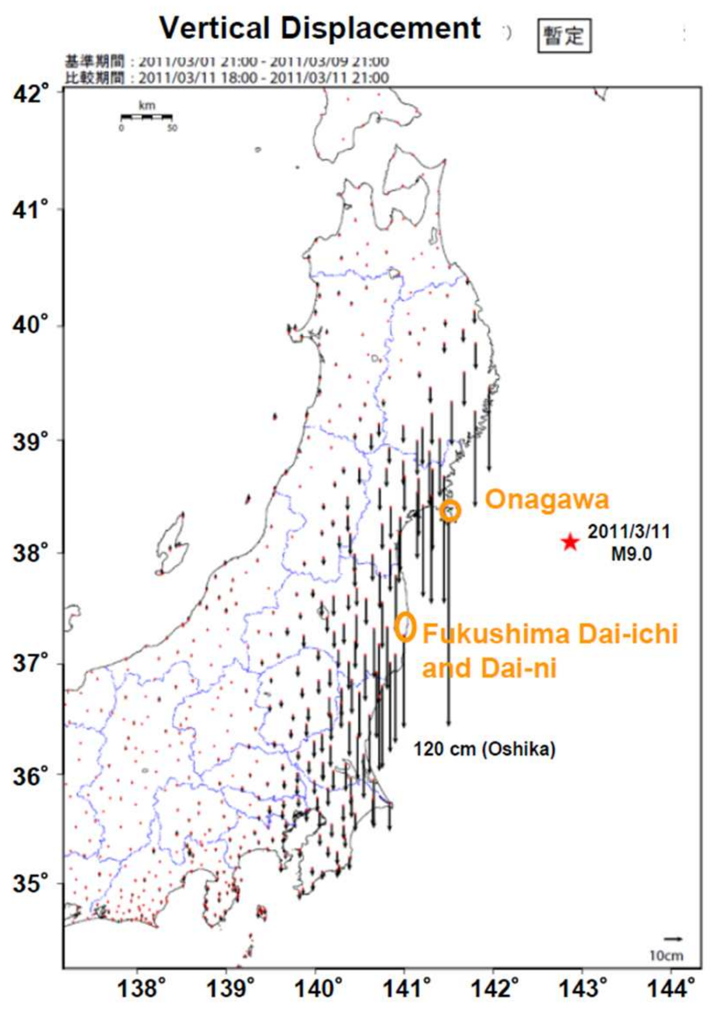
Coseismic Crustal Deformation





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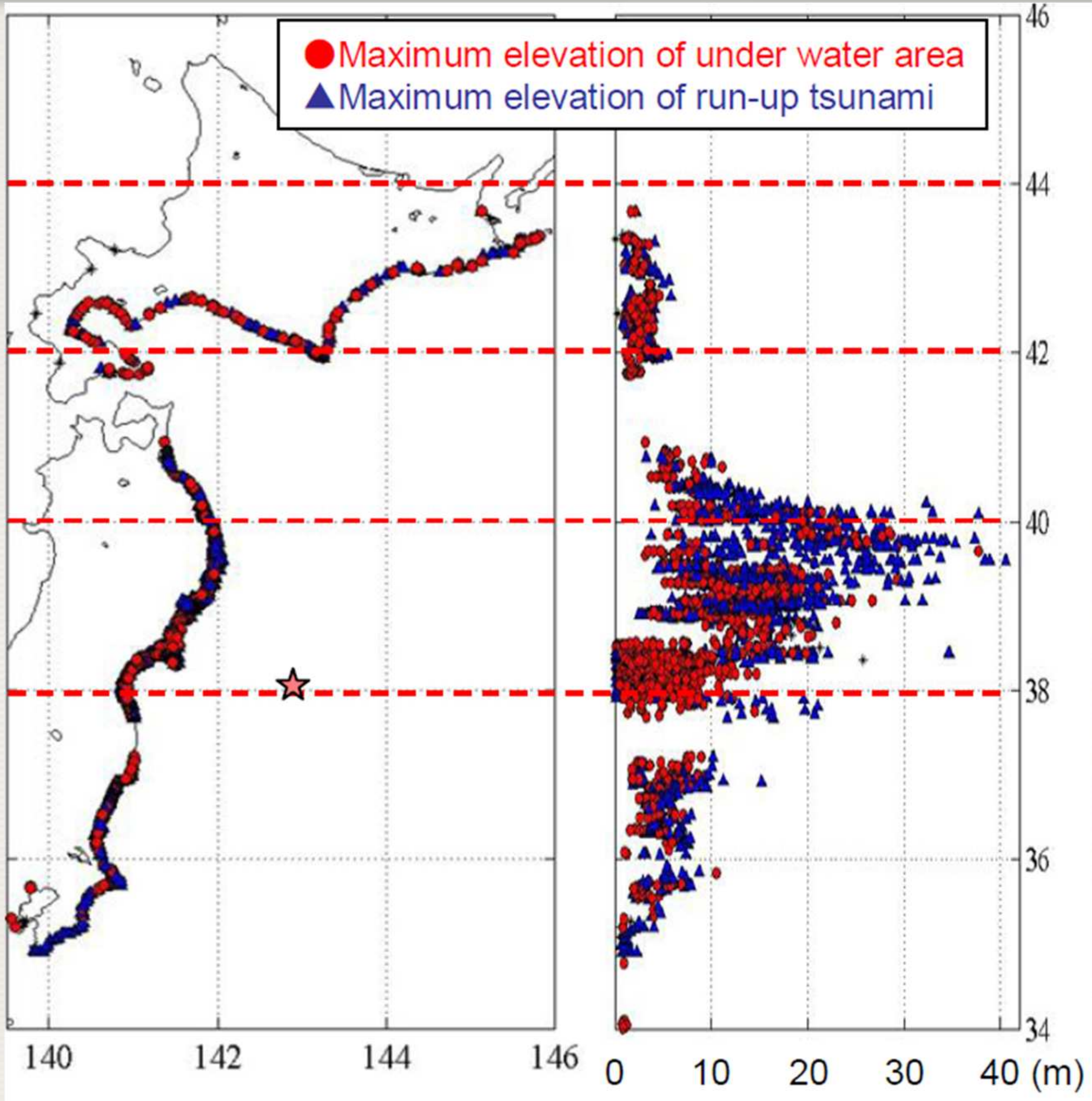
Maximum Elevation of Tsunami



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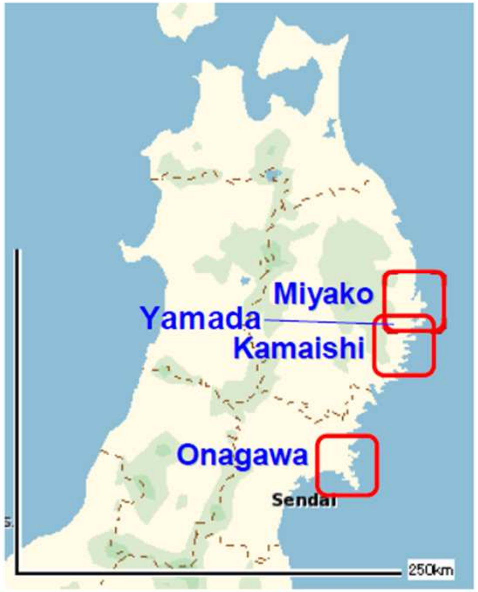
Damages of Seawall and Harbor Installation



Destruction by tsunami scouring

Destruction by wave pressure

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Casualities by the Earthquake and Tsunami

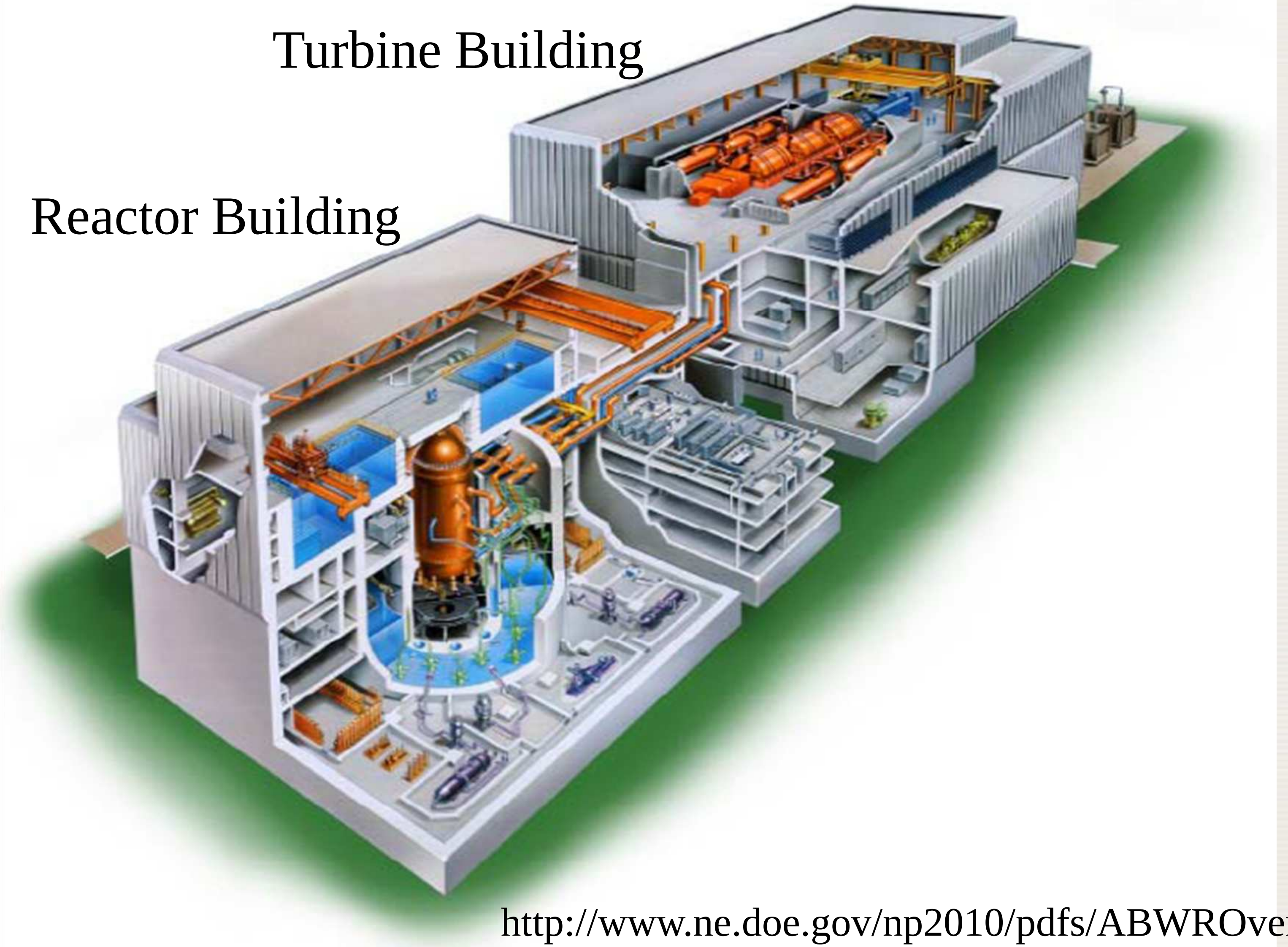
- Dead: 15,511
- Missing: 7,189

as of 30 June 2011

(The National Police Agency)

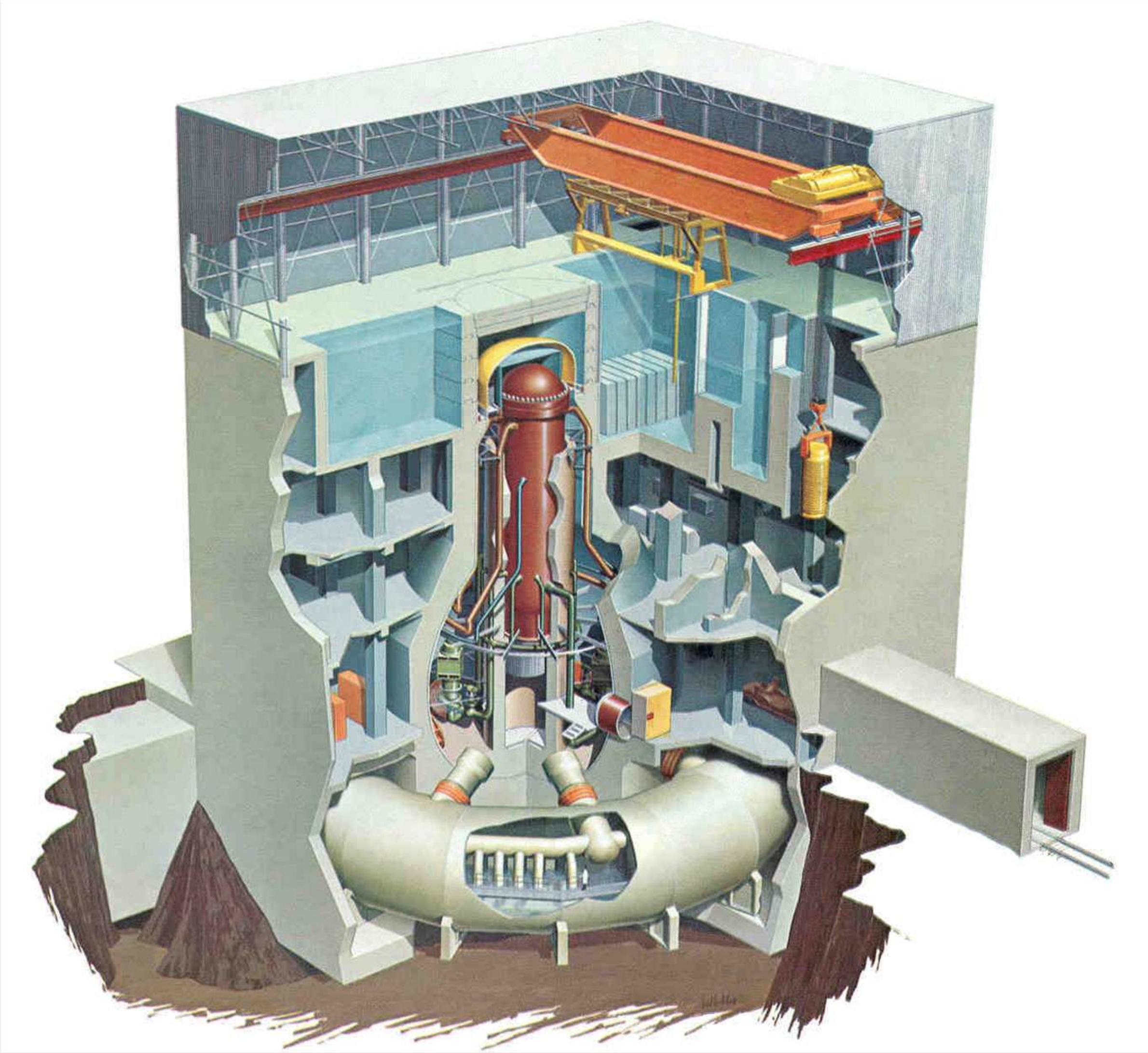
BWR Technologies and Safety Systems

Boiling Water Reactor (BWR) Plant



http://www.ne.doe.gov/np2010/pdfs/ABWROverview.pdf

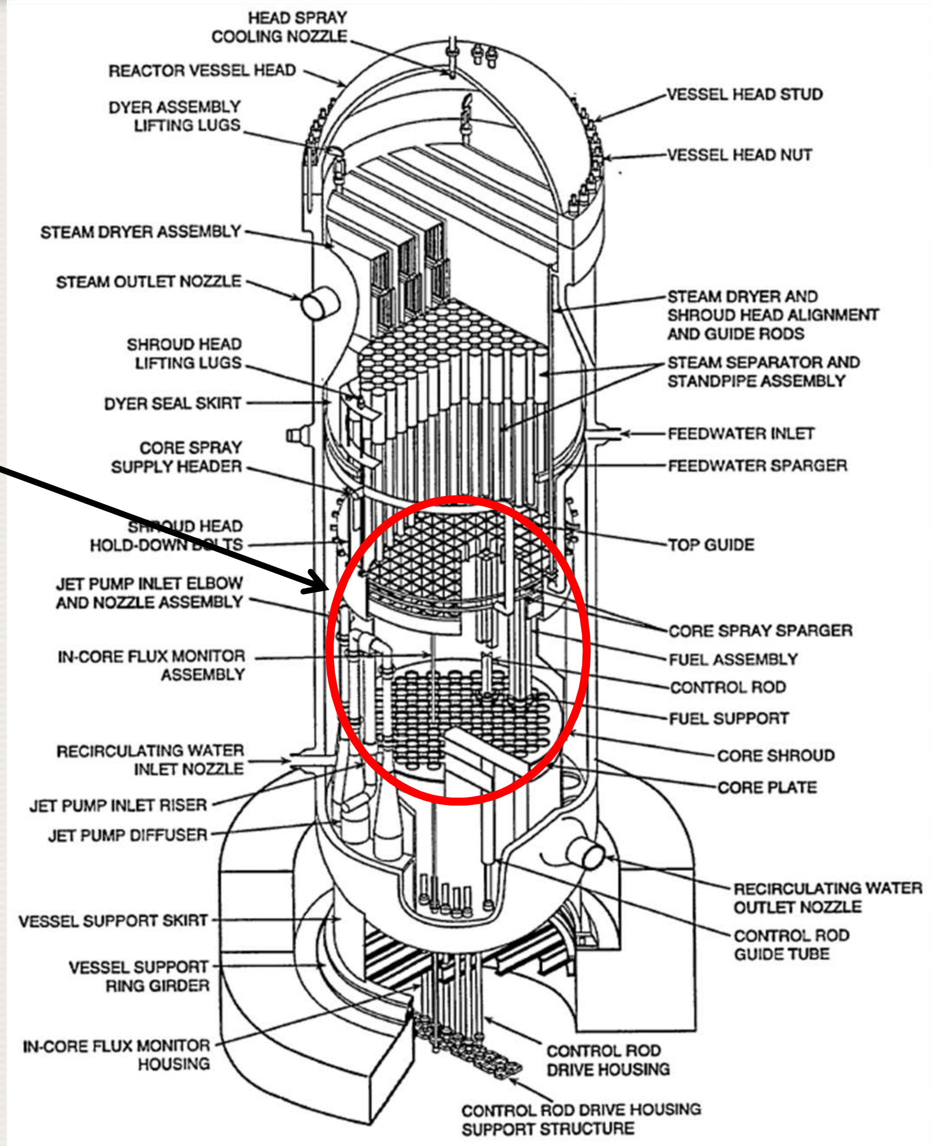
BWR: Reactor Building (R/B) and Primary Containment Vessel (PCV)



http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf

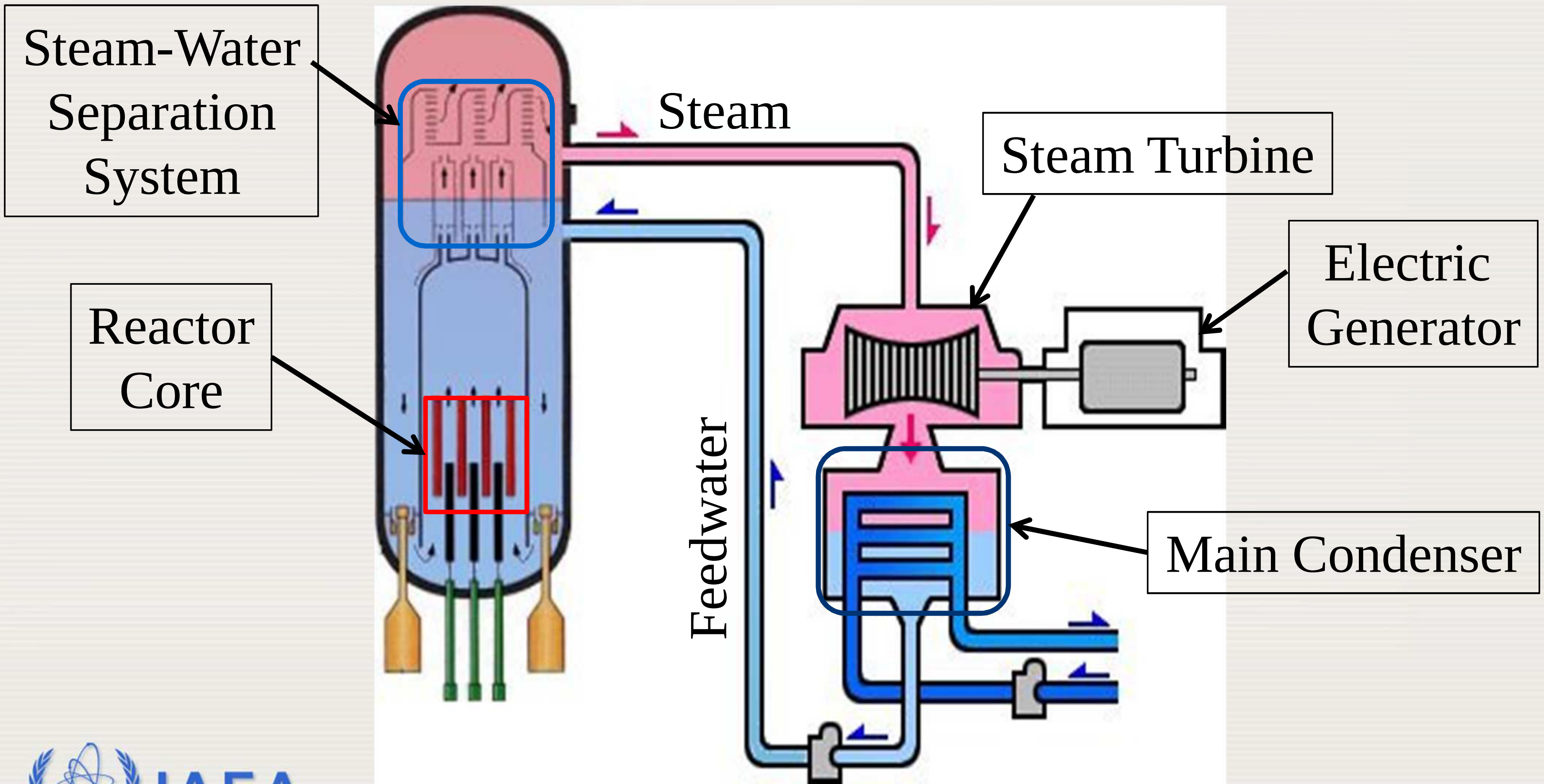
BWR: Reactor Pressure Vessel (RPV) and its Internals

Reactor Core



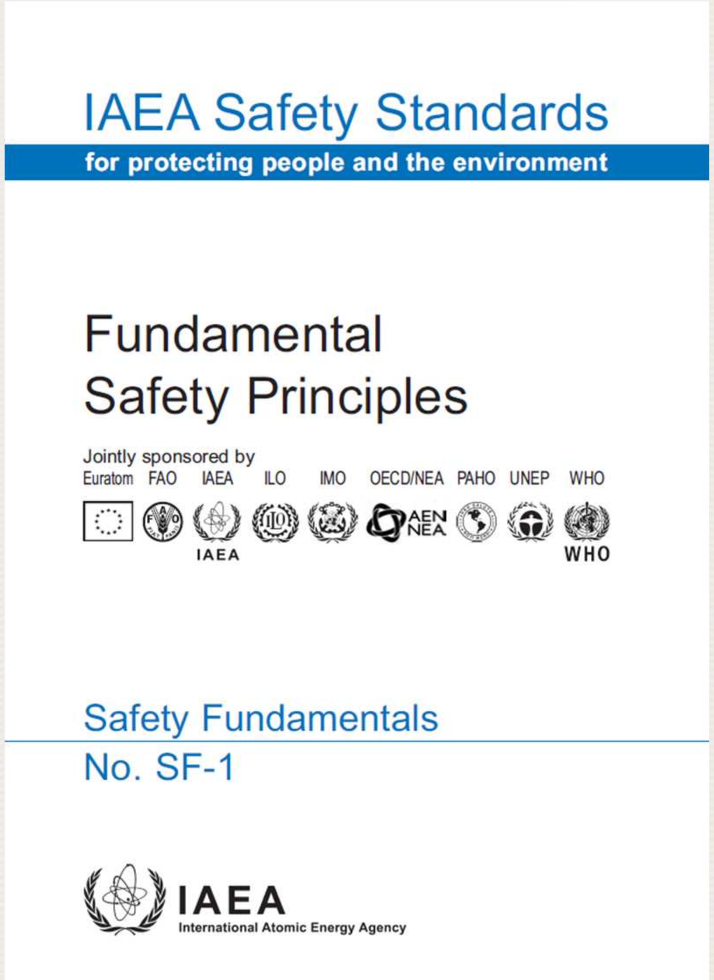
http://pbadupws.nrc.gov/docs/ML0230/ML023010606.pdf

BWR: Normal Operation



Nuclear Safety

- "Safety" in IAEA Safety Standards means the protection of people and the environment against radiation risk.
- It does not include non-radiation-related aspects of safety.



IAEA Safety Standards

for protecting people and the environment

Fundamental Safety Principles

Jointly sponsored by

Euratom FAO IAEA ILO IMO OECD/NEA PAHO UNEP WHO

Safety Fundamentals

No. SF-1

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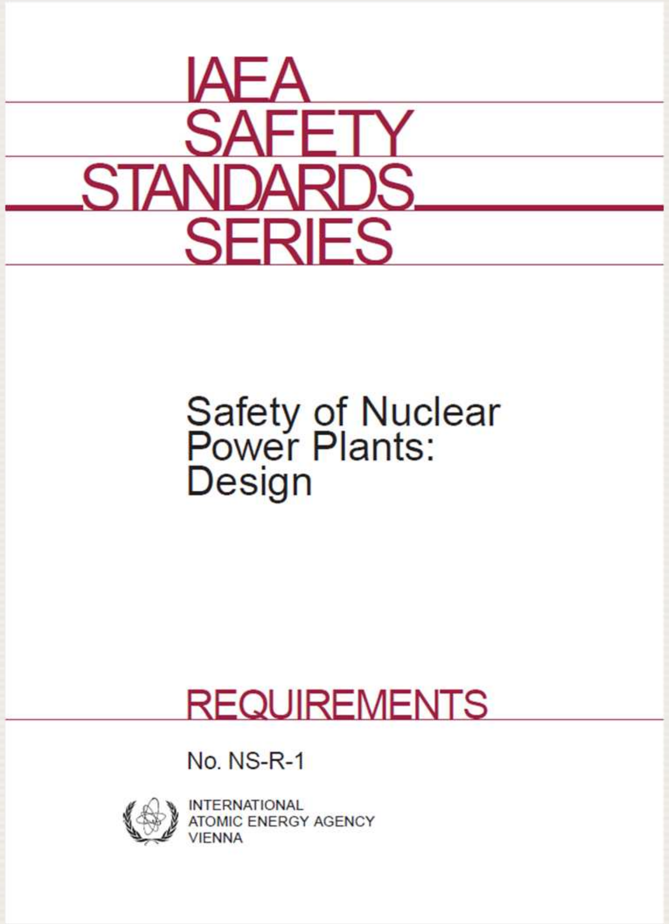
International Atomic Energy Agency

http://www-pub.iaea.org/MTCD/publications/PDF/Pub1273_web.pdf

Concept of Defence in Depth

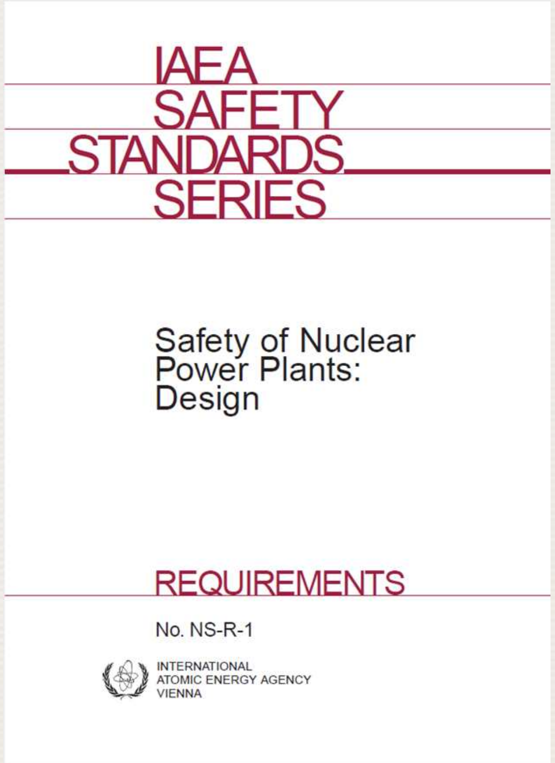
- "Application of the concept of defence in depth in the design of a plant provides a series of levels of defence (inherent features, equipment and procedures) aimed at preventing accidents and ensuring appropriate protection in the event that prevention fails."



http://www-pub.iaea.org/MTCD/publications/PDF/Pub1099_scr.pdf

Safety Functions

- “To ensure safety, the following fundamental safety functions shall be performed …:
  - (1) control of the reactivity;
  - (2) removal of heat from the core; and
  - (3) confinement of radioactive materials and control of operational discharges, as well as limitation of accident releases.”



http://www-pub.iaea.org/MTCD/publications/PDF/Pub1099_scr.pdf

Decay Heat

- Reactor cores continue to generate heat even after the fission reactions have completely stopped.
- The heat is produced by decay of fission products, which is called ‘Decay Heat’.
- The order of the decay heat is 1% of the rated power several hours after the reactor shutdown and is 0.5% at several days.
- Decay heat is a main concern in nuclear safety.

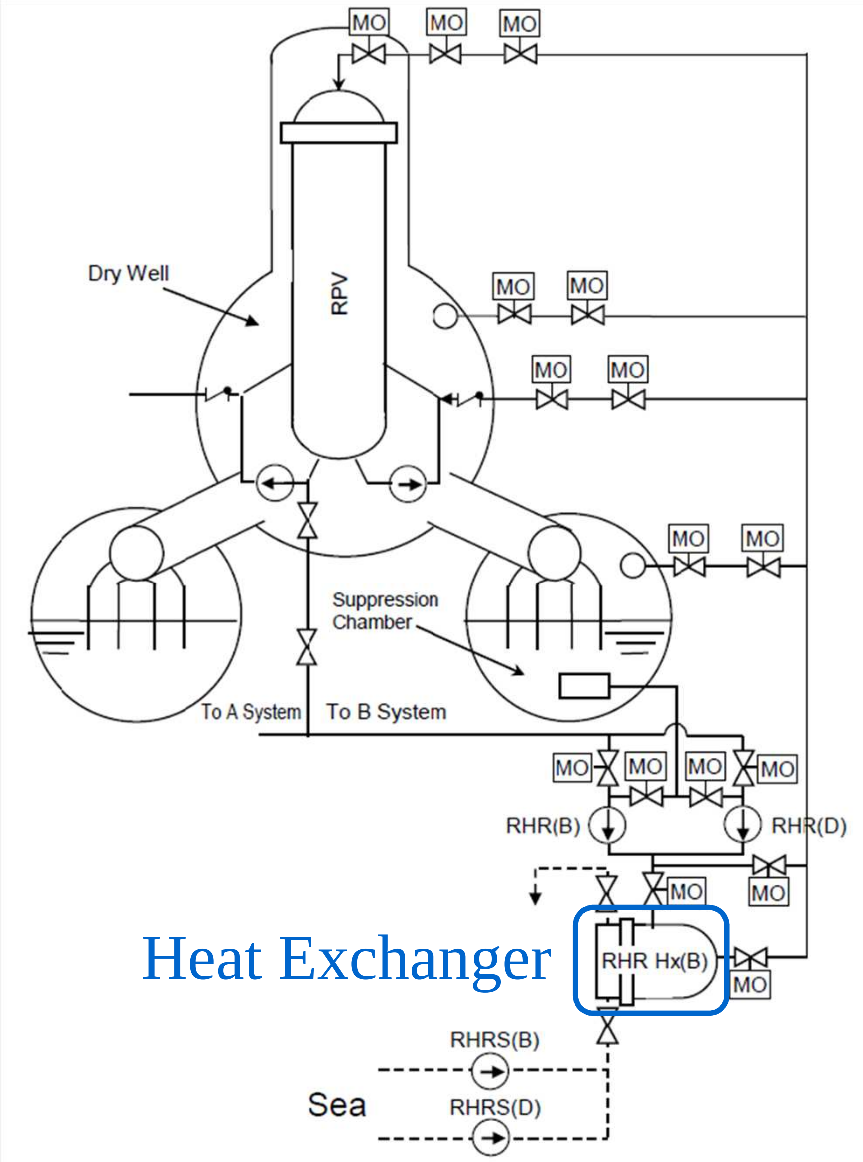
BWR Safety Systems

- Control of Reactivity
  - Control Rods (CR)
  - Standby Liquid Control system (SLC)
- Removal of Heat from the Core
  - Residual Heat Removal system (RHR)
  - Emergency Core Cooling System (ECCS)
- Confinement of Radioactive Materials
  - Primary Containment Vessel (PCV)
  - Other Barriers (RPV, Reactor/Building etc.)

Residual Heat Removal System

Main Functions:

1) Shutdown cooling mode
   - Remove decay heat after the reactor is shut down by cooling reactor water with heat exchangers.
   - Heat is discharged ultimately to the sea through sea water cooling system.
2) Low Pressure Core Injection mode (LPCI)
3) Other modes



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Emergency Core Cooling System (ECCS)

- Divided into:
  - High Pressure (HP) system; and
  - (Automatic Depressurization System +) Low Pressure (LP) system.
- Energy for operation:
  - Turbine Driven (T/D) by steam from the RPV;
  - Motor Driven (M/D) by AC power; or
  - Natural Force Driven (e.g. gravity).

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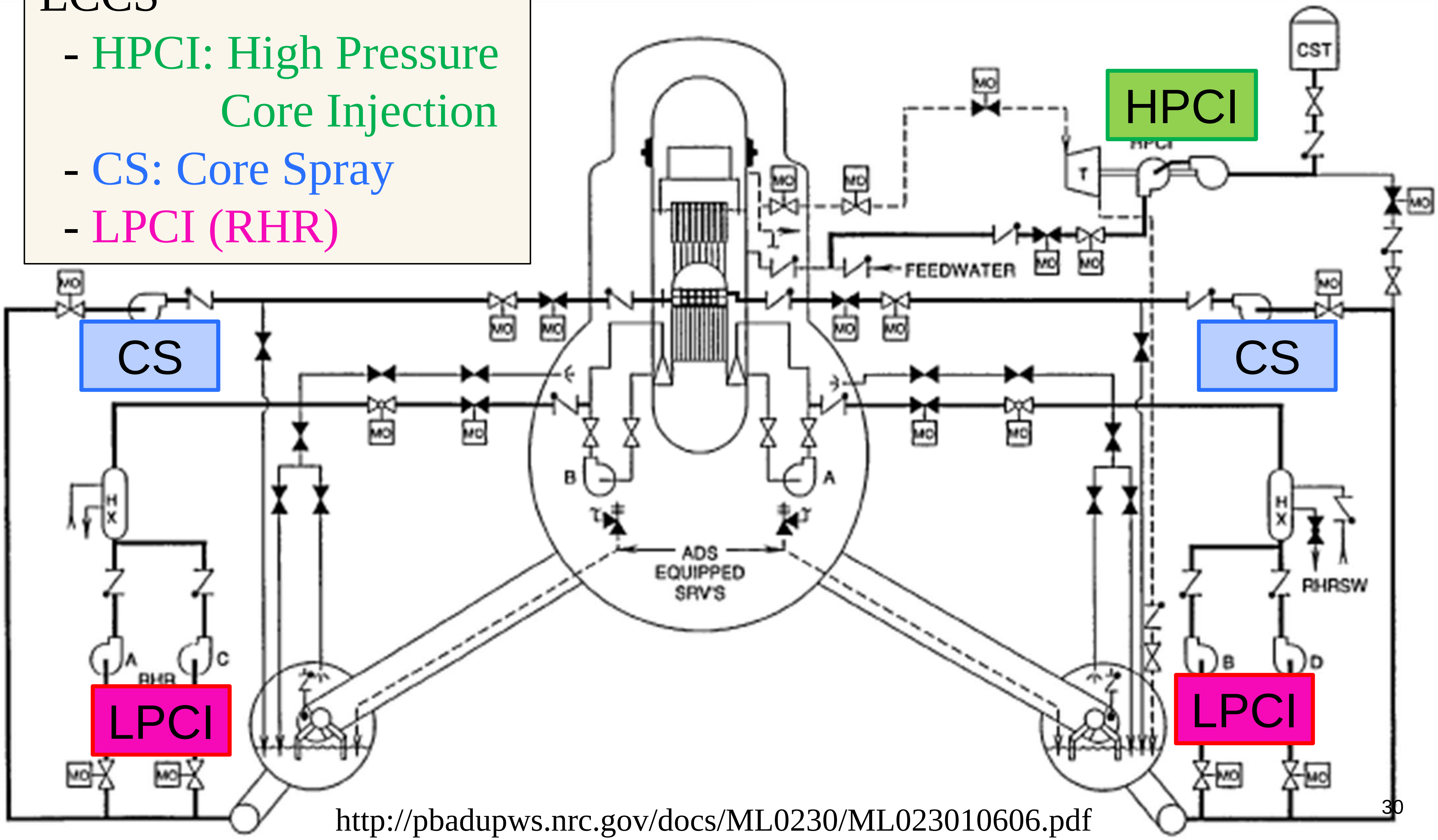
BWR/4 Emergency Core Cooling System

ECCS

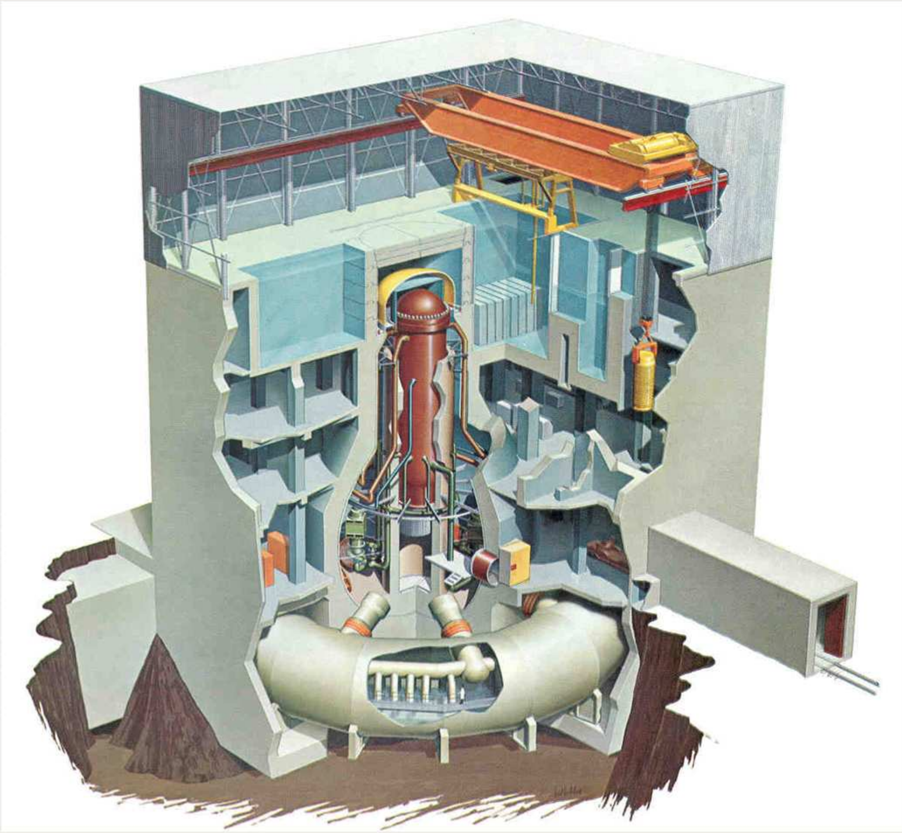
- HPCI: High Pressure Core Injection
- CS: Core Spray
- LPCI (RHR)



http://pbadupws.nrc.gov/docs/ML0230/ML023010606.pdf

BWR: Primary Containment Vessel (PCV) - MARK I Type -

- Consist of two separate volumes, a drywell and a wetwell, connecting with vent pipes.
- The drywell is a bulb-shape vessel made of steel and encloses the RPV.
- The wetwell is a torus with a large amount of water pool called ‘Suppression Pool’, where steam is injected and condensed to suppress the pressure increase in the PCV.



http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf

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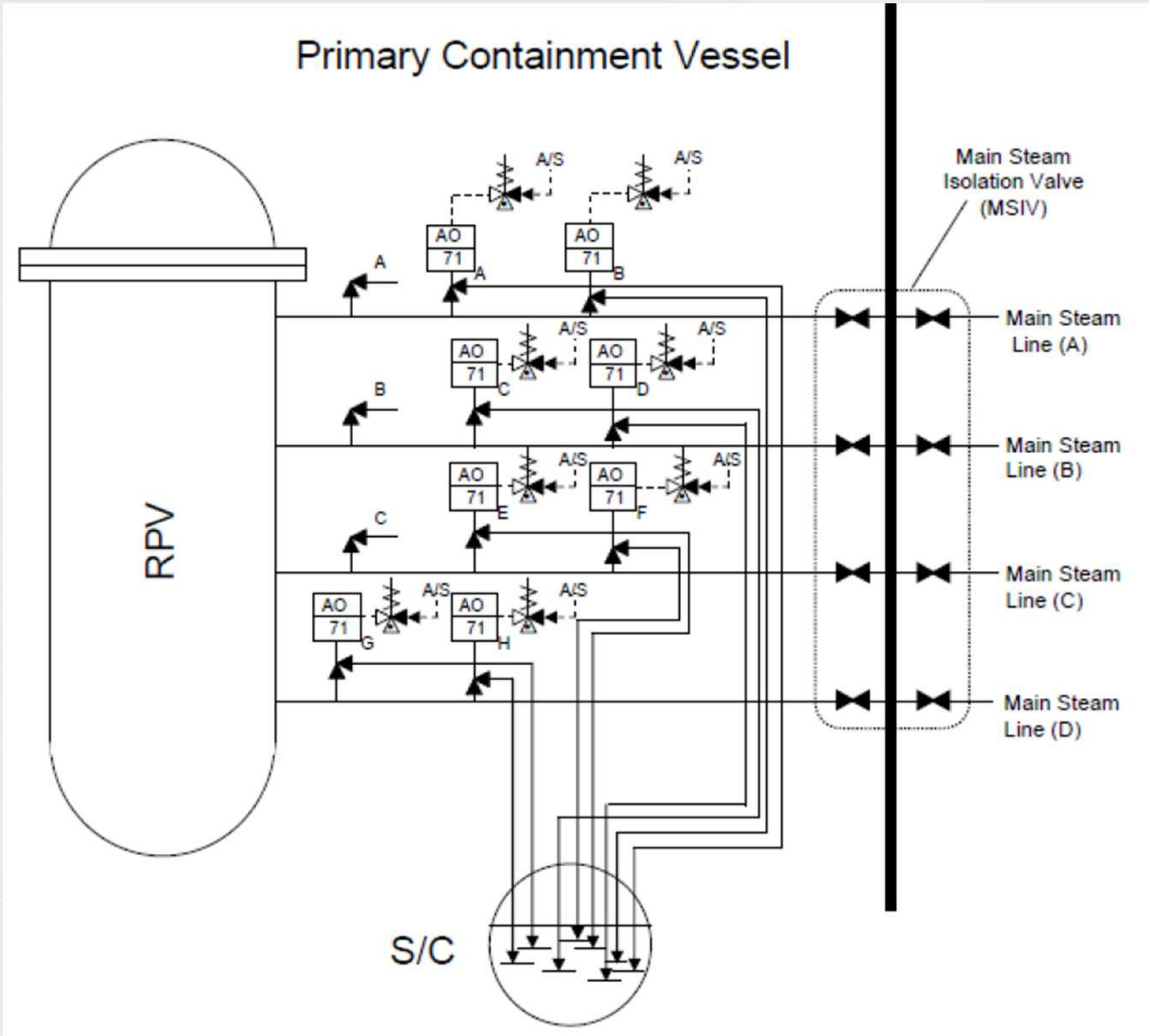
Main Steam Isolation Valve and Safety/Relief Valve (MSIV) (SRV)

- In an emergency case when the RPV needs to be isolated, the MSIV are closed.
- If the RPV pressure increases to a preset pressure level, an SRV opens automatically and steam is injected into the suppression pool.



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Event Sequence at Fukushima Daiichi

- Plant Responses and Operators Actions -

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Events Sequence after Earthquake [1] (Fukushima Daiichi NPS Unit 3)

	External Events		Internal Events and Actions	
11 March 14:46	Earthquake	⇨	Reactor Automatic Shutdown	14:47
	Loss of External Power	⇨	Emergency Diesel Generators Start	14:48
around 15:30	Tsunami			

: Favorable (Designed) Response

: Unfavorable Response

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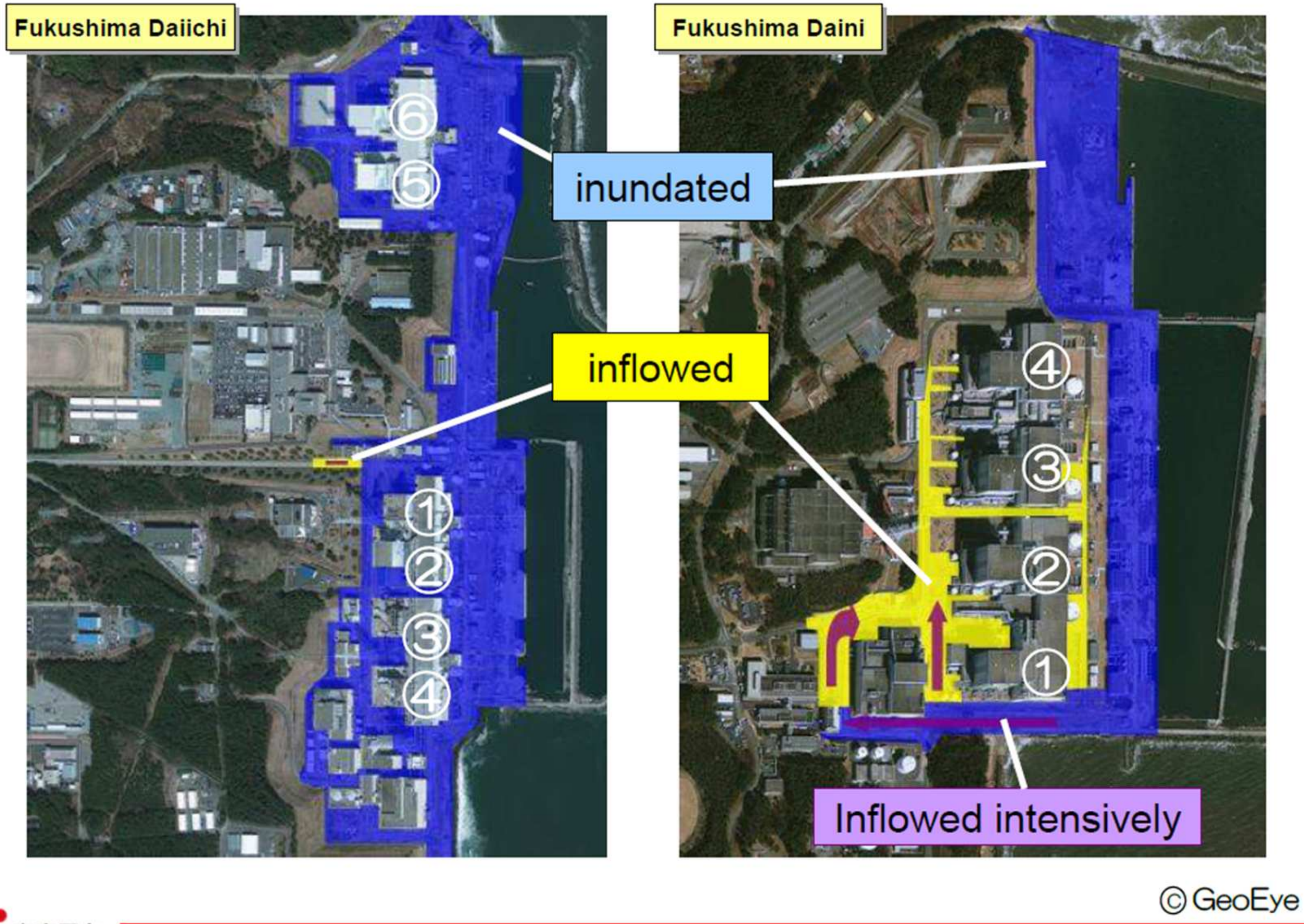
Inundated and Inflowed Area by Tsunami

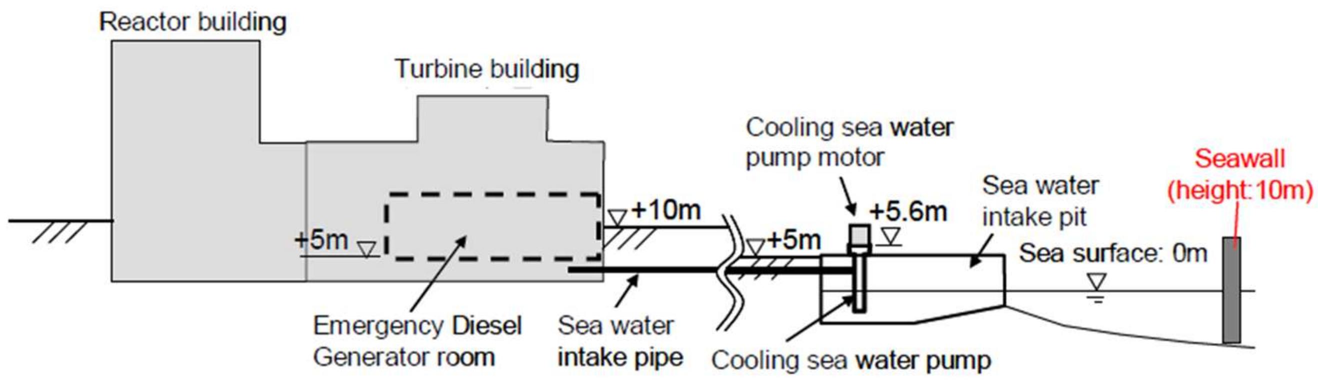
Inundated and Inflowed Area at Fukushima Daiichi and Daini Site



http://www.tepco.co.jp/en/nu/fukushima-np/f1/images/f12np-gaiyou_e_1.pdf

Fukushima Daiichi and Tsunami

Cross section of Fukushima Dai-ichi (Unit-1)



Reference: The Tokyo Electric Power Co., Inc. Release
[Online].http://www.tepco.co.jp/tepconews/pressroom/110311/index-j.html

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Seaside Components after Tsunami (Daiichi)

http://www.tepco.co.jp/en/news/110311/images/110411_1f_tsunami_1.jpg

Events Sequence after Earthquake [1]
(Fukushima Daiichi NPS Unit 3)

	External Events	Internal Events and Actions	
11 March 14:46	Earthquake	Reactor Automatic Shutdown	14:47
	Loss of External Power	Emergency Diesel Generators Start	14:48
around 15:30	Tsunami	Diesel Generators Stopped	15:38
		Cooling Sea Water Pump Stopped	
15:42	Declaration of All AC Power Loss (Station Black Out)	Water Injection by RCIC	16:03

Green : Favorable (Designed) Response

Orange : Unfavorable Response

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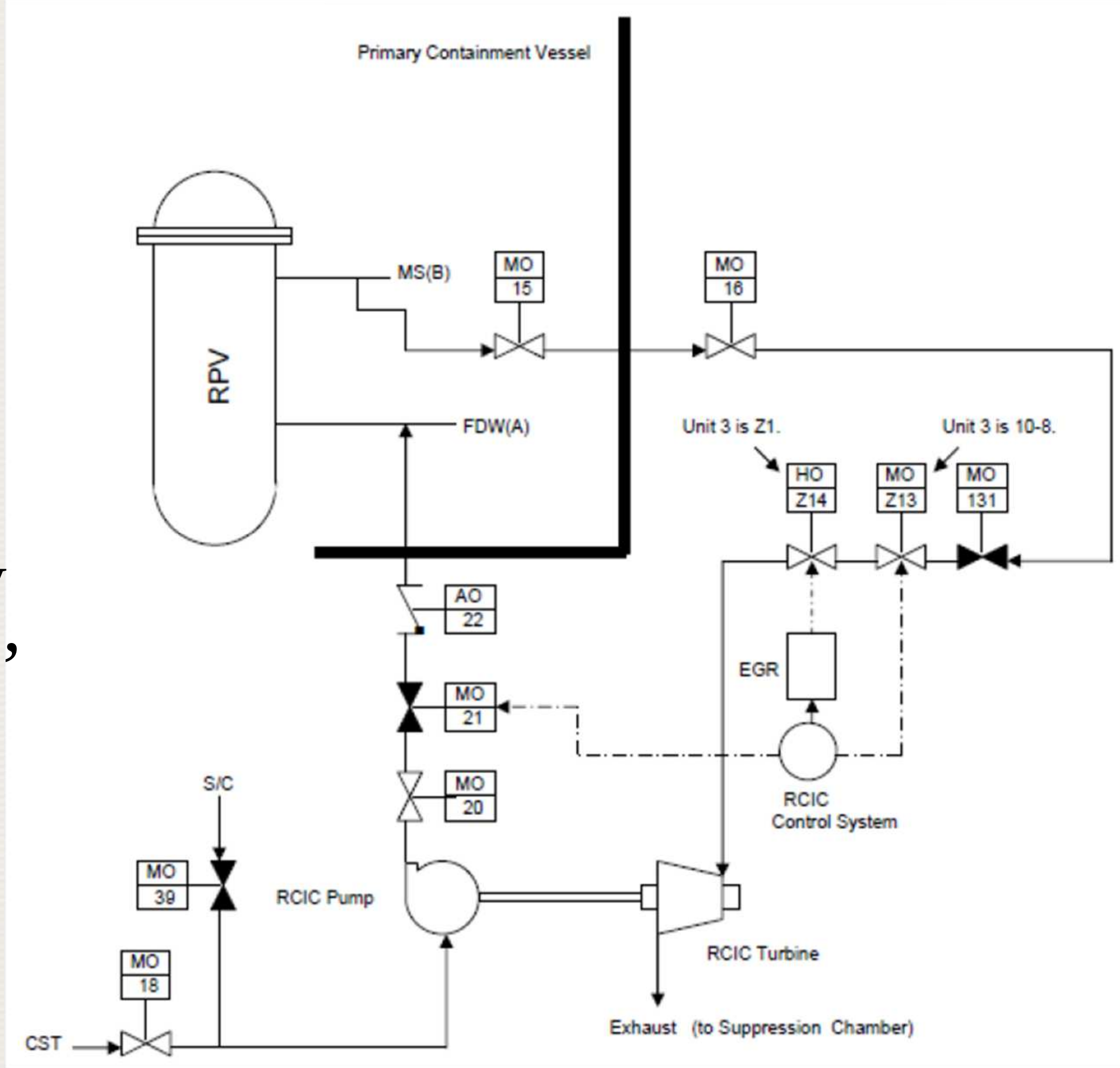
Reactor Core Isolation Cooling System (RCIC)

- To inject water into the reactor when the reactor is isolated.
- Driven by steam from the RPV.
- Actuated automatically by a ‘Low Water Level’ signal or manually.



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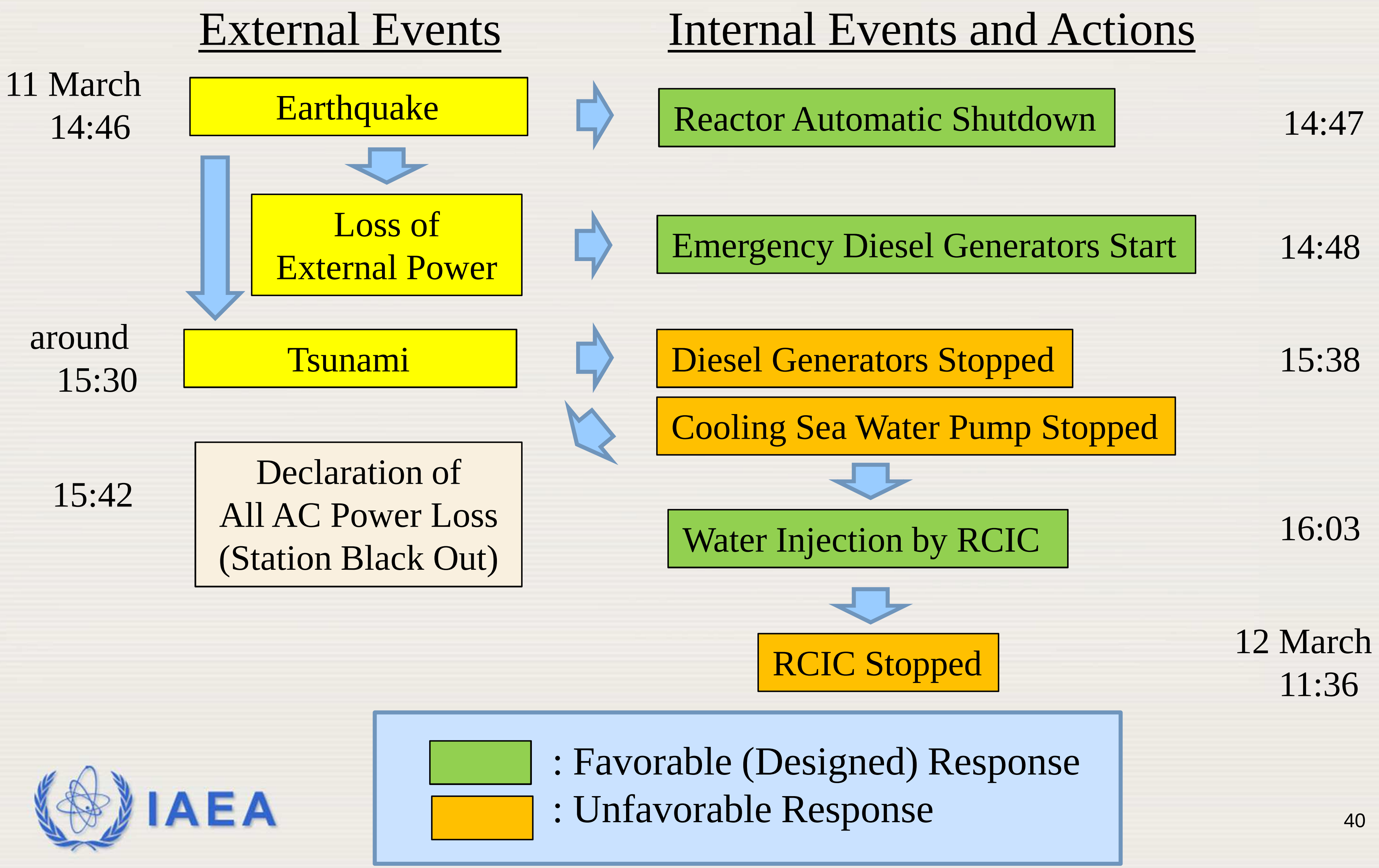
Events Sequence after Earthquake [1]
(Fukushima Daiichi NPS Unit 3)



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Events Sequence after Earthquake [2]
(Fukushima Daiichi NPS Unit 3)

External Events

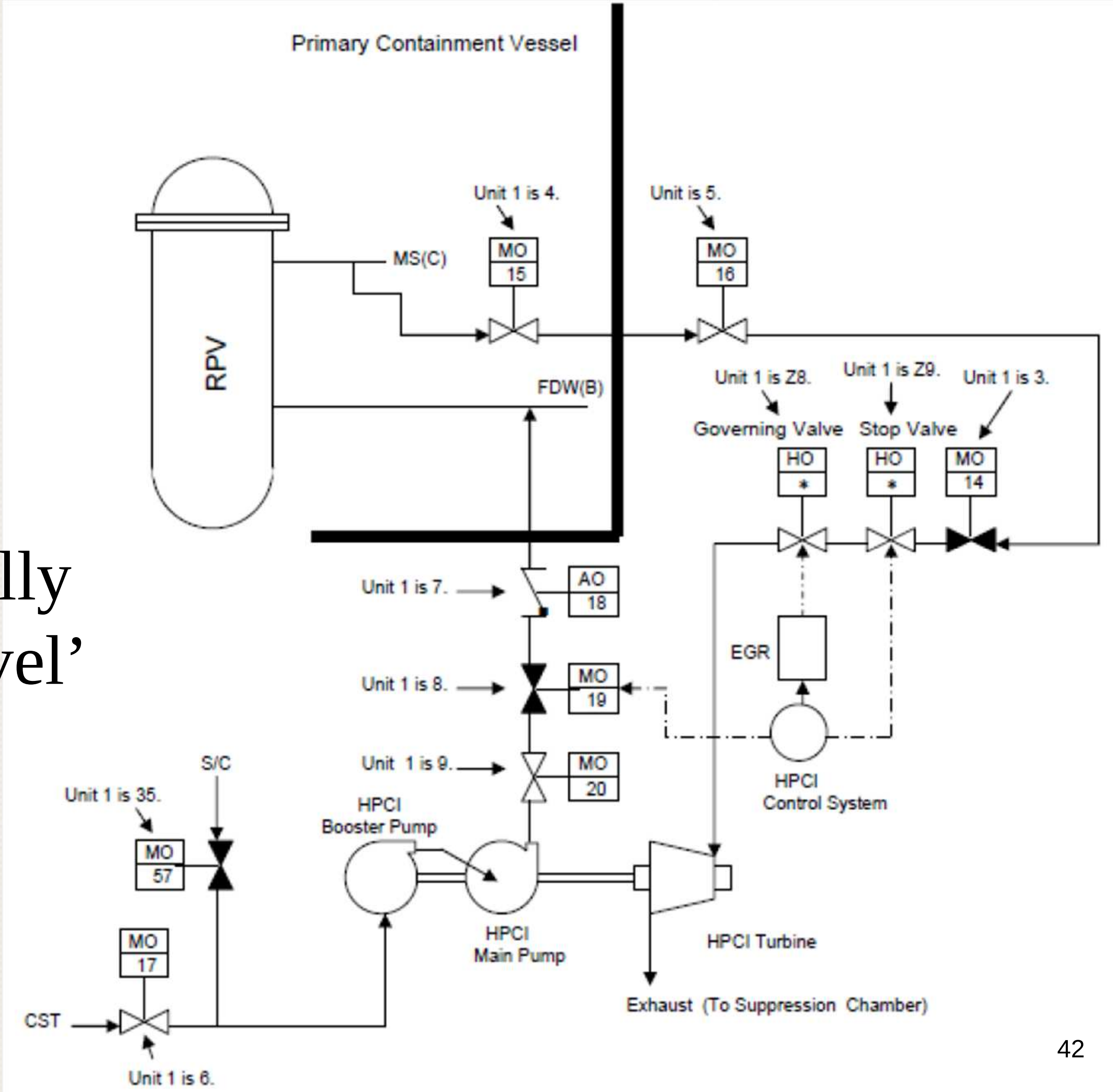
Internal Events and Actions

Water Injection by HPCI

12 March
12:35

High Pressure Core Injection System (HPCI)

- To inject water into the reactor in an emergency case.
- Driven by steam from the RPV.
- Actuated automatically by a 'Low Water Level' signal or manually.



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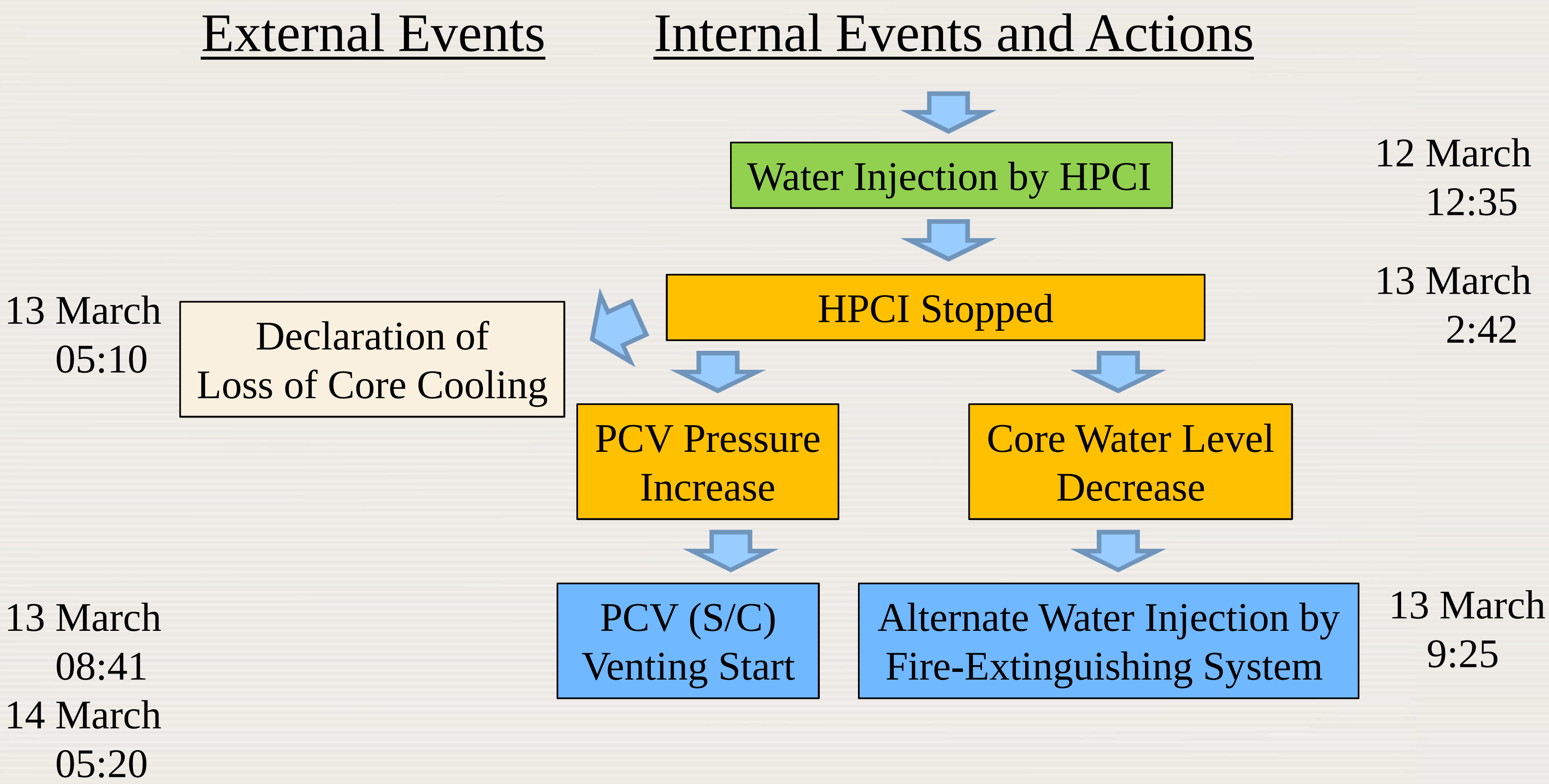
Events Sequence after Earthquake [2]
(Fukushima Daiichi NPS Unit 3)



Accident Management (AM)

- Prevention and mitigation measures to a Severe Accident, an event that significantly exceeds the design basis event and could result in serious damage to the reactor core.
- Implemented by TEPCO after Chernobyl accident voluntarily (, not required by law):
  - ✓ AM Guidelines prepared;
  - ✓ PCV vent and alternate water injection systems installed; and
  - ✓ Operators trained.

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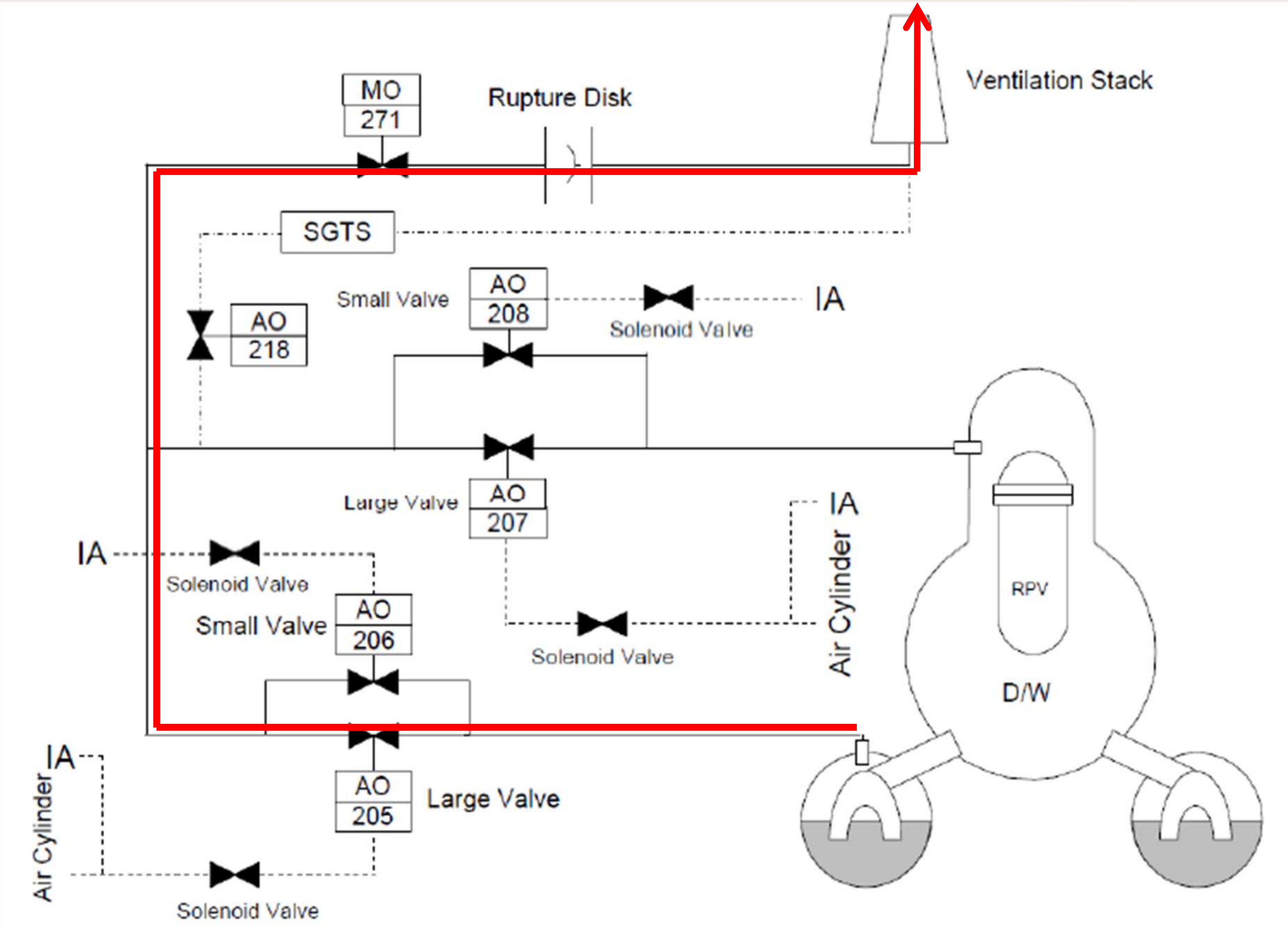
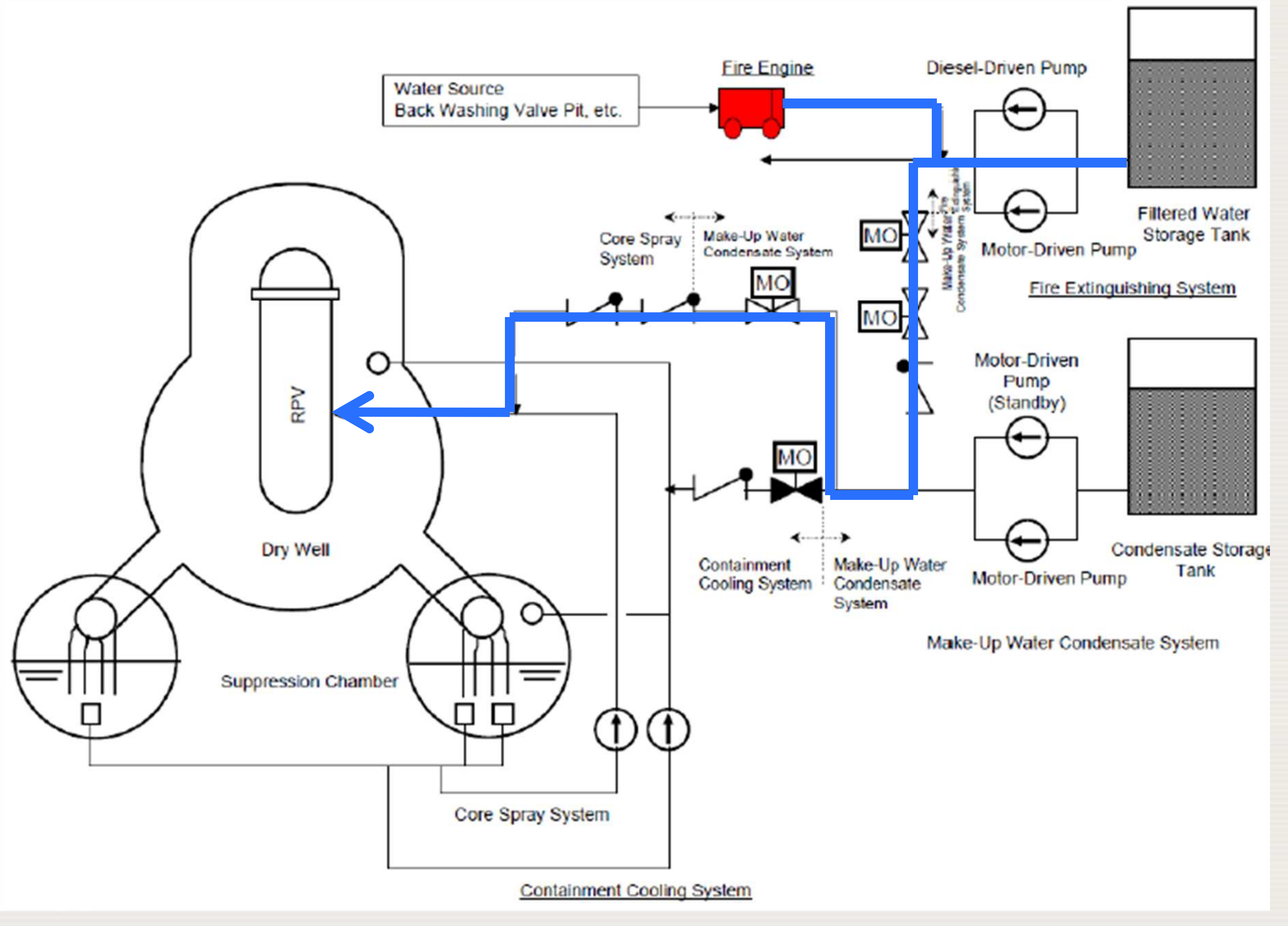
PCV Venting System



Alternate Water Injection System



Events Sequence after Earthquake [2]
(Fukushima Daiichi NPS Unit 3)

External Events | Internal Events and Actions

Water Injection by HPCI — 12 March 12:35

HPCI Stopped — 13 March 2:42

13 March 05:10 — Declaration of Loss of Core Cooling

PCV Pressure Increase

Core Water Level Decrease

PCV (S/C) Venting Start

Alternate Water Injection by Fire-Extinguishing System — 13 March 9:25

13 March 08:41, 14 March 05:20 — Controlled Discharge of Radioactive Materials

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Events Sequence after Earthquake [3] (Fukushima Daiichi NPS Unit 3)

<u>External Events</u>

<u>Internal Events and Actions</u>

PCV Venting Start

Alternate Water Injection by Fire-Extinguishing System

Venting line?

Fuel Uncovered/Damaged

Hydrogen Generation

Hydrogen Accumulation in Reactor Building (R/B)

Leakage?

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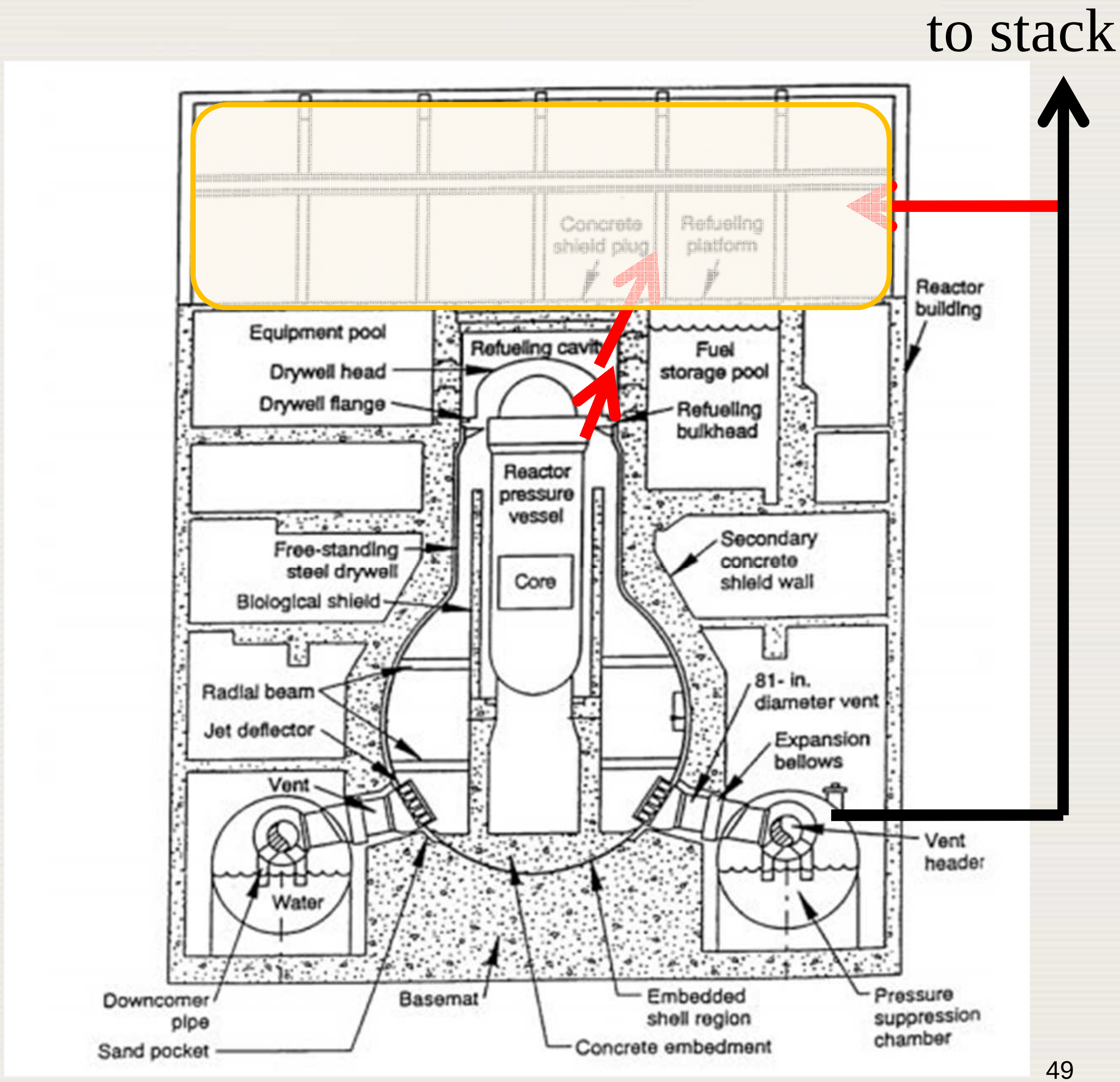
BWR: Primary Containment Vessel (PCV) - MARK I Type -

- Two possibilities to accumulate hydrogen gas in the upper part of the R/B.
  - Leakage from the PCV; or
  - Reverse flow from venting line.



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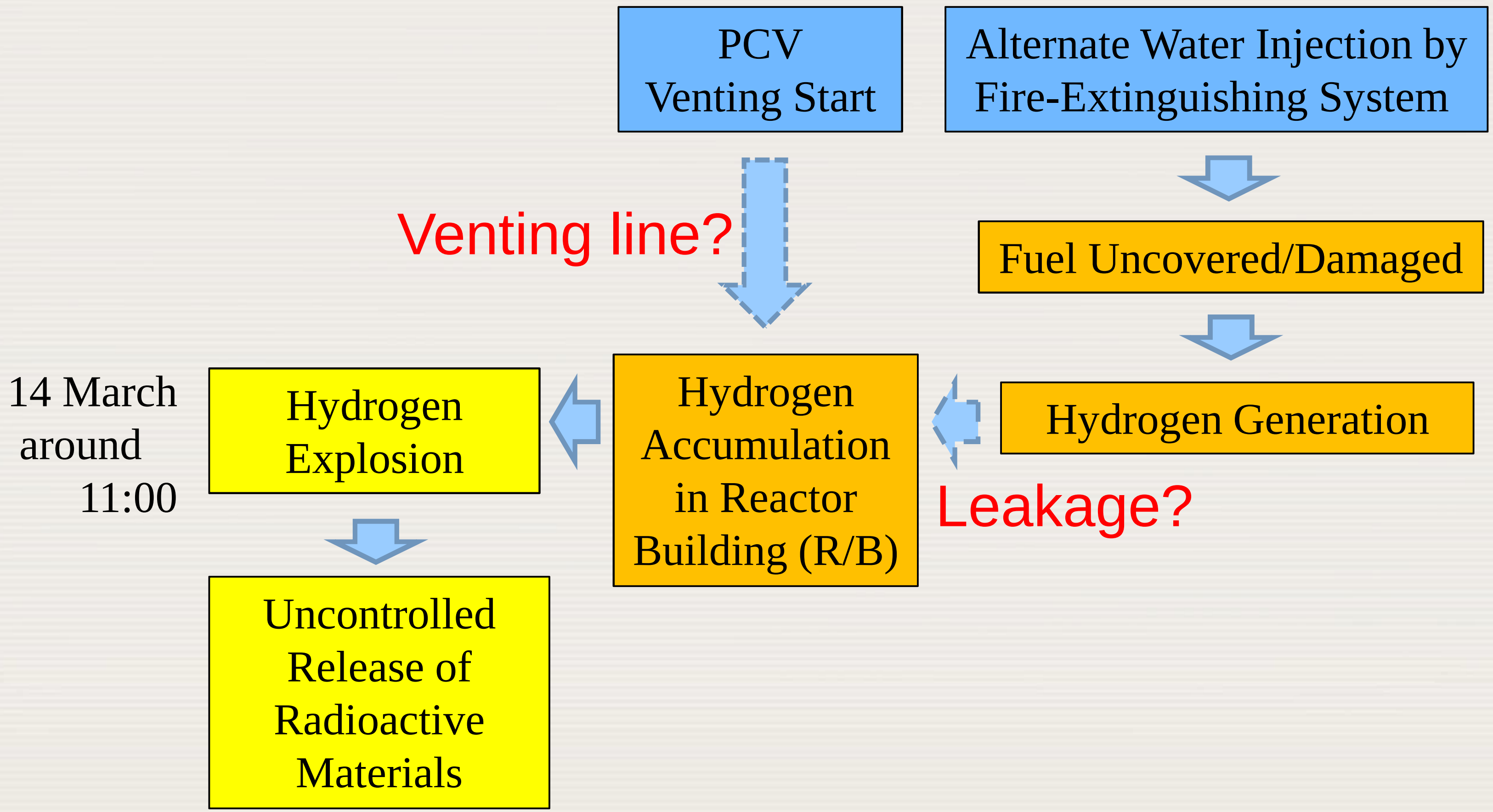
Events Sequence after Earthquake [3]
(Fukushima Daiichi NPS Unit 3)

External Events   Internal Events and Actions



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Unit 3 after Explosion (April 10)

http://www.tepco.co.jp/en/news/110311/images/110411_1f_5.jpg

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Preliminary Lessons Learned

Preliminary Lessons Learned : Design Aspect

- Safety Functions
  - Reactivity control was fully satisfied.
    - All control rods were inserted into the core successfully in spite of much higher acceleration than the expectation.
  - Heat removal was satisfied at first, but failed finally.
    - All external powers were lost simultaneously, but Emergency Diesel Generators (D/Gs) started automatically as designed.
    - Tsunami made all D/Gs inoperable and destroyed the sea water cooling system.
    - RCIC and HPCI worked without AC power and cooled the core for the first 1.5 days (Unit 3).
  - Confinement of radioactive materials was failed.

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Preliminary Lessons Learned : Design Aspect (continued)

- Design Basis
  - Protective measures against natural hazards should be reviewed and strengthened if necessary.
    - The height of tsunami exceeded the expectation and destroyed the seaside structures and components.
  - Power supply is essential. Both external and internal emergency power should be more reliable. And long-term ‘All AC Power Loss’ should be prepared.

Preliminary Lessons Learned : Design Aspect (continued)

- Accident Management (AM)
  - AM should be enhanced to prevent hydrogen explosion.
    - AM was considered and prepared before the accident, and it was helpful to some extent.
    - But it was not enough to prevent hydrogen accumulation and explosion in the R/B.

      (The path to the R/B has not been identified.)
  - The on-site Emergency Response Centre demonstrates workers could stay under a severe circumstance.
    - Seismically robust, suitably shielded against radiation, ventilated and well equipped Centre is necessary.

Daily Meeting at Emergency Response Center (Fukushima Daiichi NPS)

http://www.tepco.co.jp/en/news/110311/images/110408_base-isolation_4.jpg

Current Status and Recovery Plan

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Current Status (Fukushima Daiichi NPS)

- Units 1-3: Injecting fresh water by temporary motor-driven pumps continues in order to cool the fuels in the reactors.
- Units 1-3: Pumping out of the contaminated water with high radioactive materials in the turbine buildings in progress.
- Unit 4: No fuels in the reactor.
- Unit 5&6: Under cold shutdown.

Plant Status: Fukushima Daiichi

Plant Status: Fukushima Daiichi

- Units 1-3: Injecting fresh water by temporary motor-driven pumps in order to cool the fuels in reactors.
- Units 2: Have launched stable circulating cooling by installing temporary heat exchangers in order to cool the fuels in spent fuel pool (SFP).
- Units 1-3: Found contaminated water with high radioactive materials in turbine buildings. Pumping out of the water into the Central Radioactive Waste Disposal Facility, etc. is in progress.
- Unit 1: Injecting N_2 into PCV to lower the possibility of hydrogen explosion. Also scheduled for Units 2&3.
- Units 5&6: Under cold shutdown.

			#1 460MW	#2 784MW	#3 784MW	#4 784MW	#5 784MW	#6 1,100MW
Pre-Earthquake Status			Operating			Shutdown for Outage		
After Earthquake	Shutdown		○ Automatic Shutdown			—	—	—
	Cooling	Reactor	△ Offsite Power Freshwater	△ Offsite Power Freshwater	△ Offsite Power Freshwater	– Fuels have been removed	○ Cold Shutdown	○ Cold Shutdown
		Pool	△ Freshwater	○ Circulating cooling system	△ Freshwater	△ Freshwater	○	○
	*Containment		X Highly contaminated water	X Highly contaminated water	X Highly contaminated water	△	○	○

*There are damages on upper part of the Reactor buildings of Unit 1,3 and 4. There is a possibility of malfunction of containment in suppression chamber of Unit2. Holes were drilled on the roof of reactor buildings of Units 5 and 6 to prevent hydrogen accumulation.

*Results of the provisional analysis show that the fuel pellets of Unit 1melted and fell to the bottom of RPV at a relatively early stage after the tsunami reached the plant. However, as the temperature of the RPV of Unit 1 is in the range of 100℃ - 120℃, stable cooling is being achieved.

http://www.tepco.co.jp/en/nu/fukushima-np/f1/images/f12np-gaiyou_e_2.pdf

Recovery Plans

- TEPCO Chairman's Announcement on 17 April.
  - The 1st Stage (in 3 months):
    - Cool the reactors in a stable manner; and
    - Prevent water with high levels of radioactivity from flowing out of the plant.
  - The 2nd Stage (in 6 to 9 months):
    - Achieve a cold shutdown of the reactors; and
    - Reduce the total amount of radioactive water.
- On-going with minor modifications.

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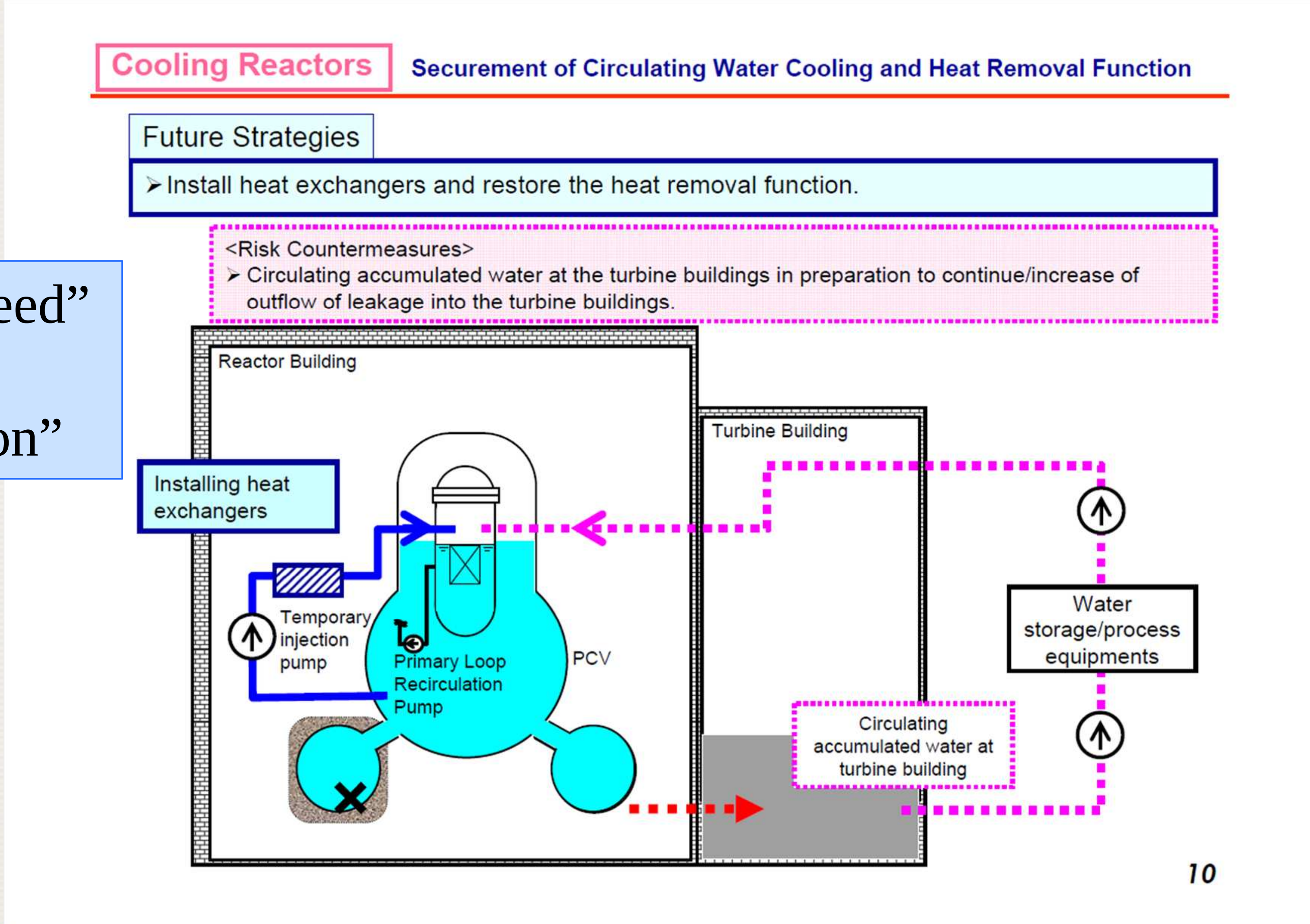
Recovery Plan: Cooling Reactors

“Feed and Bleed”

“Circulation”



Summary

Summary

- One of the most severe nuclear accidents has occurred at Fukushima Daiichi NPS triggered by the earthquake off the northeast coast of Japan and the subsequent tsunami waves.
- Efforts to stabilize the reactor units continue now and it is expected to take several months.
- To date no health effects have been reported as a result of radiation exposure from the accident.
- We should learn lessons to enhance safety of nuclear facilities in the world.

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Main Information Sources

1. "Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety – The Accident at TEPCO's Fukushima Nuclear Power Stations –", Government of Japan, June 2011 (http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html)
2. "Analysis of Operating Records and Accident Records Fukushima Daiichi NPS at Time of the Tohoku-Pacific Ocean Earthquake and an Evaluation of its Effects", Tokyo Electric Power Company, 23 May 2011. (In Japanese) (http://www.nisa.meti.go.jp/earthquake/files/houkoku230523-1.pdf)
3. Status of Fukushima Daiichi and Fukushima Daini Nuclear Power Stations after Great East Japan Earthquake, TEPCO Homepage (http://www.tepco.co.jp/en/nu/fukushima-np/index-e.html)

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...Thank you for your attention.

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