The March 2011 Earthquake and Tsunami in Japan: A Nuclear Perspective

Mary Lou Dunzik-Gougar, PhD
Associate Chair of Nuclear Engineering and Health Physics
Idaho state University
and
Executive Committee of the Fuel Cycle and Waste Management Division
American Nuclear Society

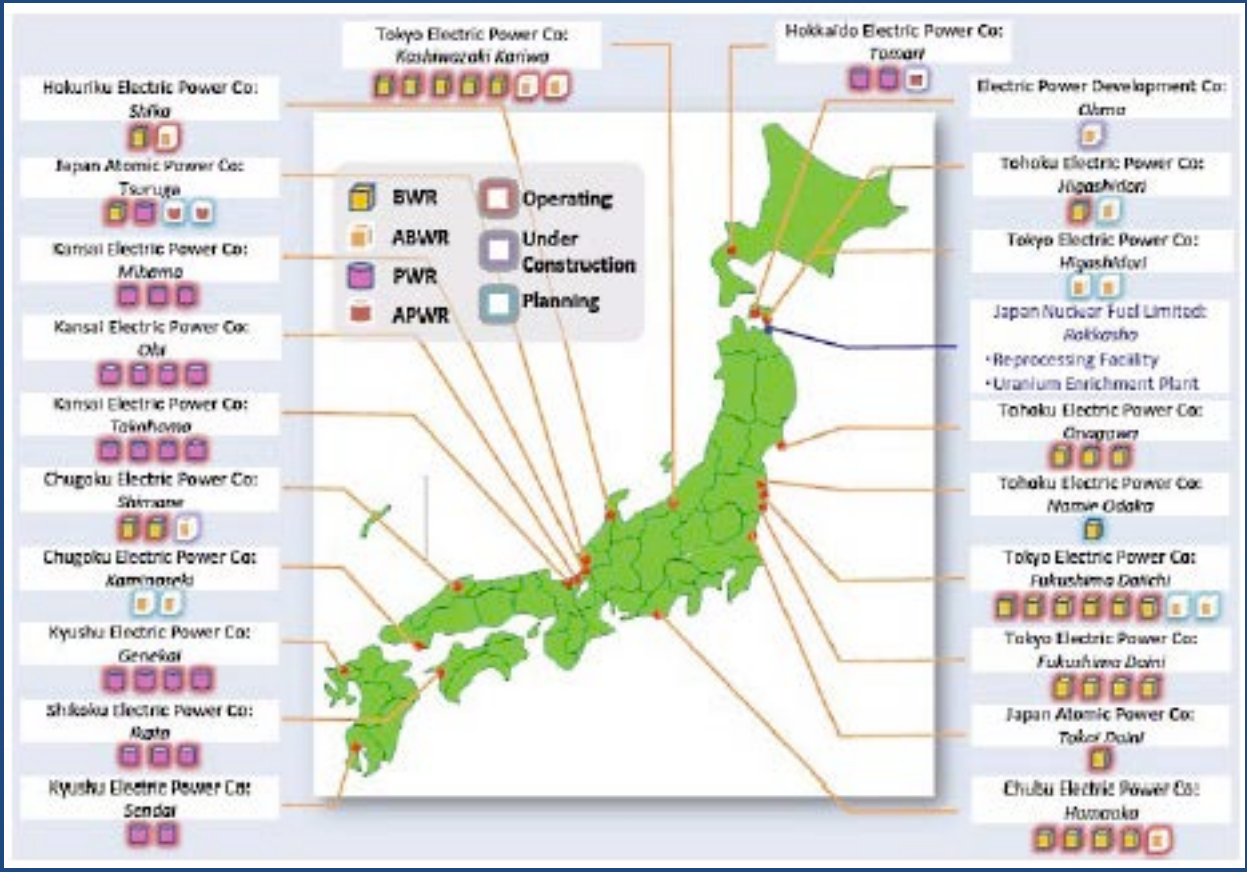
Content

1. Accident at Fukushima-1 in March 2011
2. Fukushima since the accident
3. Impact of accident and actions taken in U.S.

1. Accident at Fukushima-1 in March 2011

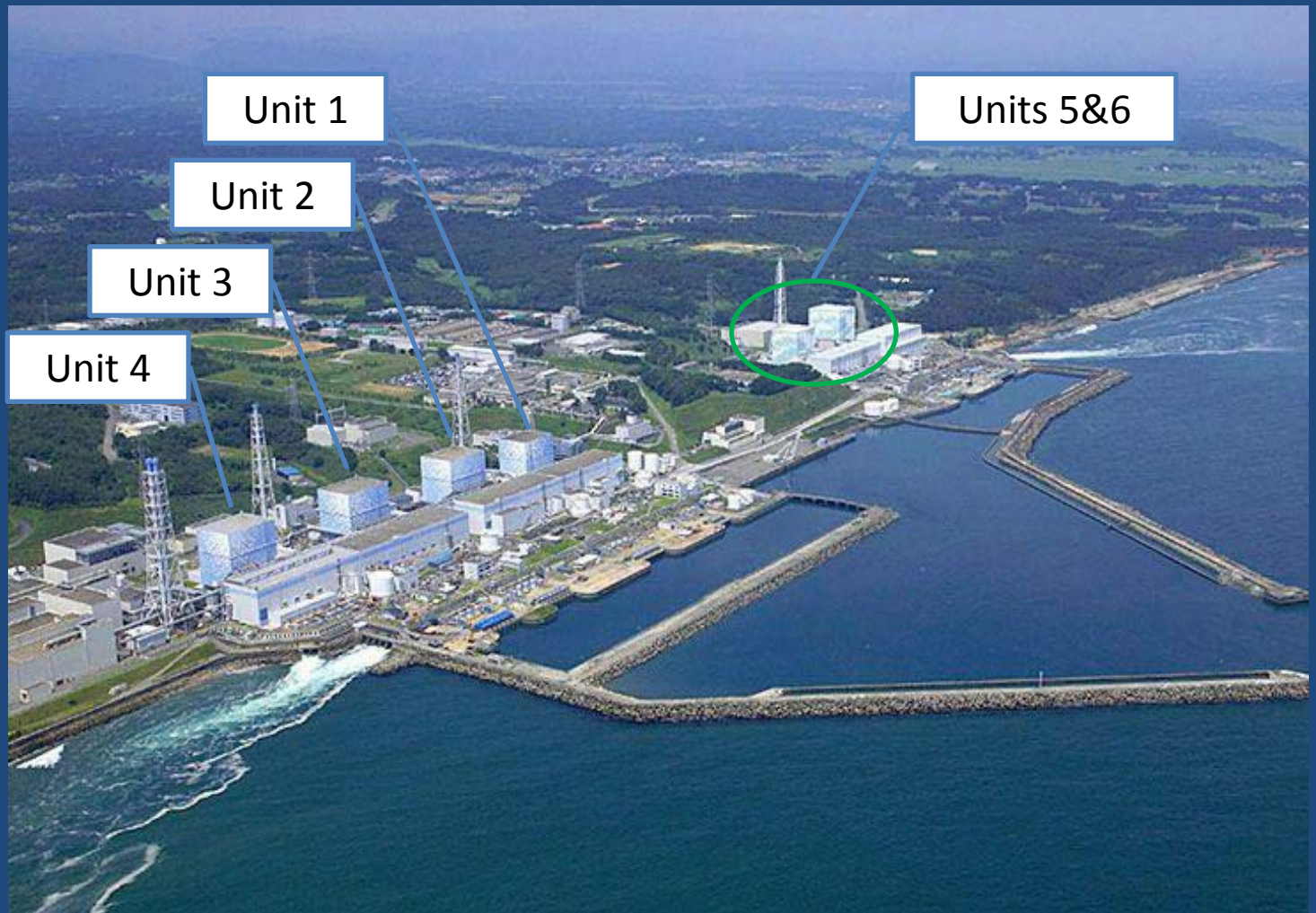
Japanese nuclear power industry

- Established in 1966 (with start of Tokai-1 NPP)
- ~ 30% of electrical power provided by nuclear power
- Plants built to withstand "design basis" accidents



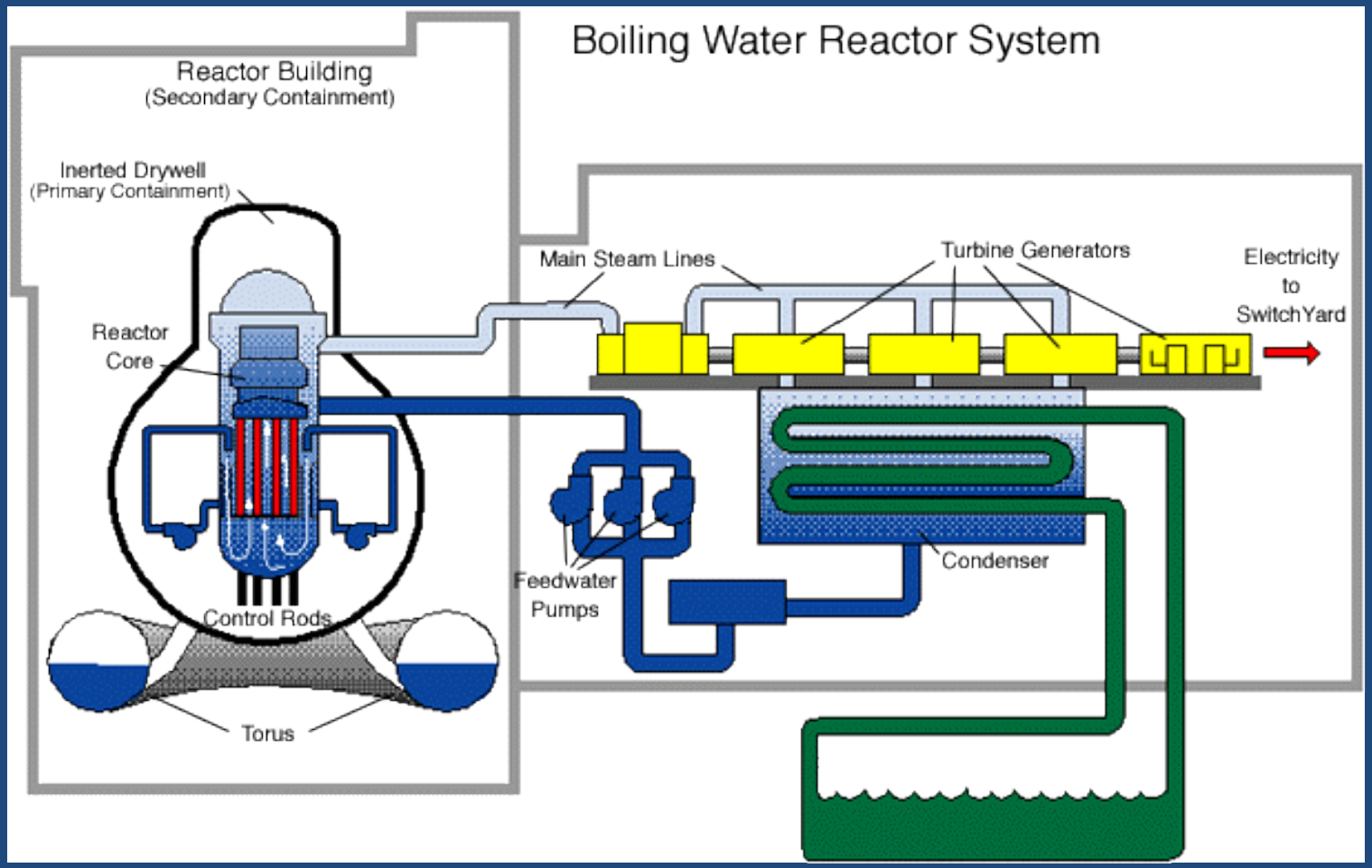
Fukushima-1 Plant – pre-earthquake status

- Units 1, 2 and 3 operating
- Unit 4 defueled, not operating (planned maintenance)
- Units 5 and 6 fueled, not operating (planned outage)



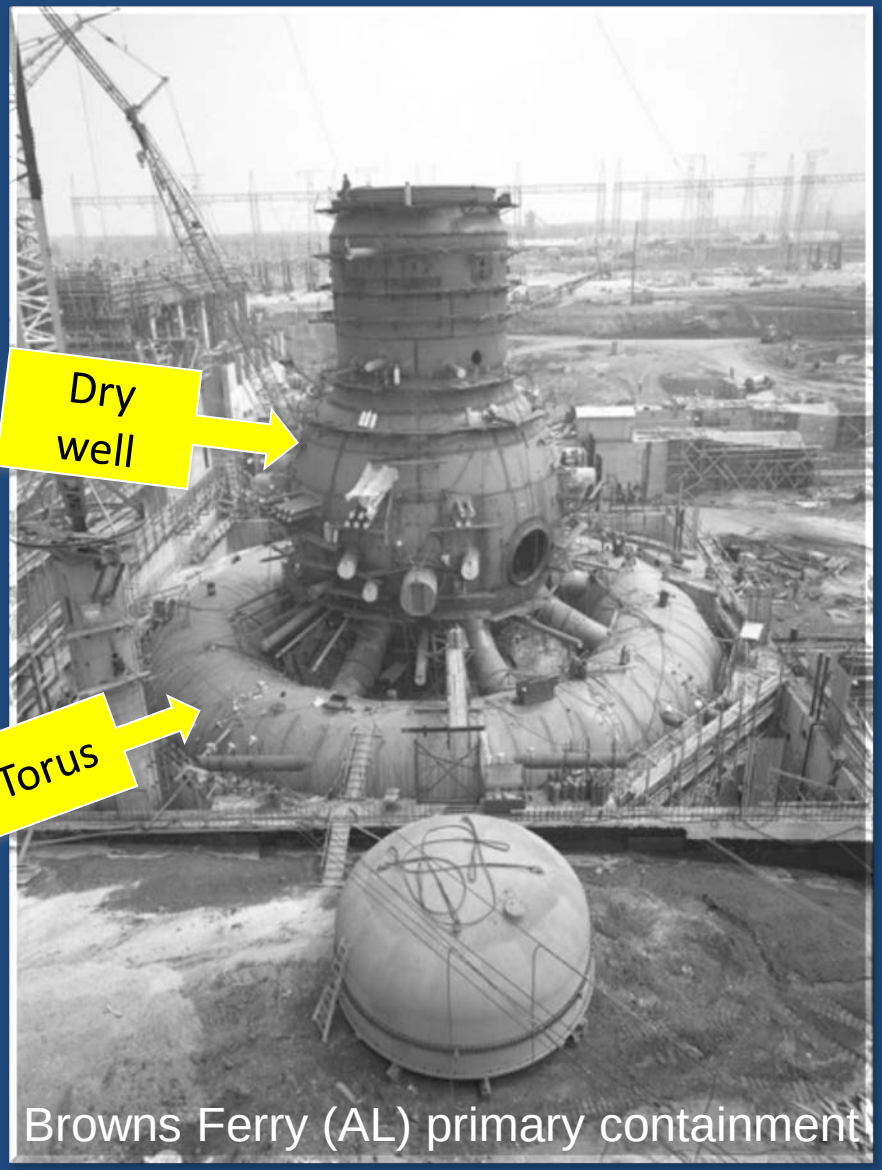
Fukushima-1 Plant

- Typical BWR-3 (Unit 1) and BWR-4 (Units 2 – 5) design
- Some similarities to Duane Arnold Plant in Iowa



Mark I Containment

- Primary containment
  - Dry well (Pear)
  - Wet well/suppression pool (Torus)
- In U.S. 23 reactors use Mark I containments
- Some similarities exist in design and operation of Japanese and US Mark I containments
- Following 9/11 terrorist attacks, NRC required licensee's to develop beyond-design-basis mitigation strategies (i.e. procedures and staging of portable equipment)



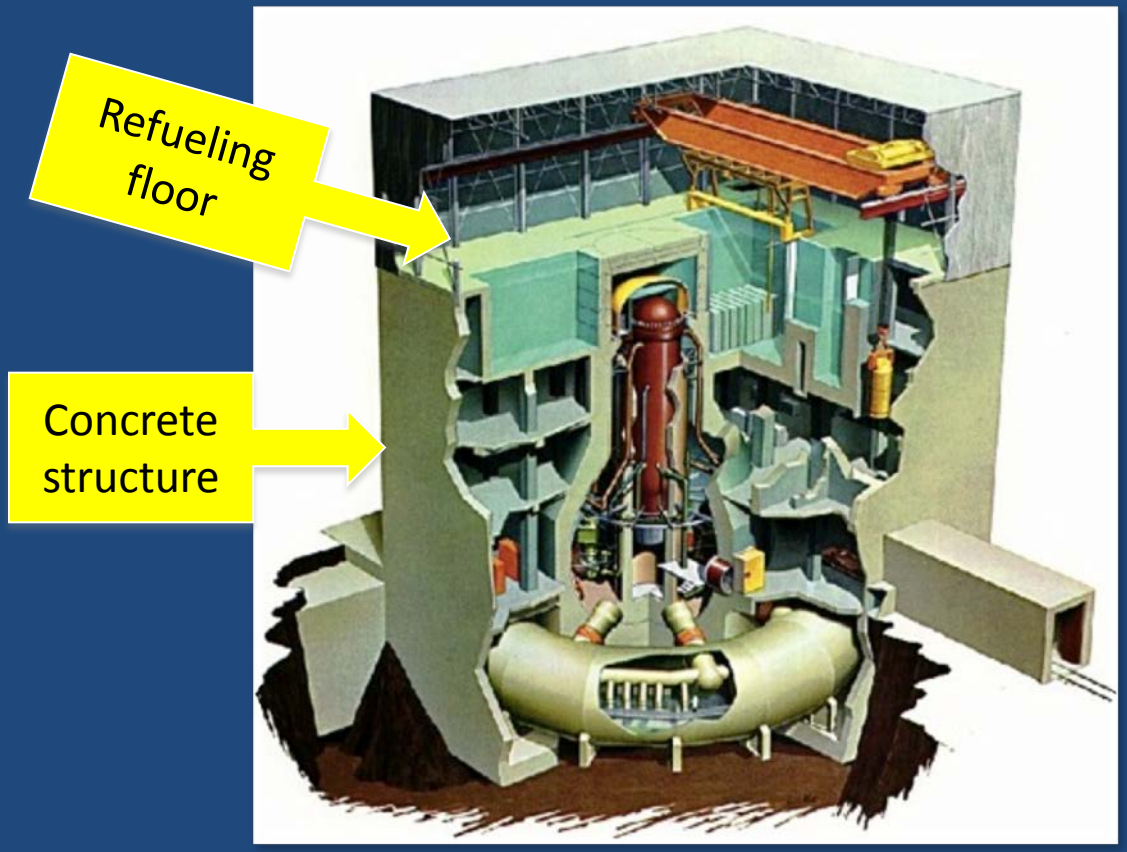
Browns Ferry (AL) primary containment

Mark I Containment

- Primary containment
  - Dry well (Pear)
  - Wet well/suppression pool (Torus)

- Secondary containment*
  - Concrete structure
  - Surrounds primary containment
  - Houses ECCS and spent fuel pool
- Metal-framed refueling floor (not part of containment)

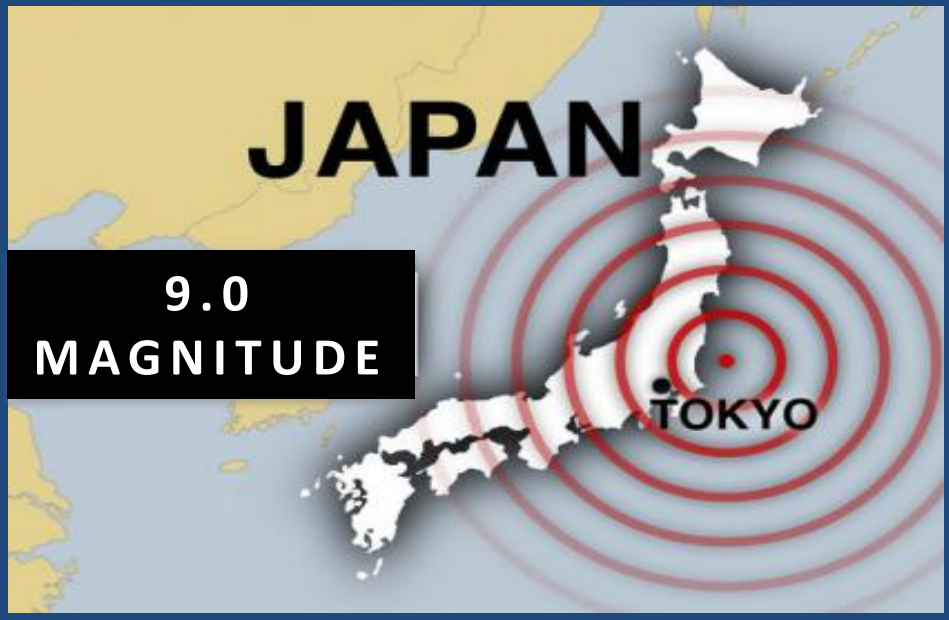
Browns Ferry (AL) primary containment



*Details of Mark I secondary containment design vary among reactor units.

The Tohoku Earthquake

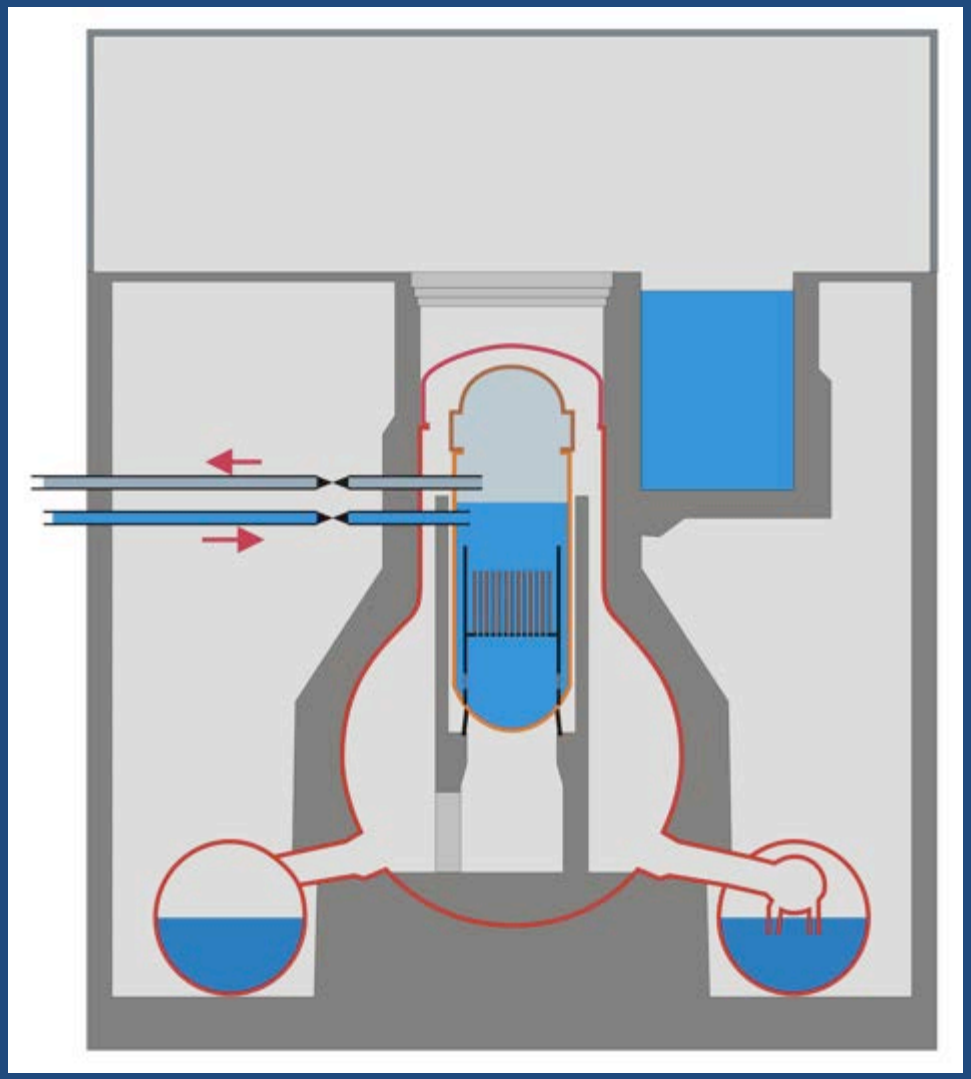
- 11 March 2011
- Largest in recorded history of Japan
  - 9.0 on Richter scale
- Among largest in world history
- Resulting Tsunami waves (series of 7) up to 15m (~ 50 ft)



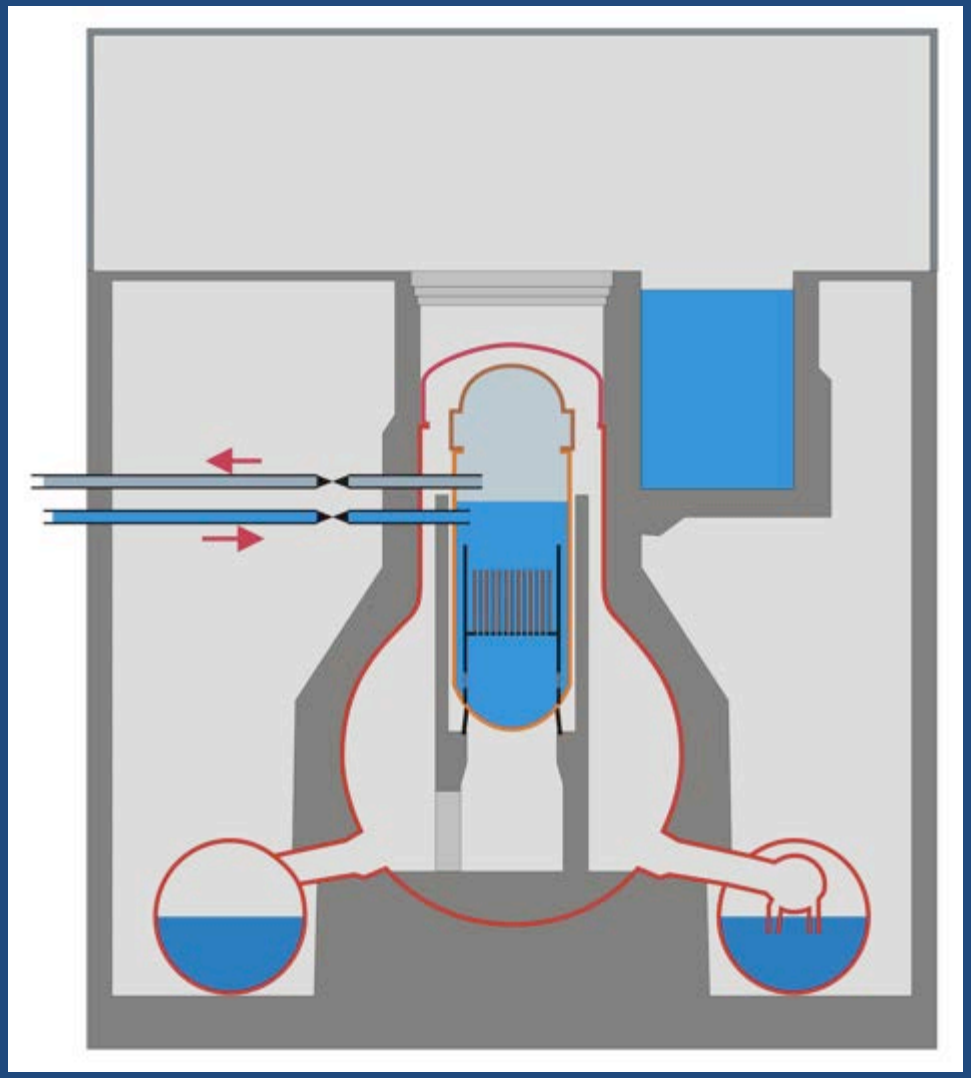
What happened at the Fukushima Daiichi Plant?

11 March 2011

- Tohoku Earthquake
  - Units 1 to 3 shutdown automatically (SCRAM), per design
  - Power generators “tripped”, per design
- Movement of plant foundation “exceeded design basis earthquake ground motion” (DBEGM) in Units 2,3,5
  - Disabled offsite power systems
  - No serious damage to onsite safety systems



- Why is losing power a problem?
  - Heat generation due to fission of uranium stops with SCRAM
  - Heat generation due to radio-active decay of fission products continues*
  - Power needed to pump water, cool core
- Emergency diesel generators provide power to the core and fuel cooling systems

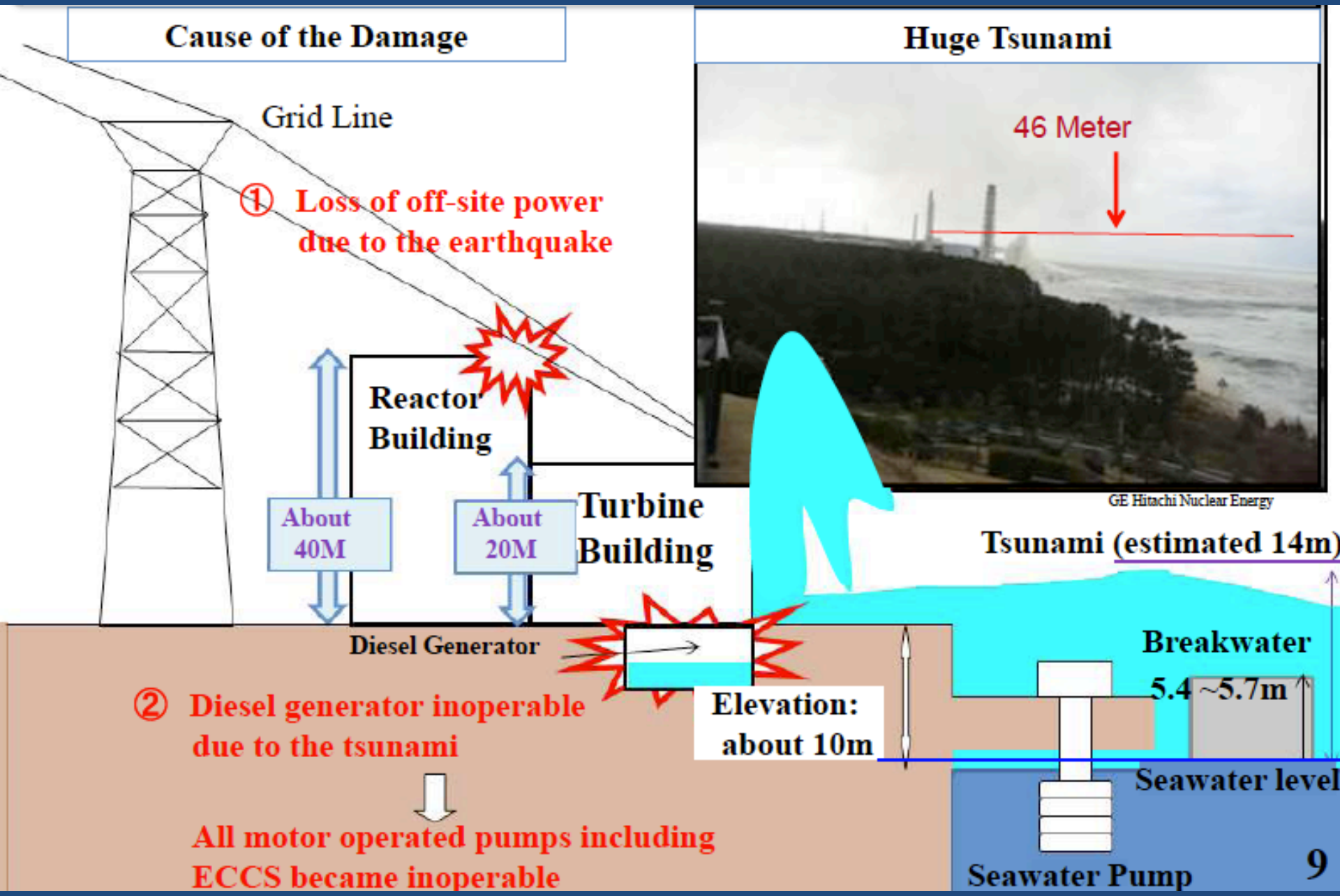


*About 1% of original thermal energy within a few hours

- Tsunami hit the plant (~55 minutes after quake)
  - Design basis Tsunami height 5.4 to 5.7 m (16.2 to 17.1 ft)
  - Actual maximum Tsunami height 14 to 15 m (42 to 45 ft)

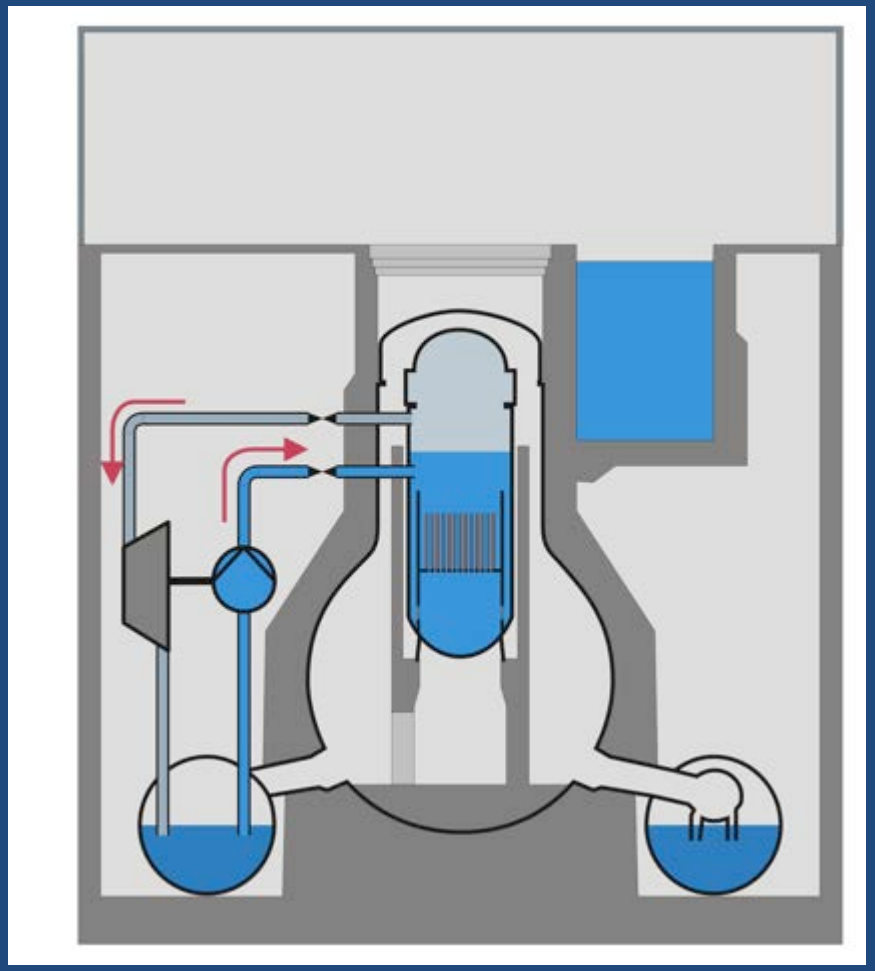
Cause of the Damage

Huge Tsunami



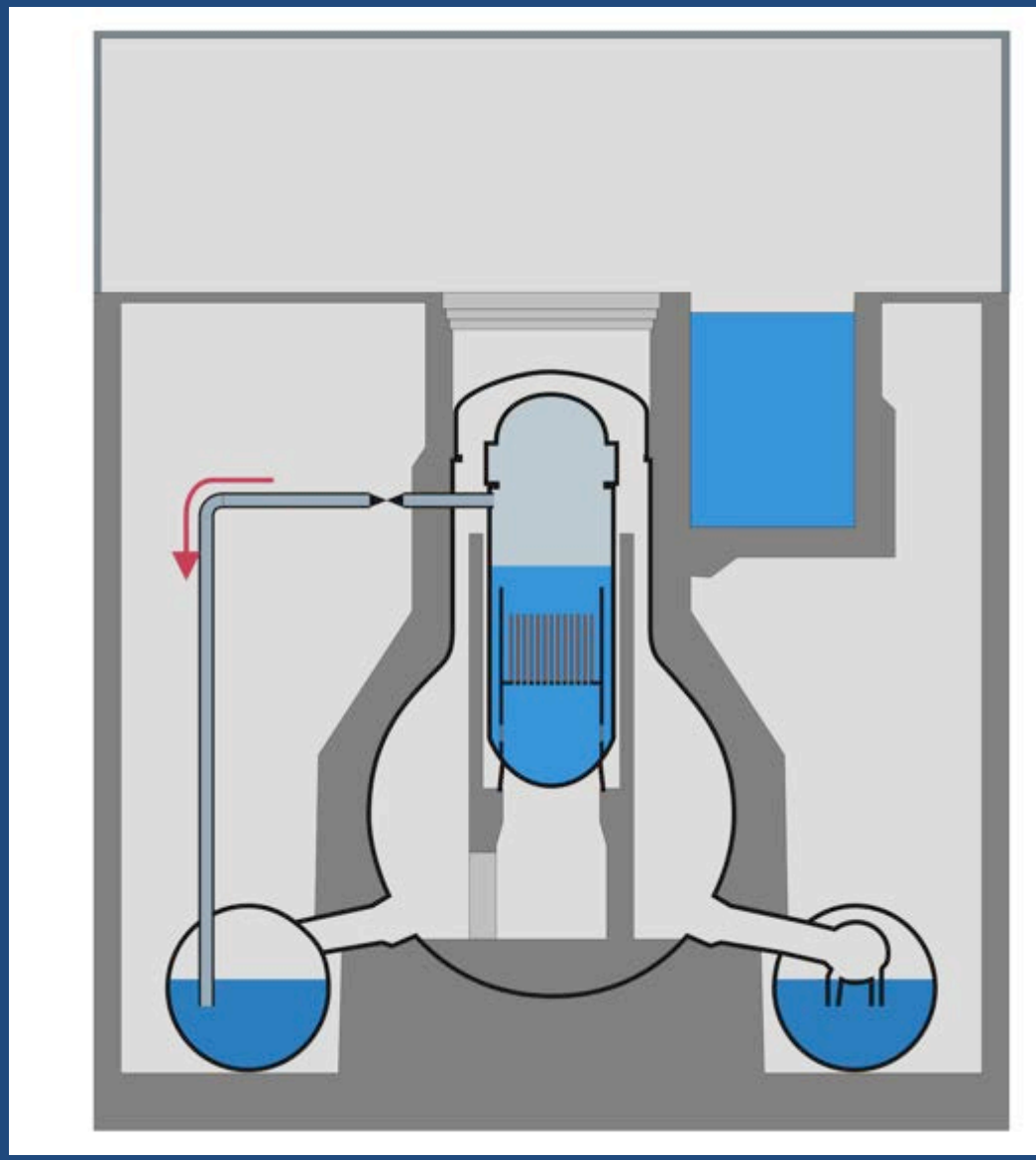
Results of Tsunami

- AC power
  - Lost for Units 1 -5
  - Unit 6 retained one operating generator, which cooled Units 5 and 6
- Battery power (used if no AC)
  - Lost in Unit 1
  - Units 2 and 3 cooled with battery power for a few hours



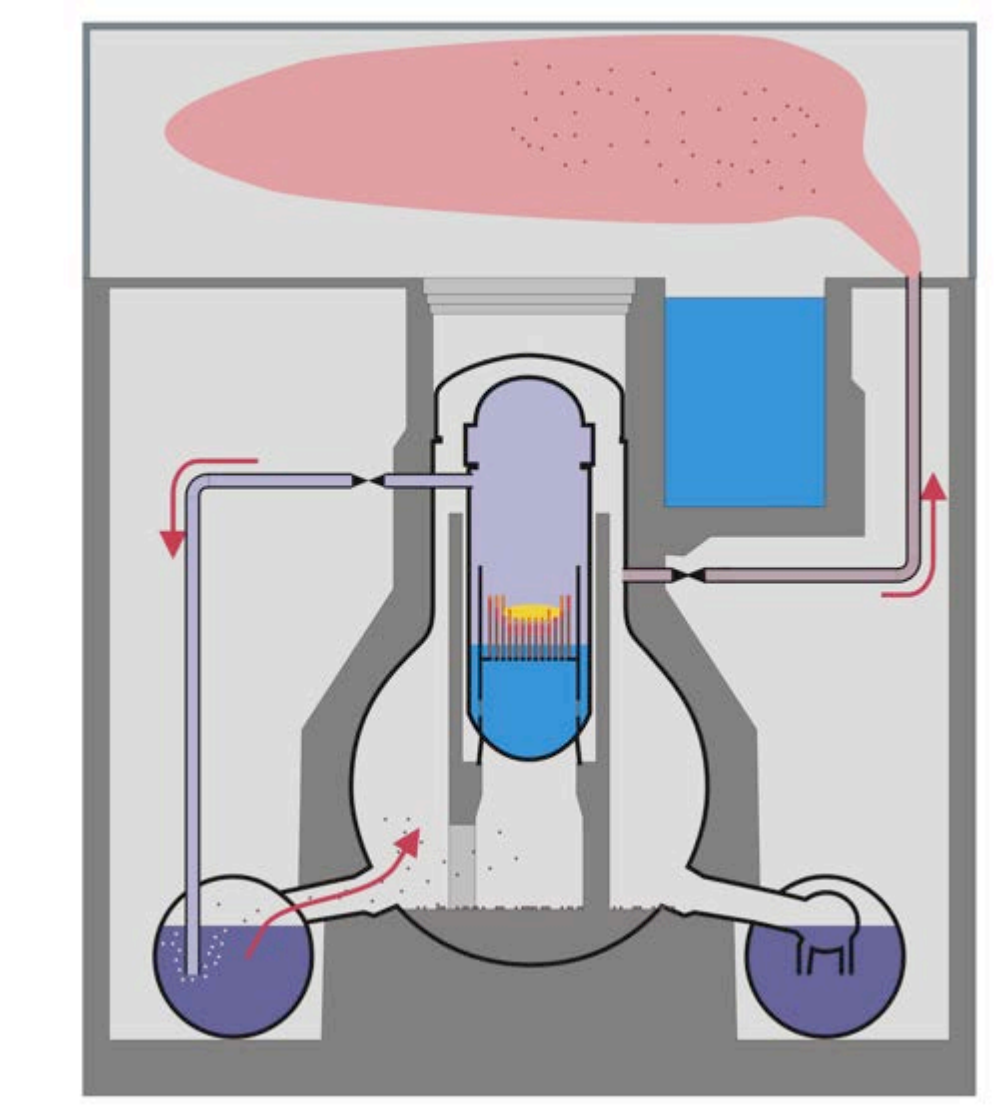
When power ran out and cooling stopped . . .

- Decay heat produces steam in reactor pressure vessel
- Relief valves discharge steam into wet well
- Some leaking from vessel, attached pipes
- Decrease in reactor coolant level



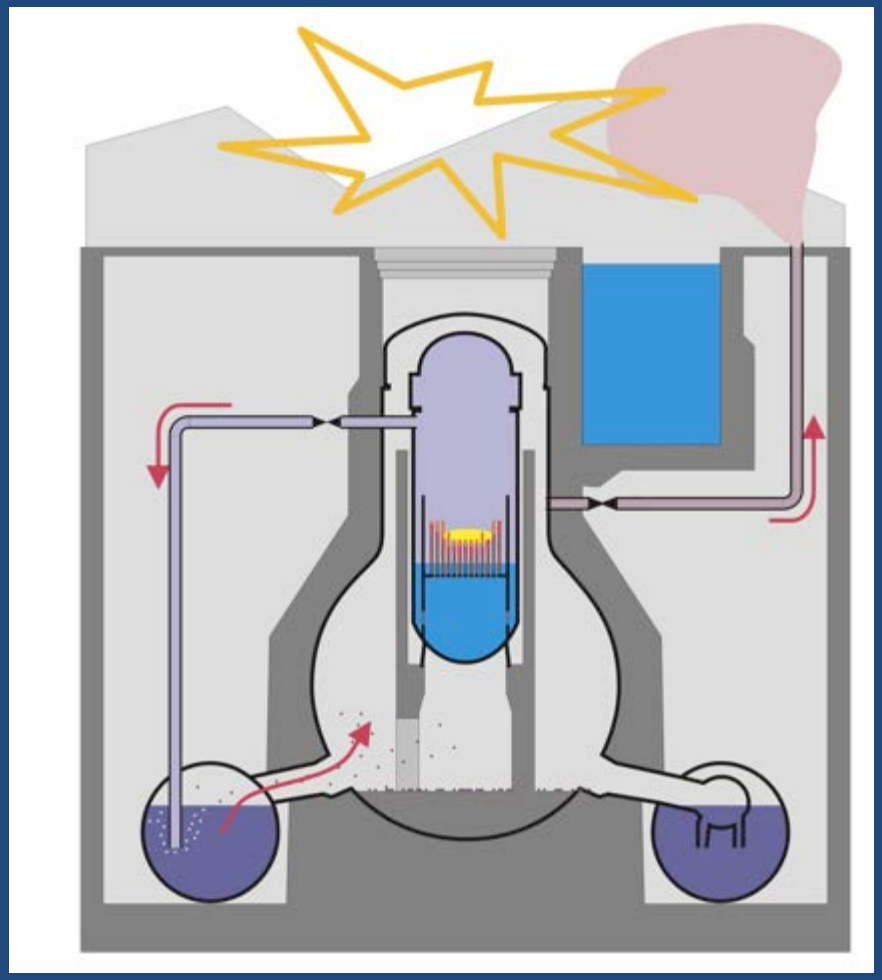
De-pressurization of containment

- Attempts to vent gas from containment to outside, some flows into the reactor service floor (Units 2,3)
- Gas also may have leaked through containment
- Hydrogen (from fuel clad degradation) and some fission products (from fuel degradation)



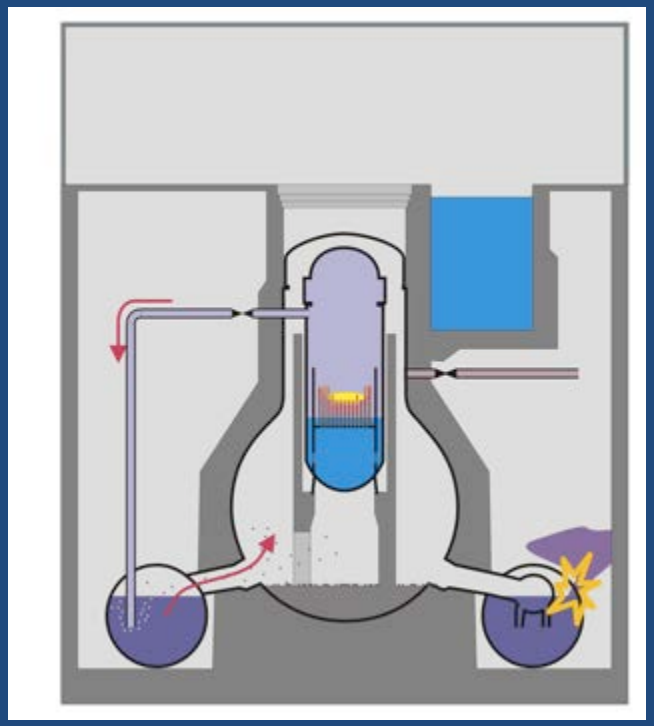
H_2 explosions

- Units 1 and 3 service areas
  - Steel frame roof destroyed
  - Concrete building intact
  - Seawater injected

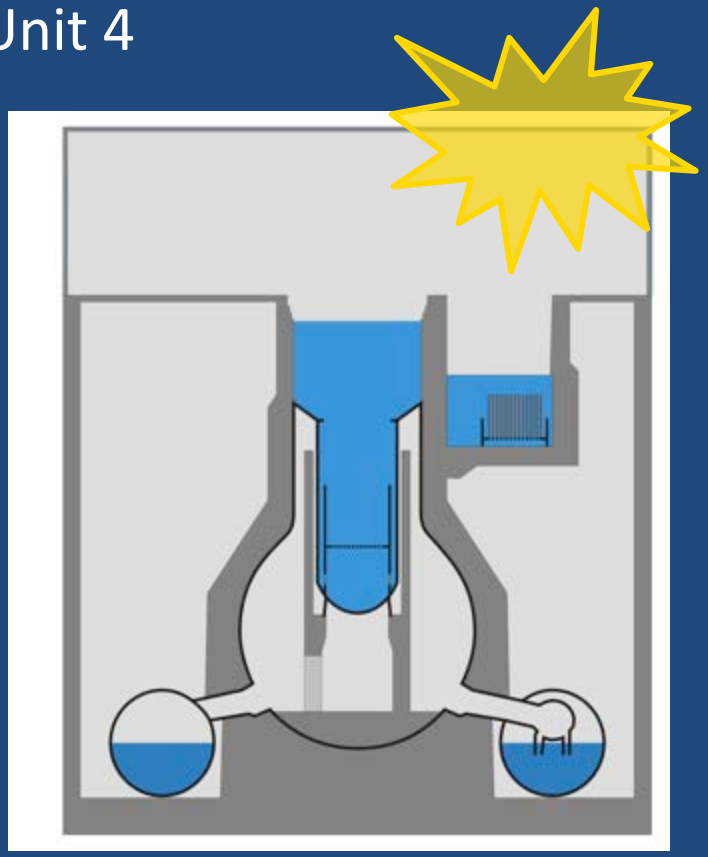


More H_2 explosions

- Unit 2

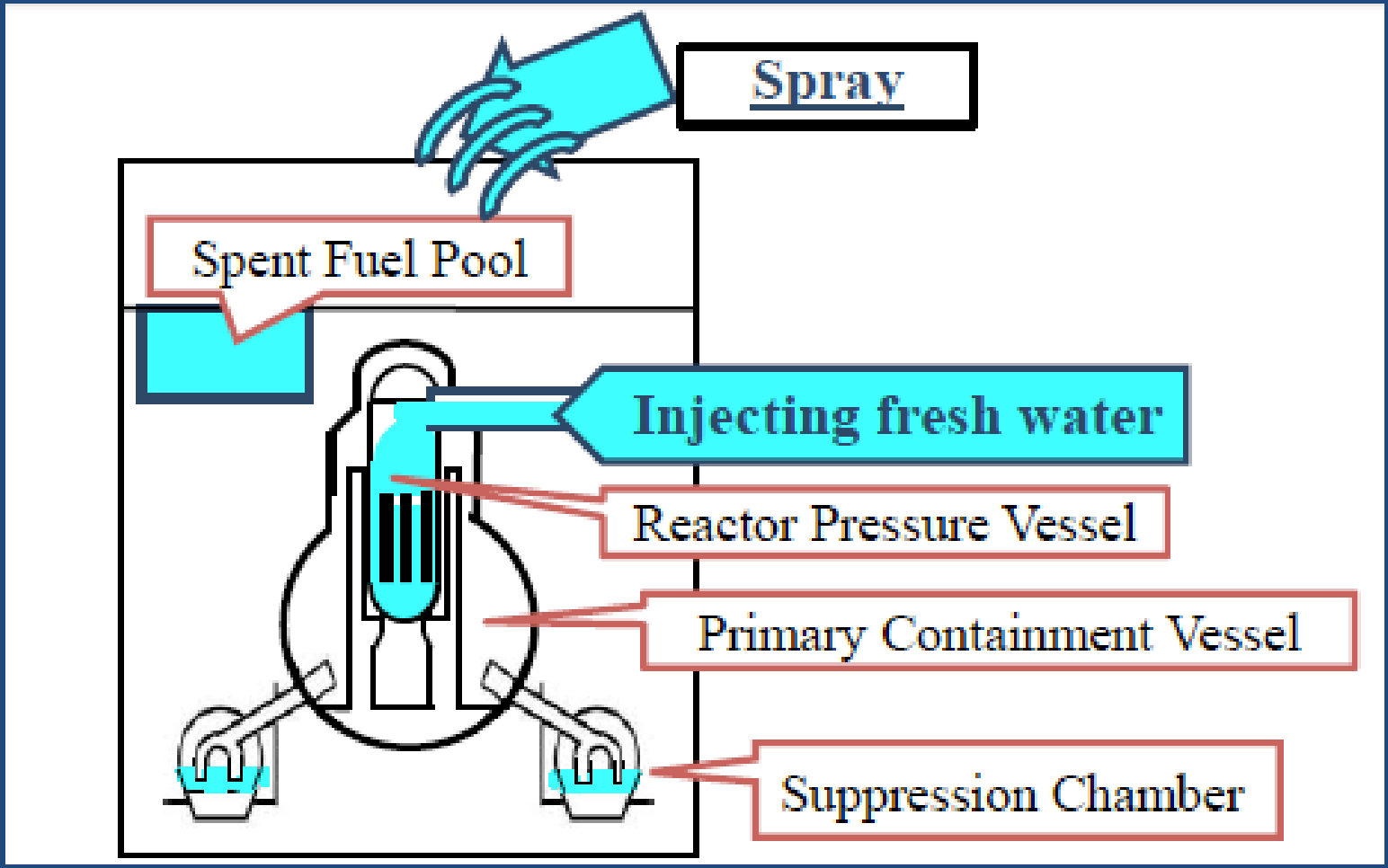


- Unit 4



16 March 2011 (Day 6)

Cooling reactors and pools in early days . . .



Lessons learned immediately by Japan . . .

- Earthquake design basis adequate
- Tsunami design basis and emergency planning insufficient for NPP and other key infrastructure
- Must diversify, increase and secure onsite power supply to avoid core damage

Current Status of the Nuclear Power Plants in Japan

(as of September 3, 2012)

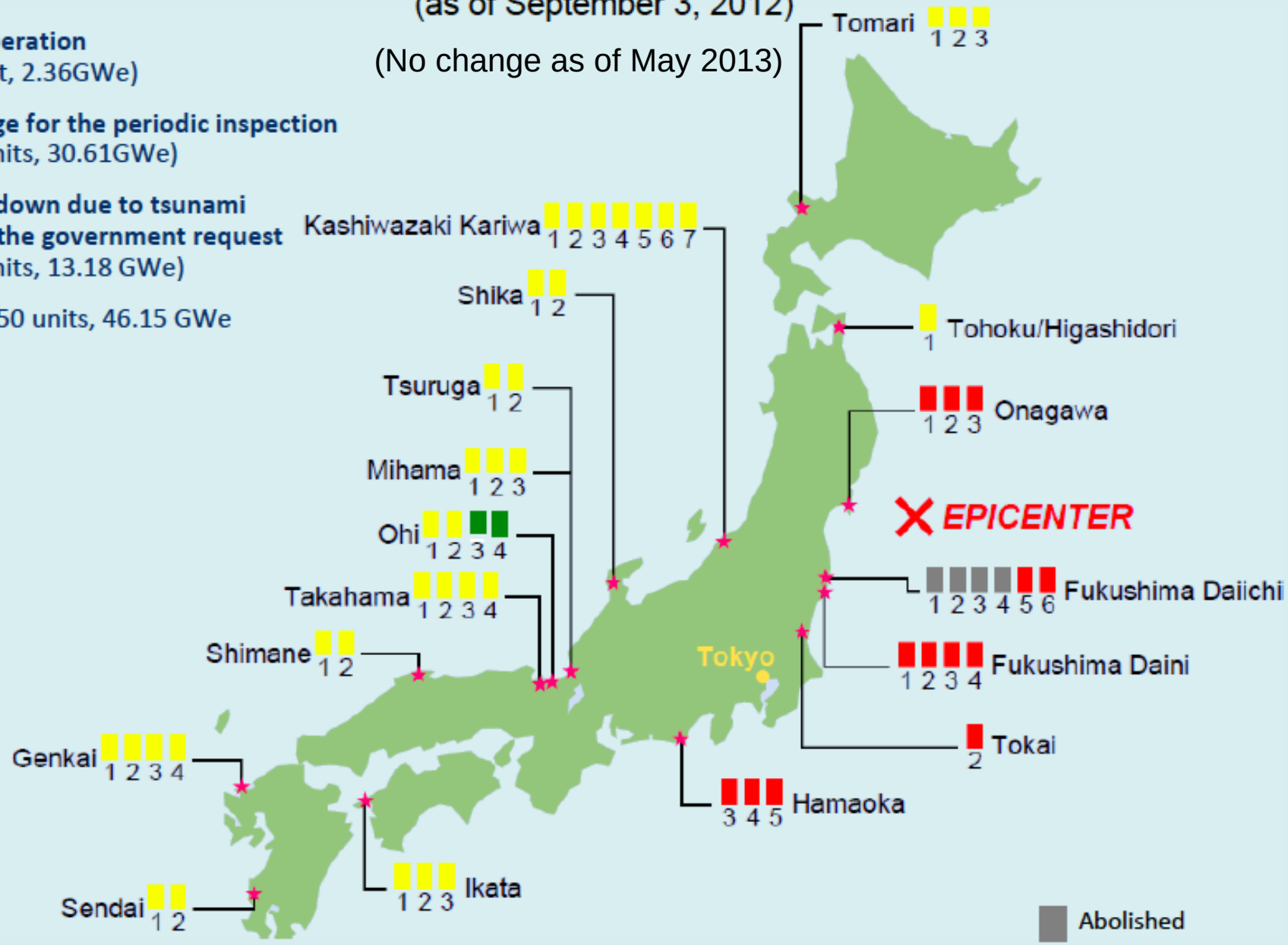
(No change as of May 2013)

: In operation
(2 unit, 2.36GWe)

: Outage for the periodic inspection
(35 units, 30.61GWe)

: Shutdown due to tsunami and the government request
(13 units, 13.18 GWe)

TOTAL : 50 units, 46.15 GWe



2. Fukushima after the accident

TEPCO's Roadmap to Restoration

I. Cooling
   a) Reactors
   b) Used fuel pools
II. Mitigation
   a) Containment, storage, processing, and reuse of rad contaminated water
   b) Mitigate release of radioactive materials to air & soil
III. Monitoring and Decontamination
   a) Monitor radiation dose in & out of power station
   b) Enhance monitoring and quickly inform of results
   c) Reduce radiation dose in evacuated areas

TEPCO's Roadmap to Restoration

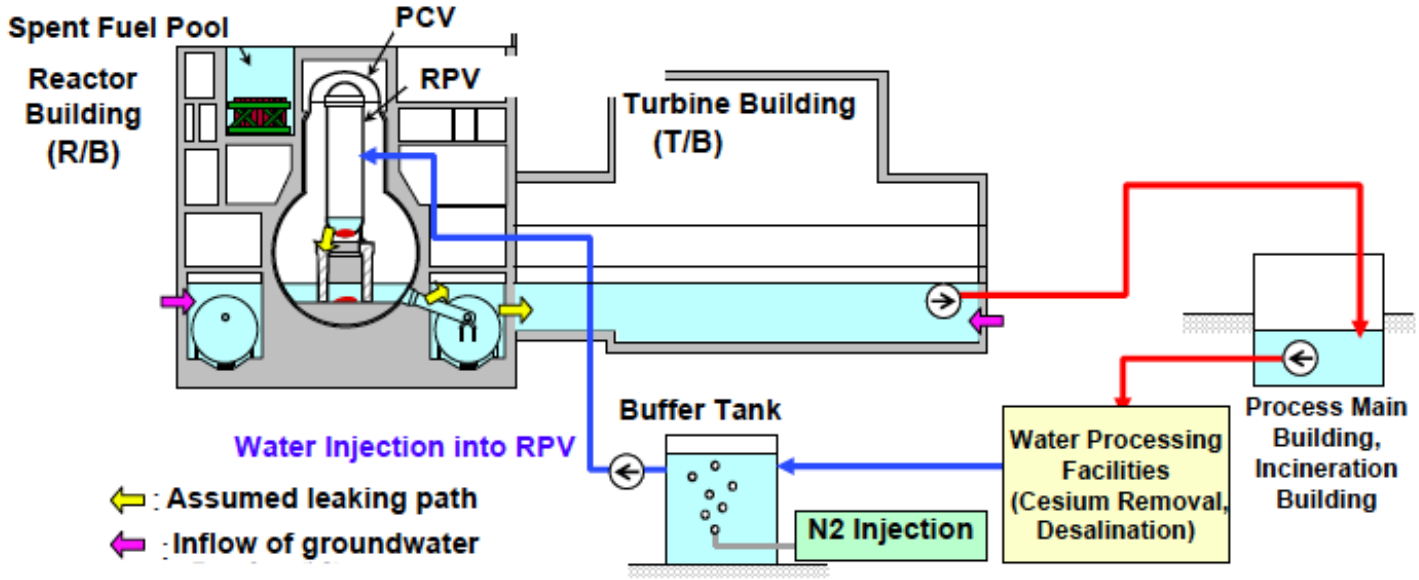
Cooling

Reactors **Circulating Water Cooling System**

- Cooling water is leaking from RPV to the basement of Turbine building through Reactor building.

  -> **"Circulating Water Cooling System" has been established; contaminated water is reused for reactor water injection after cesium and salt are removed from the water.**
- RPV water injection system consists of pumps, piping and tanks.

  ->These components have **redundancy, diversity and independency.**
- Accumulated water is on the increase due to groundwater inflow into the buildings.



Circulating Water Cooling System Overview

TEPCO's Roadmap to Restoration

I. Cooling
   a) Reactors
   b) Used fuel pools
II. Mitigation
   a) Mitigate effects of further natural events
   b) Containment, storage, processing, and reuse of rad contaminated water
   c) Mitigate release of radioactive materials to air & soil
III. Monitoring and Decontamination
   a) Monitor radiation dose in & out of power station
   b) Enhance monitoring and quickly inform of results
   c) Reduce radiation dose in evacuated areas

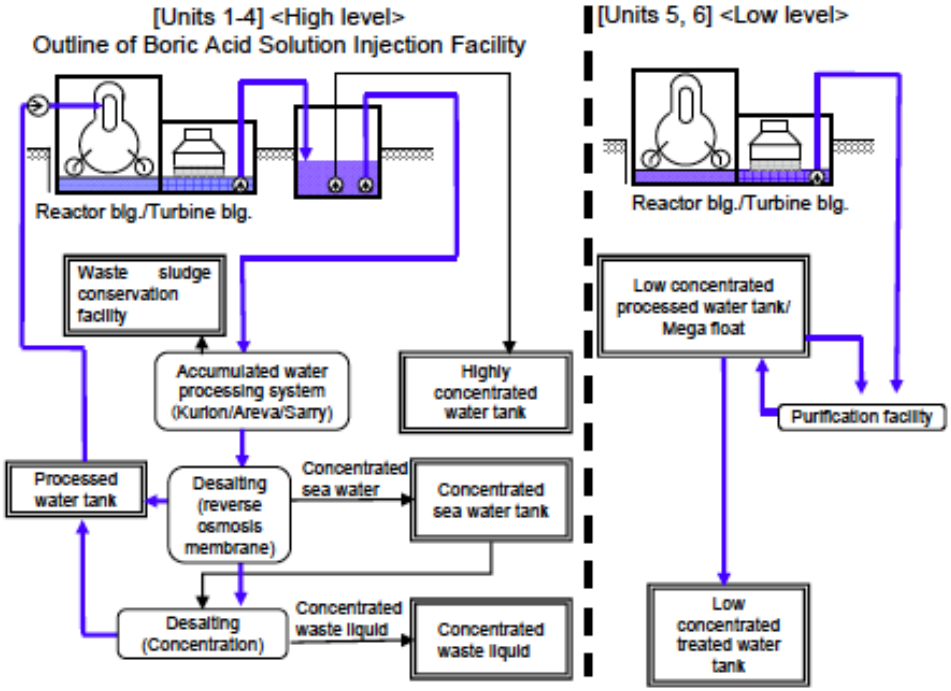
TEPCO's Roadmap to Restoration

Mitigation

Accumulated Water

"Total volume of accumulated water has been reduced"

- We confirmed "the reduction of total volume of accumulated water" due to processing the accumulated water in the buildings via stable operation of processing facilities. Following countermeasures were implemented to achieve this end.
  - ✓ Reinforcement of high-level contaminated water processing facilities, stable operation and expansion of water reuse after desalination.
  - ✓ Begun consideration of full fledged high-level contaminated water processing facilities.
  - ✓ Storage and management of waste sludge generated from high-level water processing facilities.
  - ✓ Construction of steel pipe sheet pile at the site harbor started in order to mitigate the contamination into the ocean.



TEPCO's Roadmap to Restoration

Mitigation

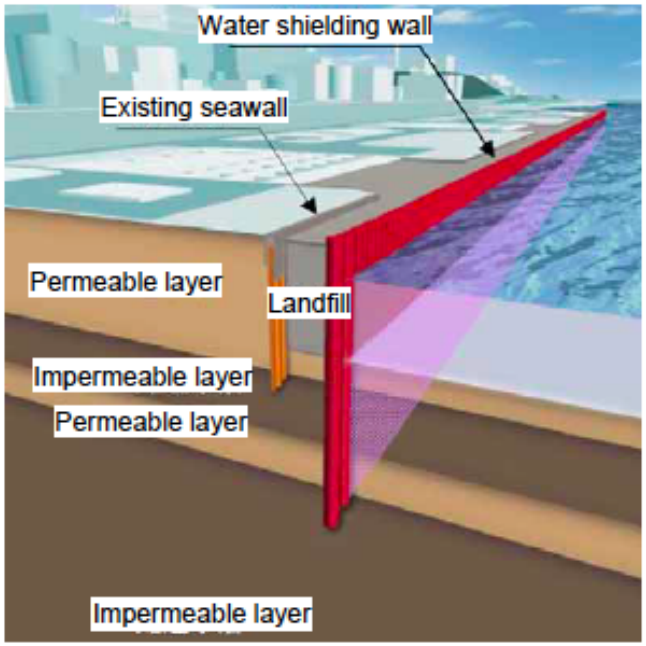
Underground water **Achieved "Mitigation of ocean contamination"**

- By controlling accumulated water flows into underground water, we implement/start preventative measures to mitigate underground water contamination as well as to halt the spread of contamination into the ocean.
  - ✓ Mitigate the leaking of accumulated water in the building by ensuring that the level of accumulated water is lower than the sub drain water level (confirm via a radioactive materials density analysis of the sub drain).
  - ✓ Start the placement of the water shielding walls in front of the existing seawall of Units1-4 (this will prevent the spread of contaminated underground water from flowing into the ocean)

Image of water shielding wall

Overview

Cross-section



TEPCO's Roadmap to Restoration

Mitigation

Atmosphere/Soil **Countermeasures to Prevent Diffusion of Radioactive Materials**

- Spraying dust inhibitor agents to mitigate spreading of powder dust containing radioactive materials.
- Completed Unit 1 reactor building cover installation (Oct. 28, 2011).
- Radiation dose at the site is being held down due to rubble removal.
  - ✓ The removed rubble and waste resulting from restoration work such as cut down trees due to site clearing were transported after we classified them by type and radiation emitting amount at storage area.
  - ✓ The rubble were placed in containers and stored indoors in accordance with their radiation emitting amount.
- Completed PCV gas control system.
  - ✓ Started operation of PCV gas control system in Unit 1 (Dec.15, 2011), Unit 2 (Oct.28, 2011) and Unit 3 (Mar. 14, 2012).

Unit 1 reactor building cover installation

Containers storing rubble

Spraying dust inhibitor agents to the buildings and site ground

Silt fence installation

Removal of rubble

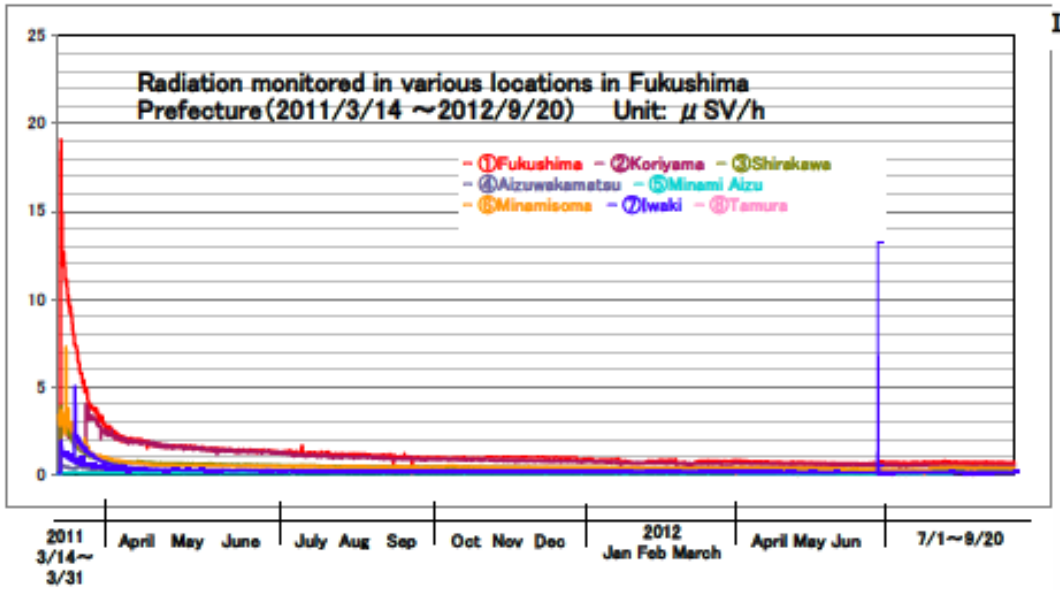
TEPCO's Roadmap to Restoration

I. Cooling
   a) Reactors
   b) Used fuel pools
II. Mitigation
   a) Containment, storage, processing, and reuse of rad contaminated water
   b) Mitigate release of radioactive materials to air & soil
III. Monitoring and Decontamination
   a) Monitor radiation dose in & out of power station
   b) Enhance monitoring and quickly inform of results
   c) Reduce radiation dose in evacuated areas

Monitoring and reporting

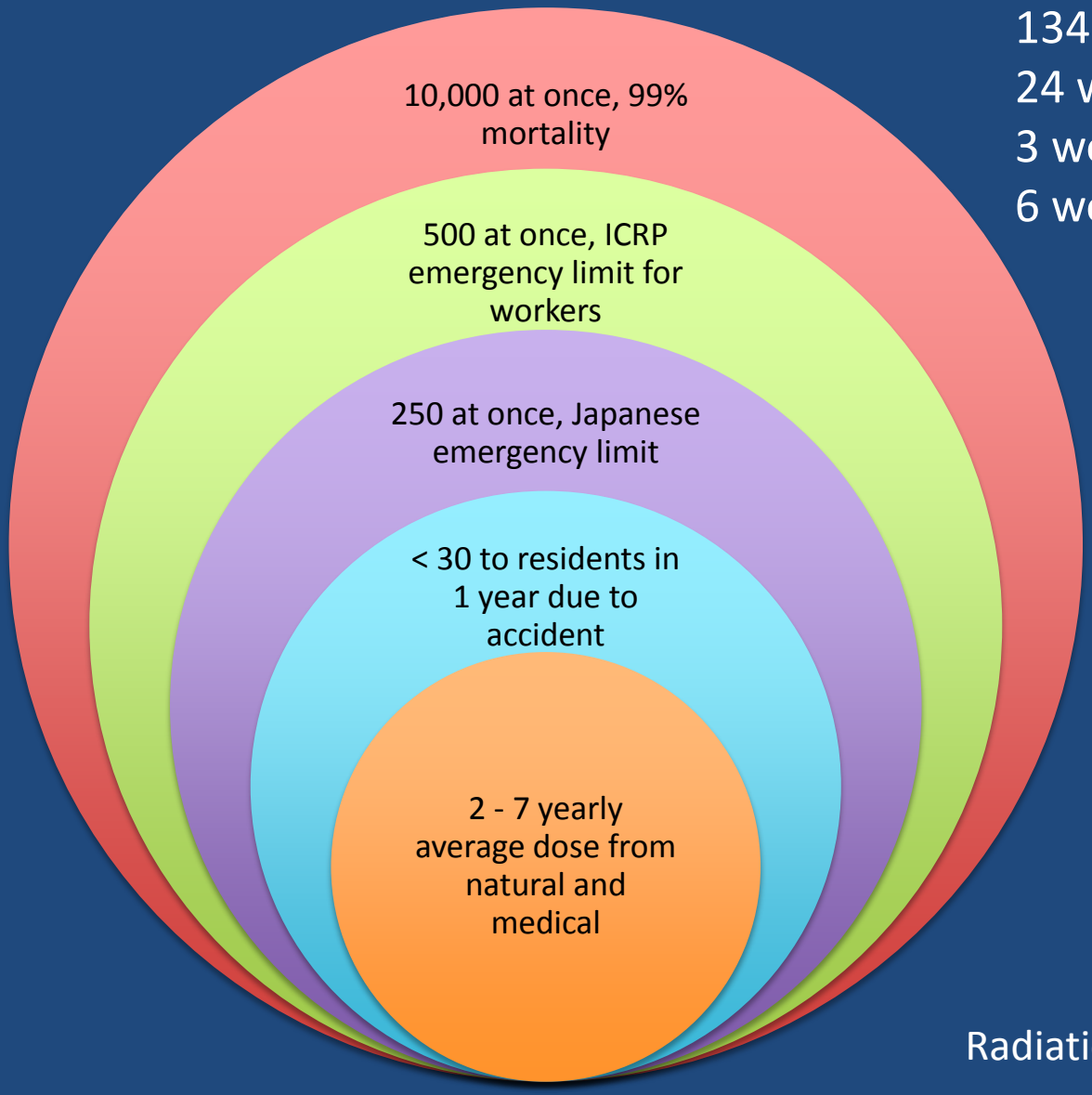
- Air
- Water (sea, rivers, drinking)
- Soil
- Food of any kind (plant or animal)

Trend of radiation in the environment at various locations



Locations for monitering

Radiation doses



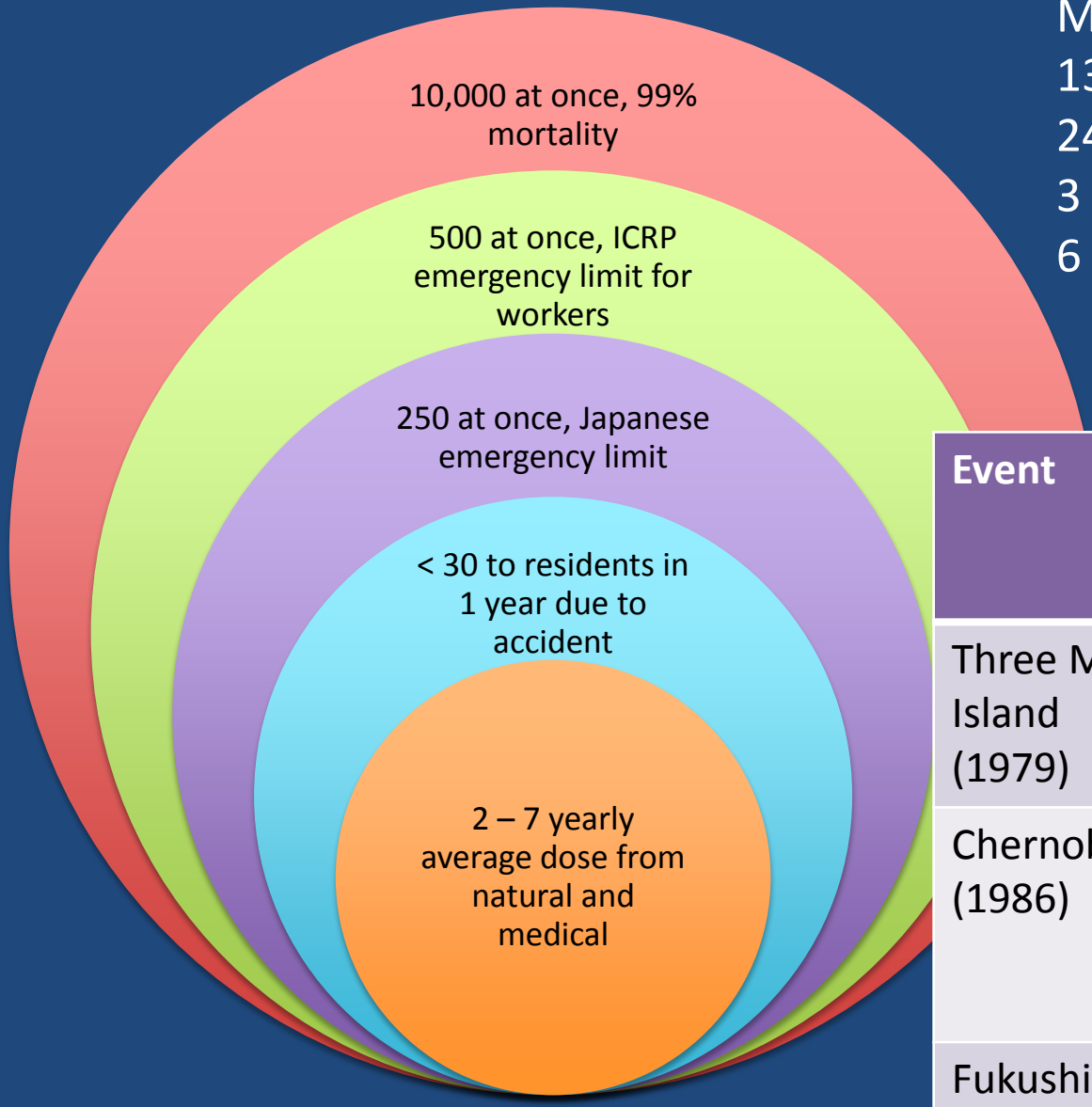
TEPCO reports doses March ‘11 - September ‘12:
134 workers received 100-150 mSv
24 workers received 150-200 mSv
3 workers received 200-250 mSv
6 workers received 250-679 mSv

No observed effects

24118 workers monitored
Average dose 12 mSv

Radiation dose units millSieverts (mSv)

Radiation doses



Radiation dose units millSieverts (mSv)

TEPCO reports doses March ‘11 - March ‘12:
134 workers received 100-150 mSv
24 workers received 150-200 mSv
3 workers received 200-250 mSv
6 workers received 250-670 mSv

- No observed effects.

Event	Dose or releases	Deaths
Three Mile Island (1979)	Minor short term dose to public (within ICRP limits)	0
Chernobyl (1986)	Major radiation release across E. Europe and Scandinavia (1.52 E19 Bq I-131 equivalent)	47+
Fukushima (2011)	Significant local contamination (7.7 E17 Bq I-131 equivalent)	0

3. Impact of Fukushima-1 accident on the nuclear industry and actions taken

US Response

Federal Regulations

Industry Response

NRC Order

- NRC issued three orders

1. FLEX - companies to enhance protection of portable emergency equipment and to obtain additional equipment to ensure facilities can cope with events that may affect multiple reactors at a site
2. Reliable hardened vents for boiling water reactors with Mark I or Mark II containments
3. Requires additional instrumentation to monitor water levels in used fuel storage pools

Industry Response

- Nuclear industry Fukushima Response Steering Committee provided responses to NRC Orders
- Coordinated through Nuclear Energy Institute (NEI)
  - NEI is the policy organization for the nuclear technologies industry

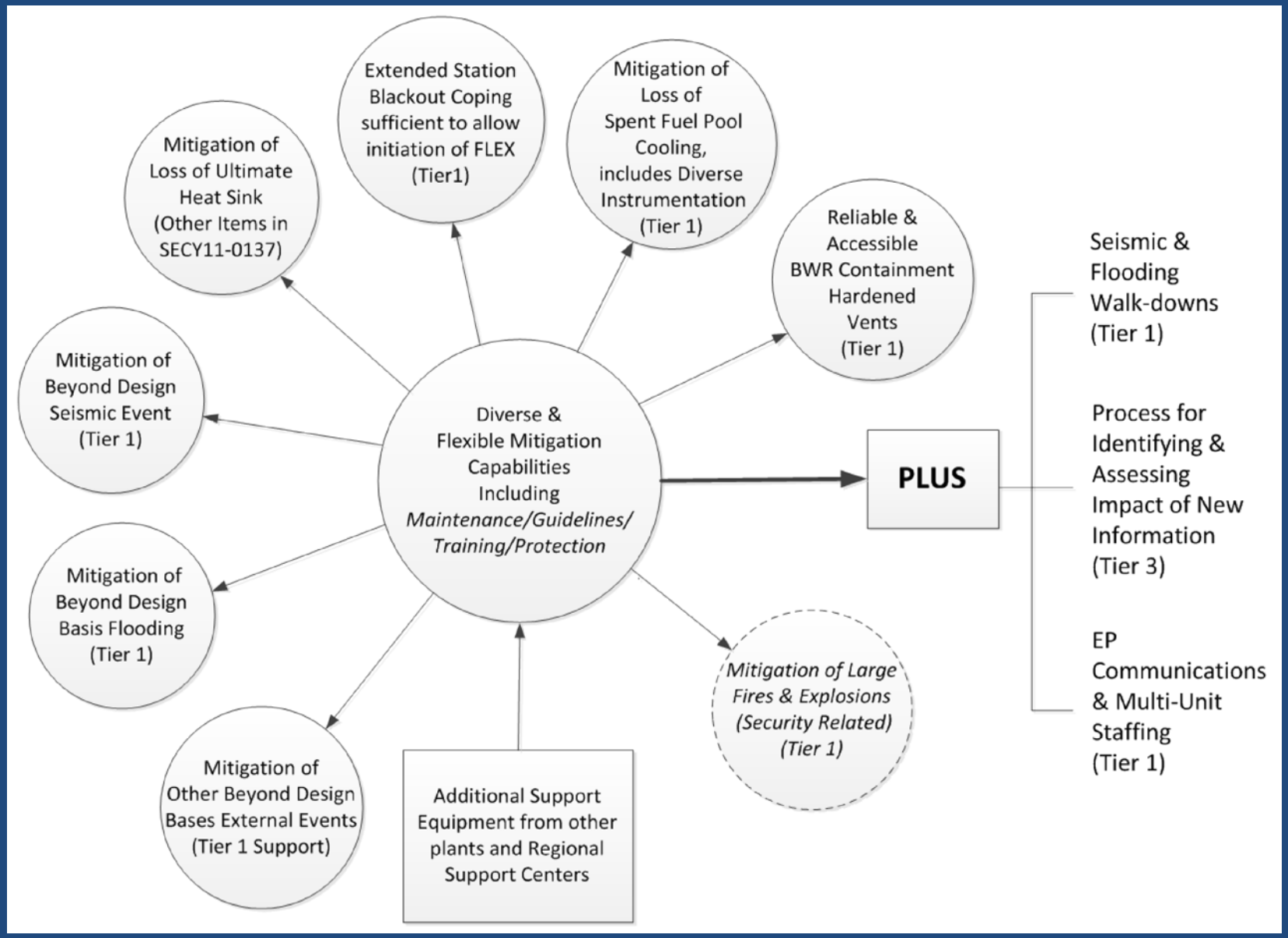
F L E X

- Approach for adding diverse and flexible mitigation strategies—or FLEX
- extended loss of alternating current (ac) power (ELAP)
- increase defense-in-depth for beyond-design-basis scenarios
- loss of normal access to the ultimate heat sink (LUHS)

FLEX Elements

- Portable equipment power and water to maintain or restore key safety functions
- Reasonable staging and protection of portable equipment from BDBEEs
- Procedures and guidance to implement FLEX strategies
- Programmatic controls that assure the continued viability and reliability of the FLEX strategies.

Overview of FLEX Concept



Flex Objectives & Guiding Principles

- The objective of FLEX
  - to establish an indefinite coping capability to prevent damage to the fuel in the reactor and spent fuel pools
  - to maintain the containment function

- Both by using installed equipment, on-site portable equipment, and pre-staged off-site resources

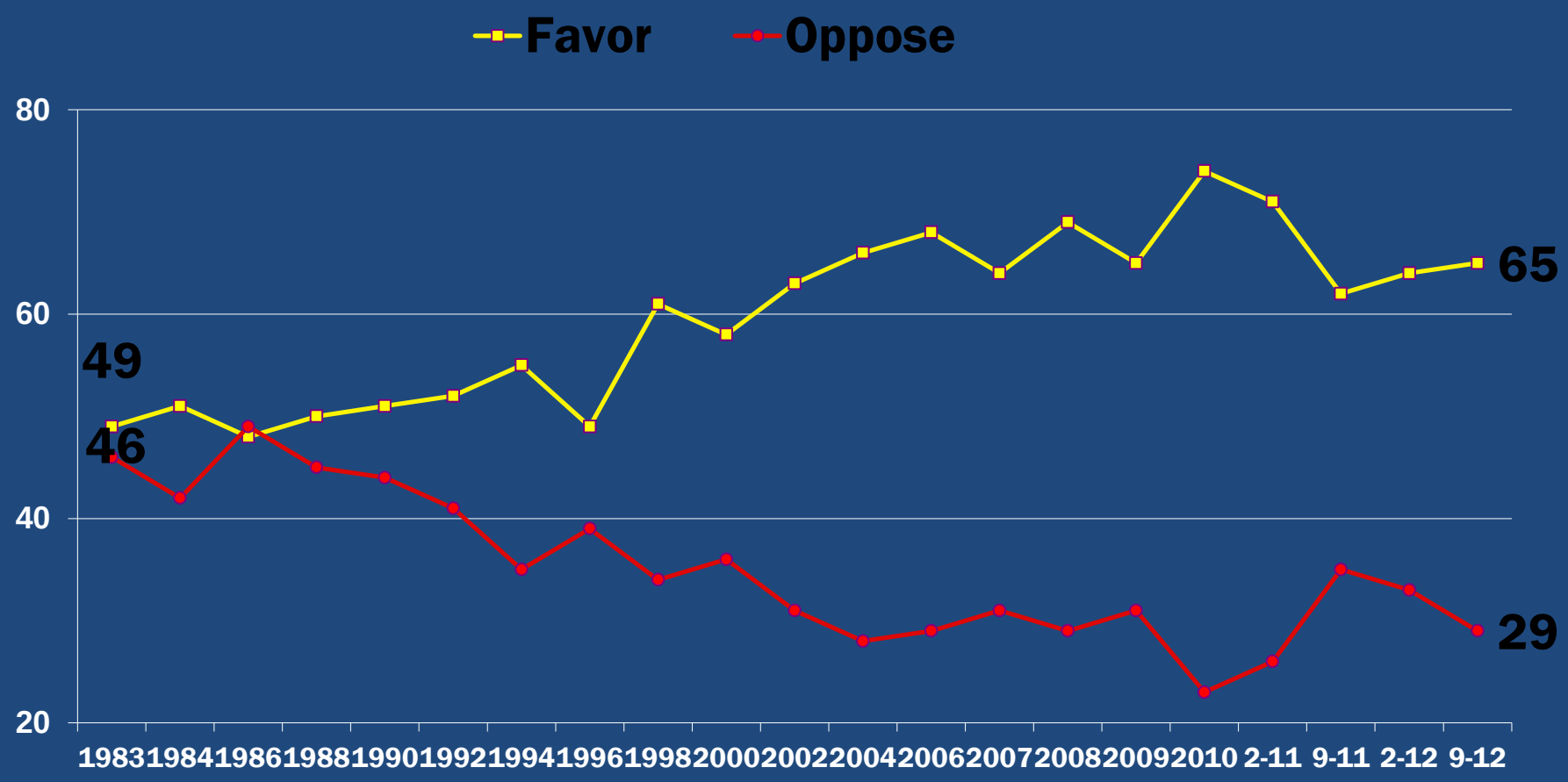
Off-Site Resources

- Pre-staged off-site resources will be housed at two locations
- One on the east coast and one near the west coast
  - The west coast site will be in Arizona (Phoenix metropolitan area)

4. Perspective

65% Favor Nuclear Energy

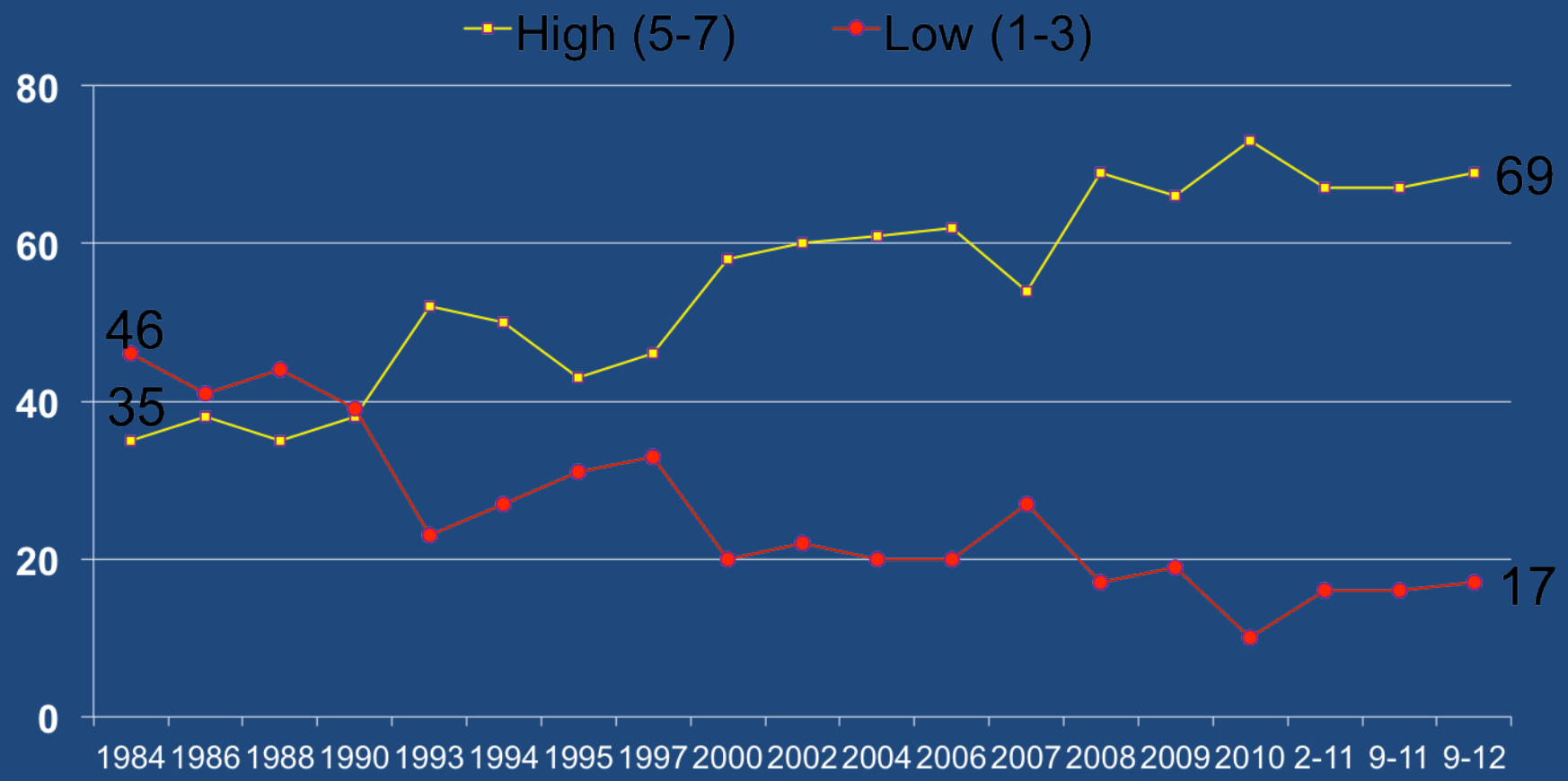
(U.S. Public Opinion, Annual Averages until 2012, Percentages)



Bisconti Research, Inc.

69% Rate Nuclear Power Plant Safety High

(Doubled since 1984!!!)



Bisconti Research, Inc.

The BIGger post-tsunami picture along the northeast coast of Japan

- Number of buildings damaged/destroyed: >332,400
- Number of roads, bridges, railways: 2100, 56, 26
- Number of people displaced: 131,000
- **Number of people dead or missing: > 20,000**
- Number of deaths due to tsunami at NPP: 2
- Number of deaths due to radiation exposure: 0
- Number of cases of radiation sickness: 0

Perspective

Relationship between Health and Radiation Dose

Effective dose equivalent (mSv)

10000

(Whole body exposure) 99% mortality 7,000～10,000

(Whole body exposure) 50% mortality 3,000～5,000

1000

(Whole body exposure) decrease of lymphocyte 500

Maximum permitted for staff working in emergency cases (only Fukushima Daiichi case) 250

Maximum permitted for staff working in emergency cases (ordinary) 100

100

Maximum permitted for radiation workers in one year 50

Radiation exposure in daily life

Natural Radiation at Guarapari Beach, Brazil (per year) 10

10

Chest X-Ray computed tomography (one time) 6.9

Natural Radiation per person (per year, world average) 2.4

1

Regular public space (except medical area) 1.0

Abdominal X-Ray for health check up (one time) 0.6

Tokyo – New York flight (round trip) 0.19
(radiation varies depending on the flight altitude)

0.1

The target figure around Nuclear Power Plant area (per year) 0.05

(Note) The amount of natural radiation is including the effect of inhalation of Radon.
(source) UNSCEAR 2000 Report, "Sources and Effects of Ionizing Radiation" etc.

Spent Fuel Pool

- Spent Fuel Cooling - Makeup with Portable Injection Source
- SFP Parameters - Reliable means to determine SFP water level
  - to prevent undue distraction of operators
  - to identify conditions when makeup/spray is required