WHAT HAPPENED IN FUKUSHIMA - A TECHNICAL PERSPECTIVE

The Nuclear Accidents at the Mark 1
Boiling Water Reactors (BWR)
at Fukishima Daiichi Units 1 - 4
and Implications for American BWR

LBNL EETD noon Seminar - April 5, 2011

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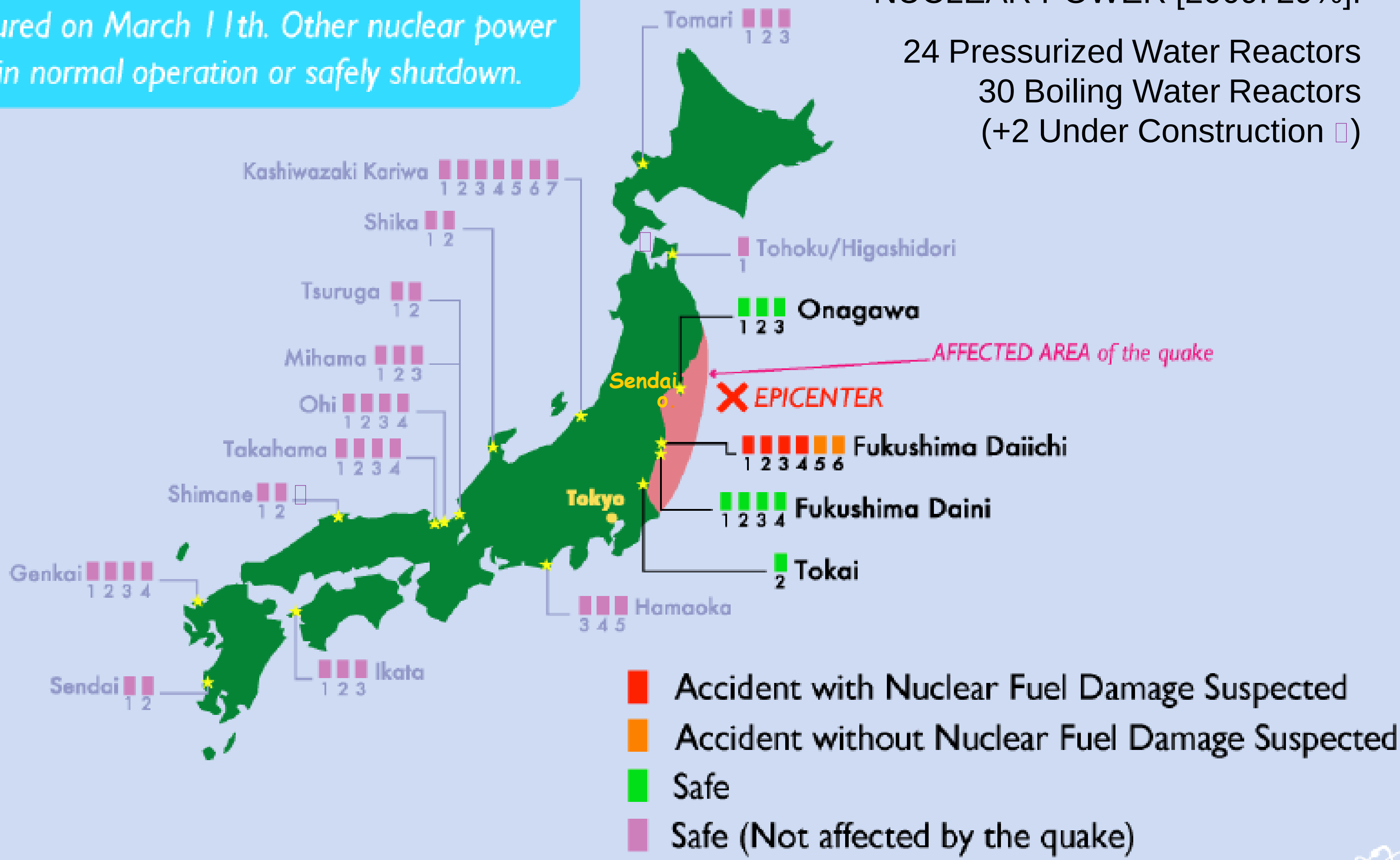
The accident that brings environmental impact is going on at several units in Fukushima Daiichi nuclear power Station after the earthquake occured on March 11th. Other nuclear power plants in Japan are in normal operation or safely shutdown.

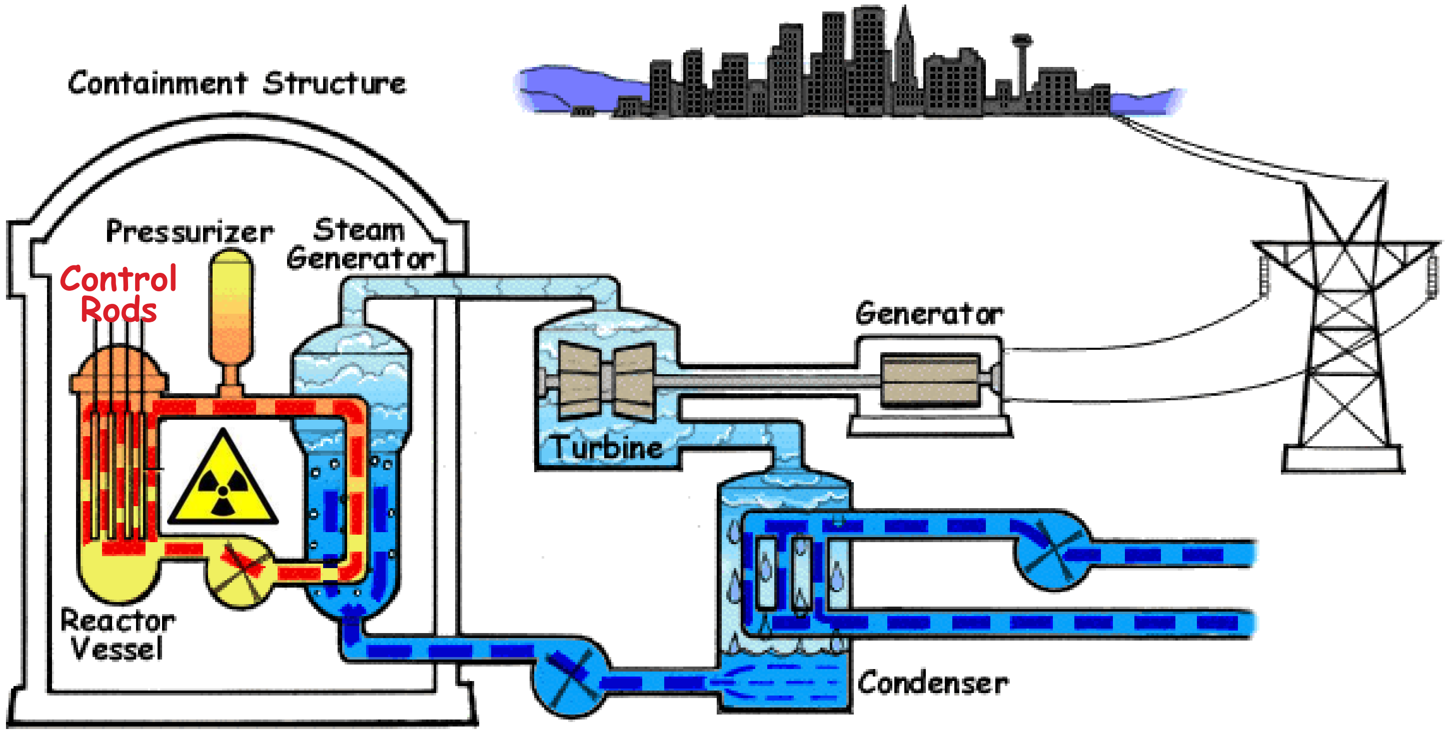
JAPAN: HEAVY RELIANCE ON NUCLEAR POWER [2009: 29%]:

24 Pressurized Water Reactors
30 Boiling Water Reactors
(+2 Under Construction □)



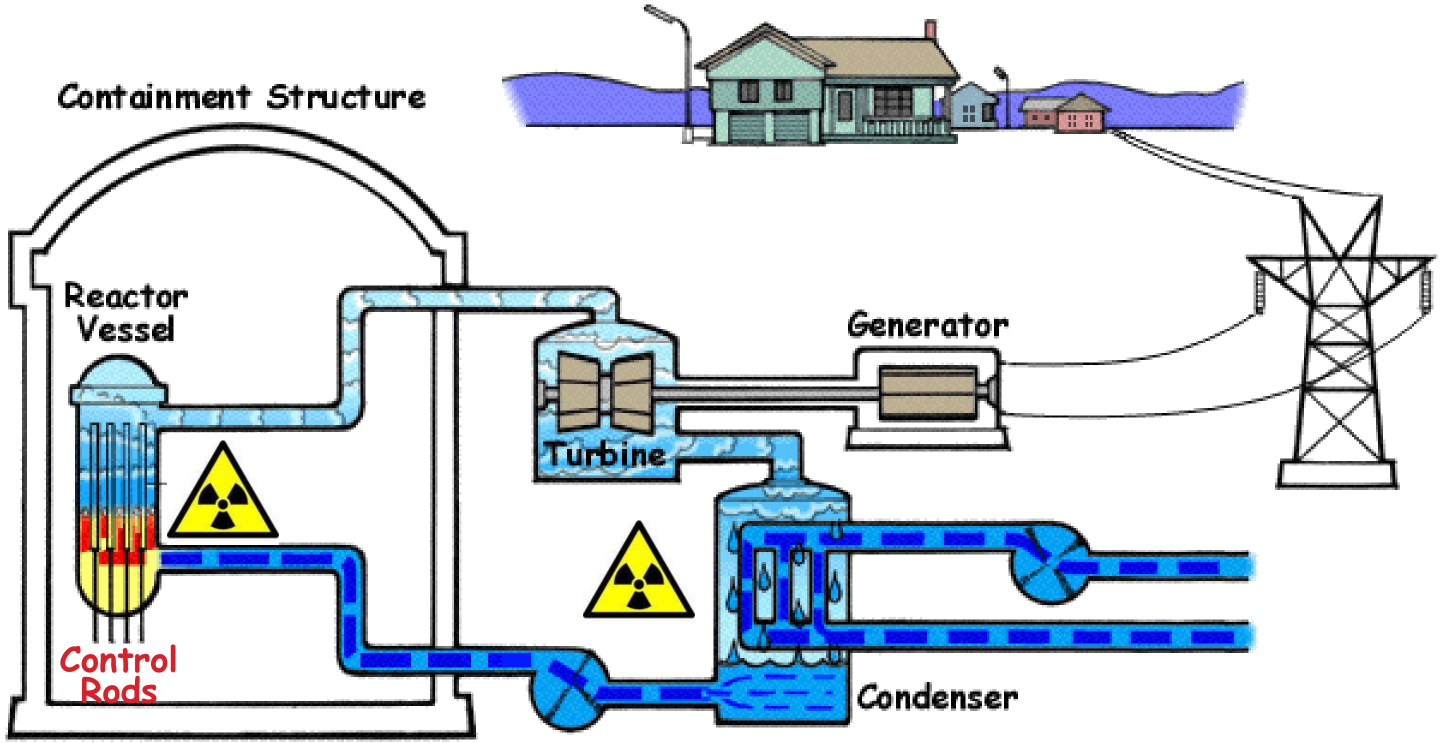
Source: Japan Atomic Industrial Forum (JAIF)

What is a Pressurized Water Reactor [PWR]?



Adapted from U.S. Nuclear Regulatory Commission (NRC), PG&E (Photo)

What is a Boiling Water Reactor [BWR]?



Adapted from U.S. Nuclear Regulatory Commission (NRC)

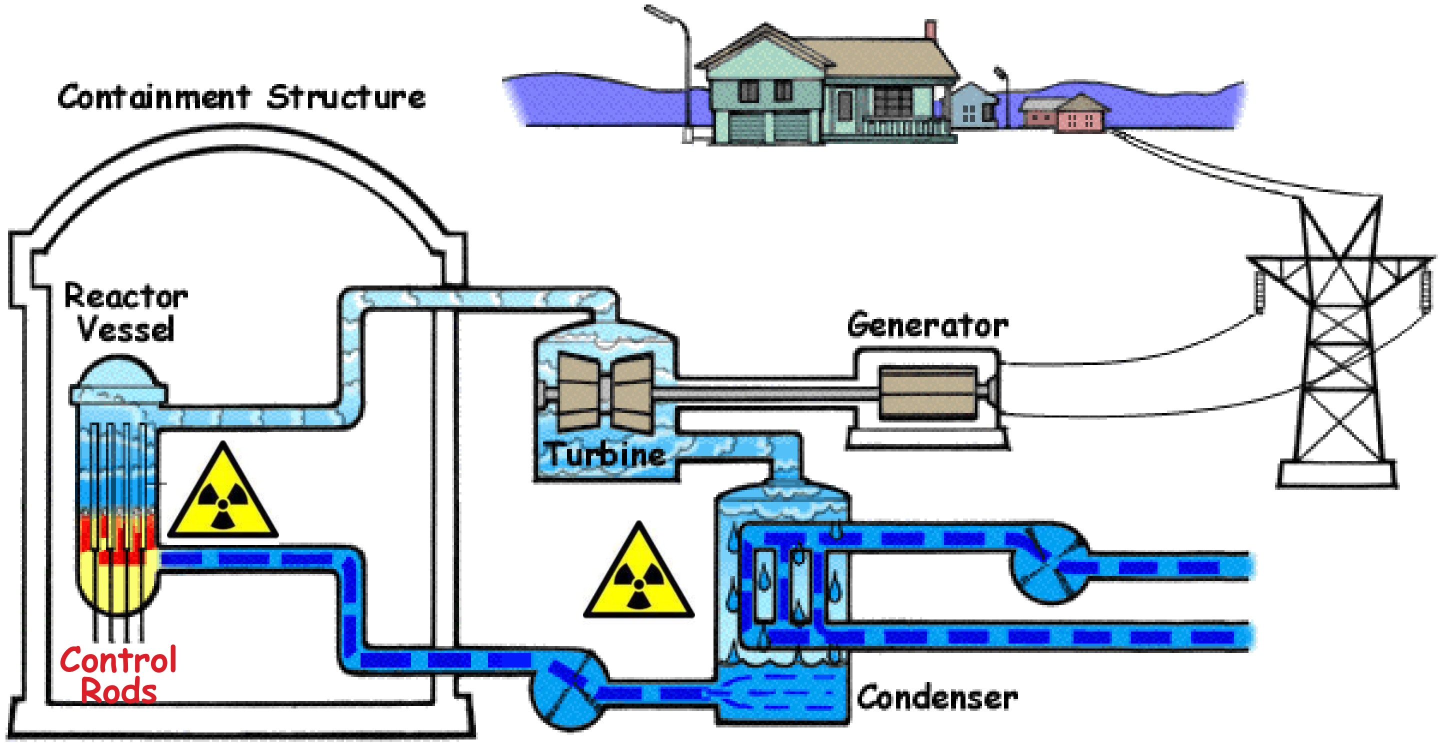
Key Advantages of Boiling Water Reactors:

(Besides generating CO_2-free electricity)

- Fewer components due to no steam generators and no pressurizer vessel (overcompensates larger reactor size due to lower enrichment)
- Operate at a substantially lower pressure (about 75 atmospheres) compared to PWR (about 158 atm) and lower fuel temperature
- Because of single major vendor (GE/Hitachi), current fleet of BWRs have predictable, uniform designs. Invaluable for first responders
- Convenient method for controlling power by simply changing pump flow
- Steam-driven Emergency Core Cooling System (ECCS) directly operated by steam produced after a reactor shutdown (but valves are controlled by battery power)

Sources: GE, Industry, Braun/Stanford Presentation (3/25/2011)

What is a Boiling Water Reactor [BWR]?



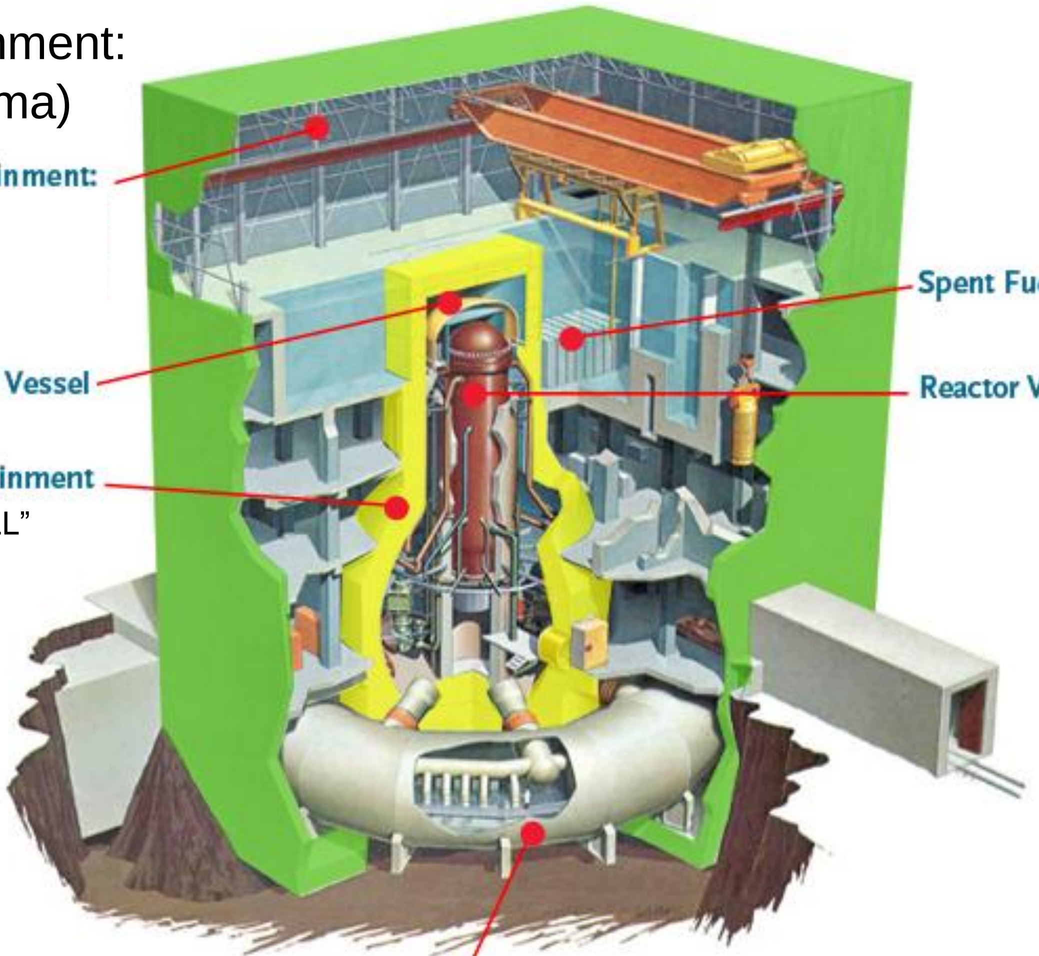
Adapted from U.S. Nuclear Regulatory Commission (NRC)

Key Disadvantages of Boiling Water Reactors:

- Single Coolant Circuit - Contamination of the turbine by short-lived radiation (N_{16})
- Requires active cooling for up to to several days following shutdown. Heat generation rate initially 6% of normal power operation, ~1% after 1 day, and ~0.5% after 5 days (enough to melt reactor core)
- Spent fuel pool exposed on top of reactor building in weak secondary containment
- No major BWR reference accident ever happened until Fukushima that could be used for “benchmarking” accident frequencies – this led to overconfidence in BWR design (as explained later)

Sources: GE, Budnitz (2010), Braun/Stanford Presentation (3/25/2011)

BWR Mark I Containment:
(All Units in Fukushima)



Source: Adapted from Nuclear Energy Institute (NEI, updated 3/23/2011)

What Happened in Fukushima Daiichi?

On March 11, 2011: 14:46 Local Time: 9.0 Earthquake off the coast

Control Rods Inserted as Planned – Shuts Down Units 1-3 [Units 4-6 not operating]

Power grid in Northern Japan fails

15:41 Local Time: **14 m (40 ft) Tsunami** hits. Plant designed only for 6.5 m Tsunami

Units 1, 2, 3, 4
(#4 in Outage)

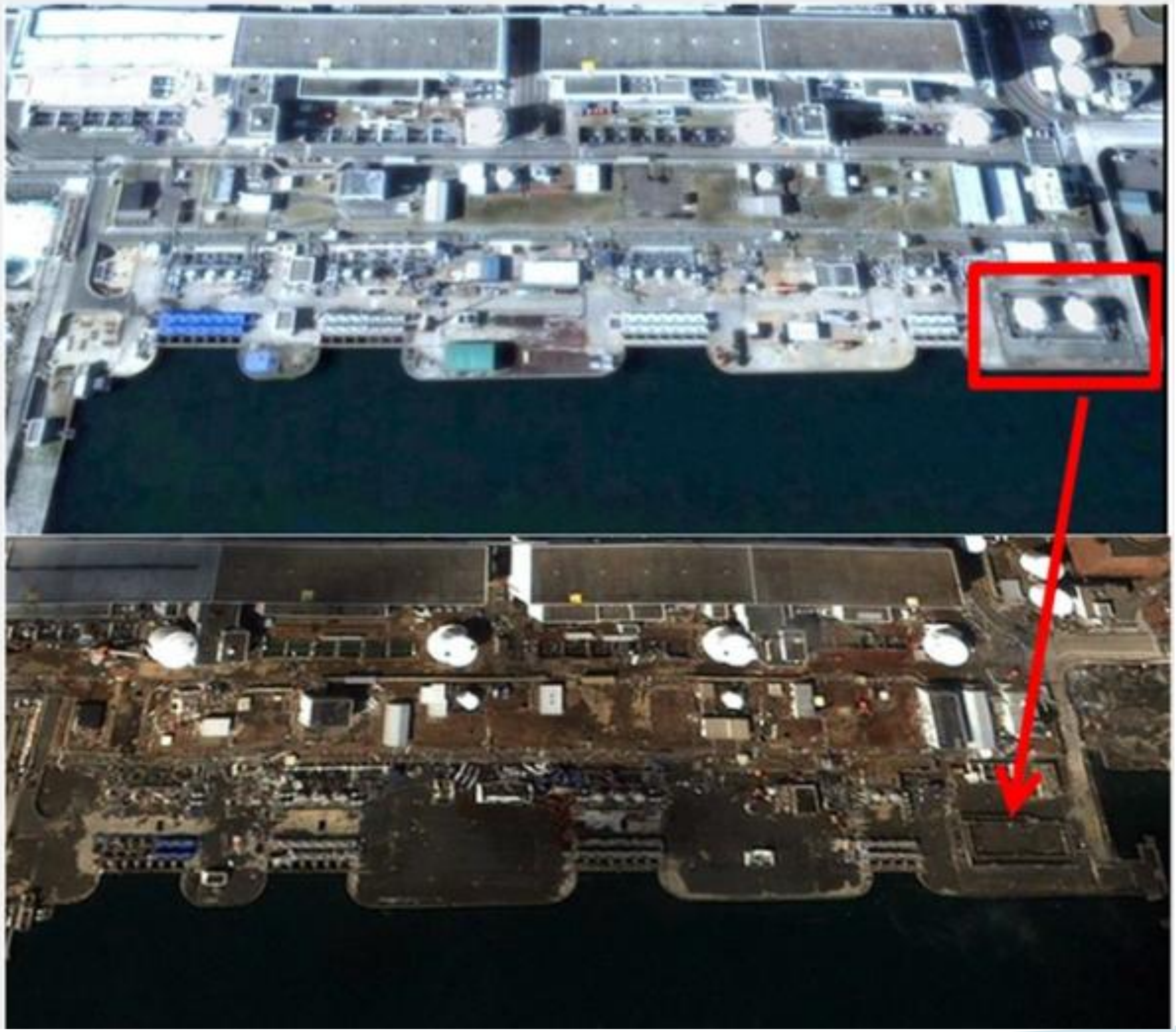
Units 5 & 6
(in Outage)

Photo: Japan Land, Infrastructure, Transport and Tourism Ministry (Kyodo)

Loss of Diesel Tanks for Emergency Generators

+ Potential Flooding of the 14 Diesel Generators

Before Tsunami



After Tsunami

Source for Photos: Digital Globe (comparison by Forbes)

Timeline of Events Between March 11 and 14, 2011

In succession, beginning in Unit 1, then 3 and then 2:

- Batteries run out / Emergency Core Cooling System (ECCS) failure
- TOTAL STATION BLACKOUT ("Beyond Design Basis Accident")
- Pressure in Reactor Vessels Rises – Steam Release Valves Open
- 300 tons of water evaporate each day
- Nuclear fuel in reactors becomes uncovered and overheats
- At ~2200°F, zirconium cladding reacts with steam and generates hydrogen
- In order to prevent containment over-pressurization and failure, hydrogen/steam is vented into atmosphere – but because of design flaw (missing hardened vent) accumulates in secondary containment buildings

Source: Braun/Stanford Presentation (3/25/2011)

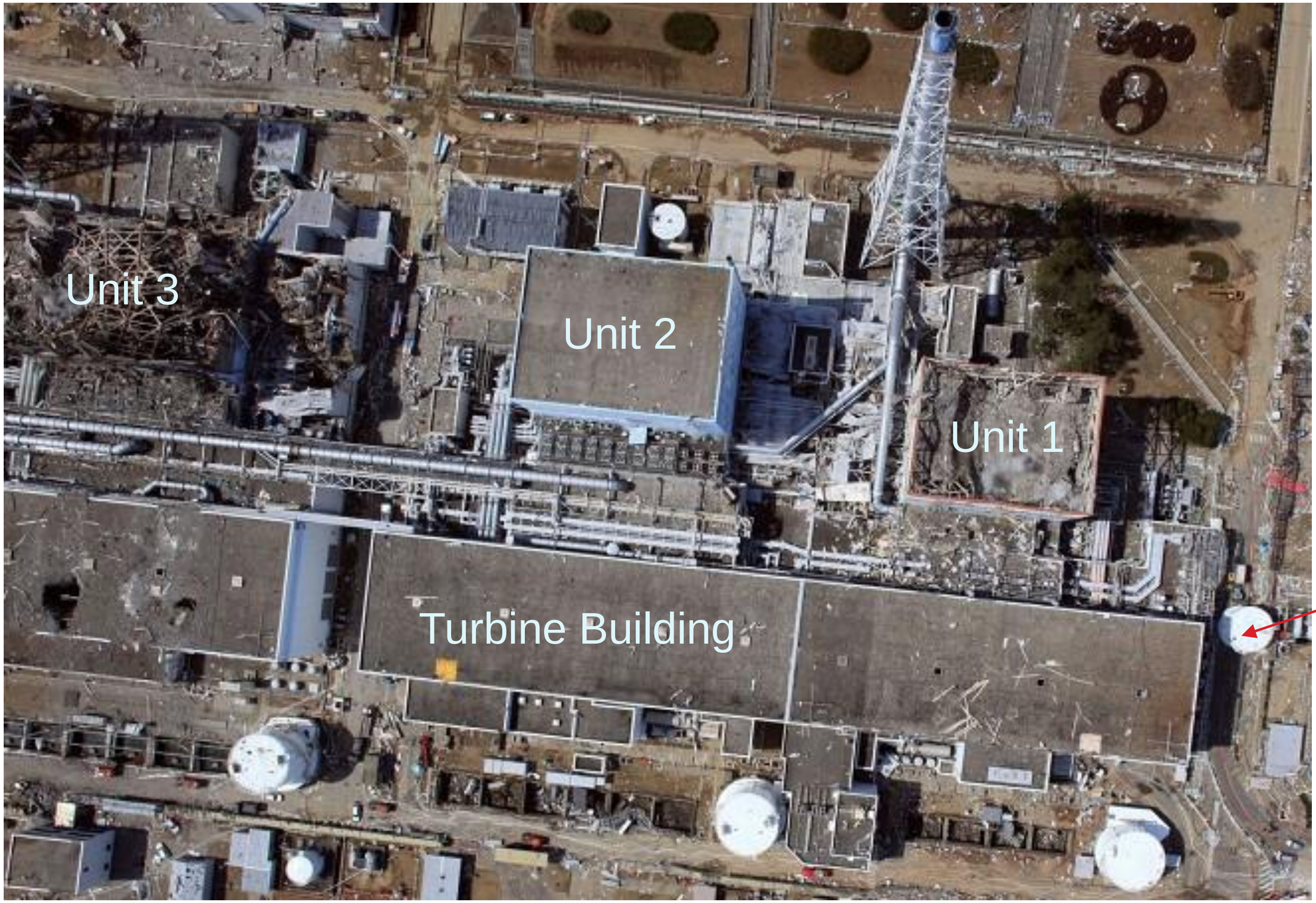
Hydrogen Explosions of outer Secondary Containment Buildings (Primary Containments Believed to be Undamaged at that Time)

March 12

March 14

Source: Associated Press

After
March 14



Source: Associated Press / TEPCO

March 15 Hydrogen Explosion and Fires in Secondary Containment Building of Unit 4 (reactor was completely emptied before accident)

- Spent Fuel Pool uncovered at Unit 4 (Earthquake damage?)
- Nuclear fuel in pool overheats and also generates hydrogen

After March 15,

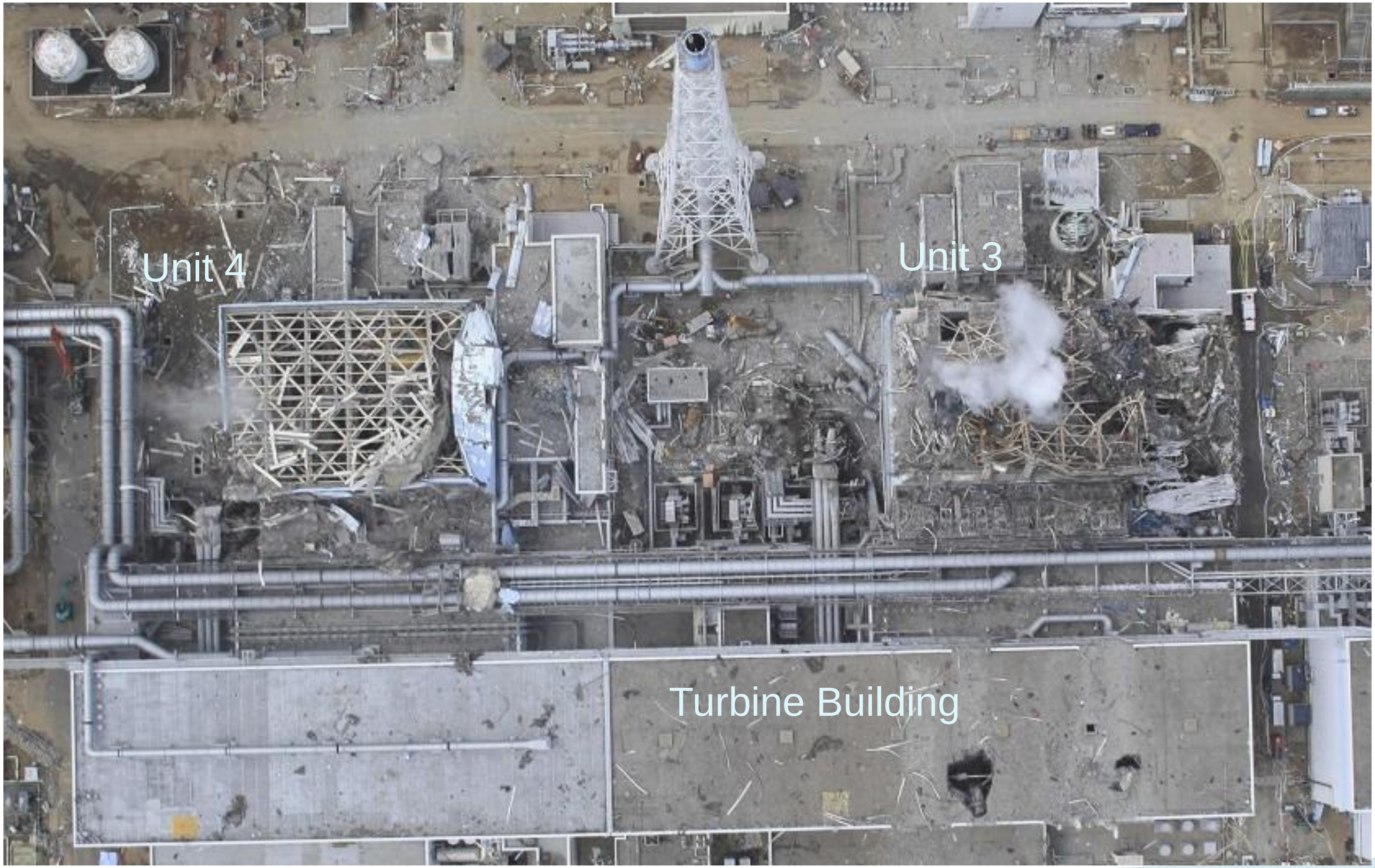
Only remaining option was to cool the reactor cores at units 1 – 3, and the spent fuel pools at all four units:

- Seawater was pumped in with mobile equipment (irreparable damage)
- Helicopters and concrete pump dump water on spent fuel pools

Unit 2 appears to have suffered primary containment damage, radioactive decay products (cesium, iodine) and plutonium released into environment.

Source: JAIF, Braun/Stanford Presentation (3/25/2011)

After March 15



Source: Associated Press / TEPCO

Truck-mounted concrete pump

160 m³ water /h

Source: Putzmeister / TEPCO

Source: Associated Press

What Went Wrong?

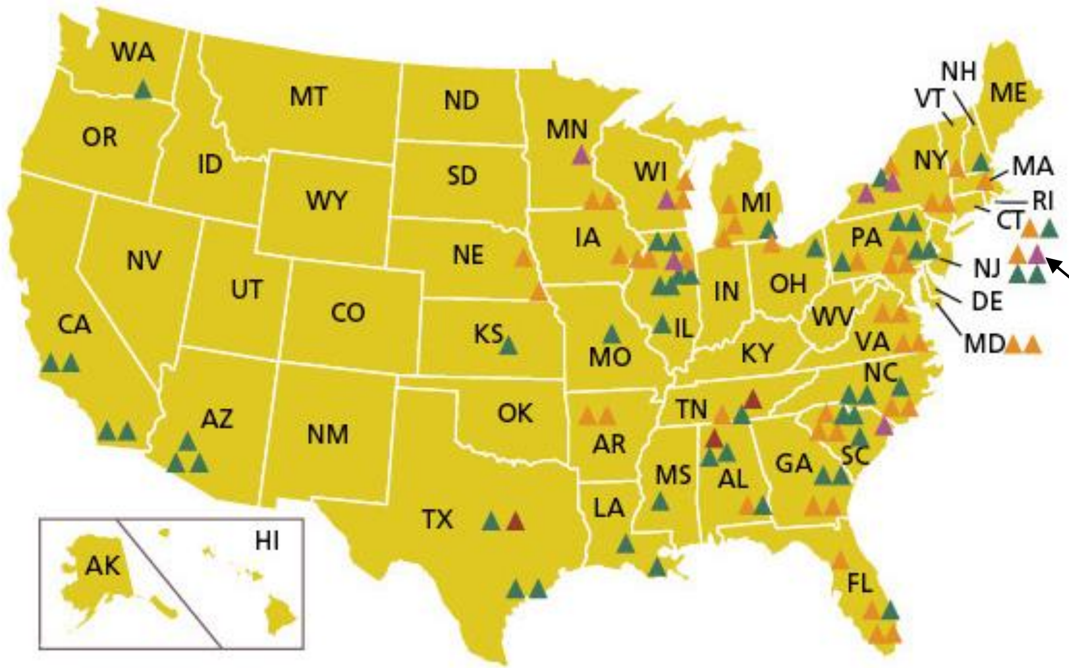
- Overconfidence in BWR design - Japan's Nuclear Safety Commission did not require improvements implemented in U.S. in 1980s.
- Historical information was ignored. Japan trench produced earthquakes of magnitude 8 or higher four times in the past 400 years - 1611, 1677, 1793, and 1896, often accompanied by Tsunamis
- Placement of diesel fuel tanks above ground on waterfront
- History of falsified records by plant owner Tokyo Electric Power (TEPCO)

Ultimately, Nothing can Prepare for at least some very huge

Beyond Design Basis Accidents

What are implications of Fukushima for US nuclear power plants?

U.S. Commercial Nuclear Power Reactors— Years of Operation by the End of 2010



Oyster Creek

Years of Commercial Operation	Number of Reactors
△ 0–9	0
▲ 10–19	3
▲ 20–29	48
▲ 30–39	46
▲ 40 plus	7

There are 23 Mark I Boiling Water Reactors Operating in the U.S. (Out of 104 PWRs and more advanced BWRs)

Source: from U.S. Nuclear Regulatory Commission (NRC)

GE Boiling Water Reactor Evolution

VBWR Vallecitos Boiling Water Reactor, Pleasanton, CA
World's First Commercial Reactor (1957-1967): 30 MWe

Sources: GE, Luke Welsh (NDA Tech)

GE Boiling Water Reactor Evolution

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1st generation

Oyster Creek, Ocean County, NJ, Oldest U.S. Operating Power Reactor (1969): 645 MWe

2nd generation

2nd generation BWRs come in different reactor and containment building designs:

Reactor	Year	Containment
BWR/1	*1960*	Mark I
BWR/2	*1969*	
BWR/3	*1971*	Mark II
BWR/4	*1972*	
BWR/5	*1977*	Mark III
BWR/6	*1978*	

Safer

Photo Sources: GE, Luke Welsh, Exelon

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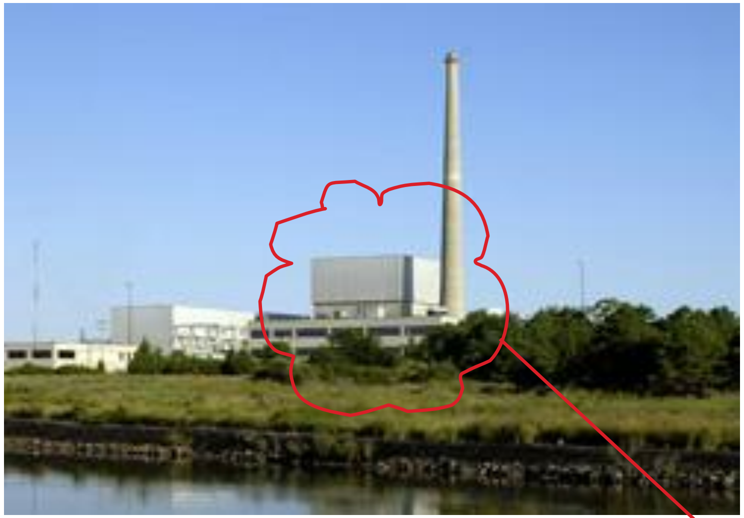

2nd generation

Mark I Containment

Fukushima 1 Units 1-6

There are 23 Mark I Boiling Water Reactors Operating in the U.S.

Photo Sources: GE, Luke Welsh, Exelon

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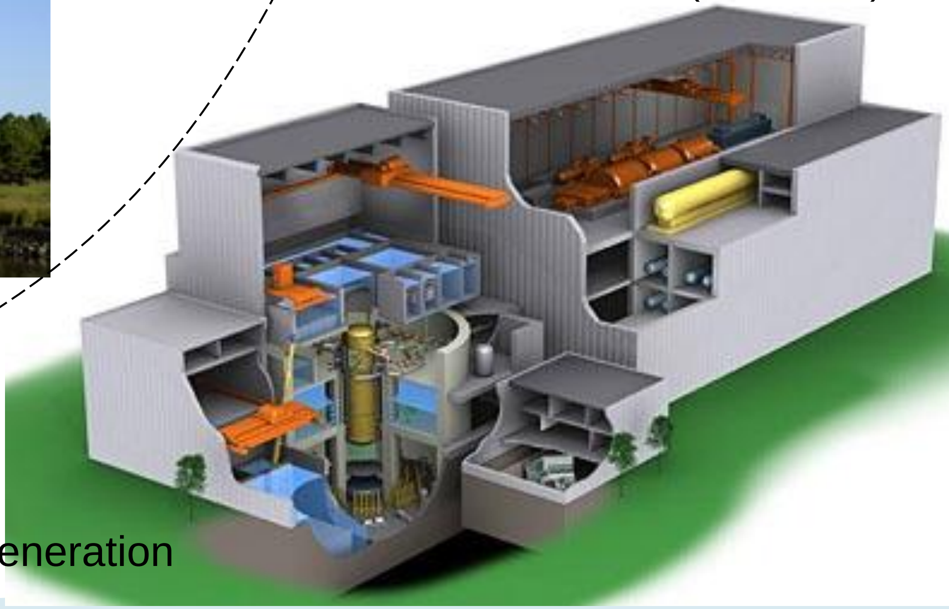
2nd generation

ABWR Advanced Boiling Water Reactor: 1350 MWe (Japan, TX)
ESBWR: 1600 MWe (4500 MWt)



3rd generation

Photo Sources: GE, Luke Welsh, Exelon

BWR Mark I Containment Modifications: (e.g. $1 billion on Oyster Creek)

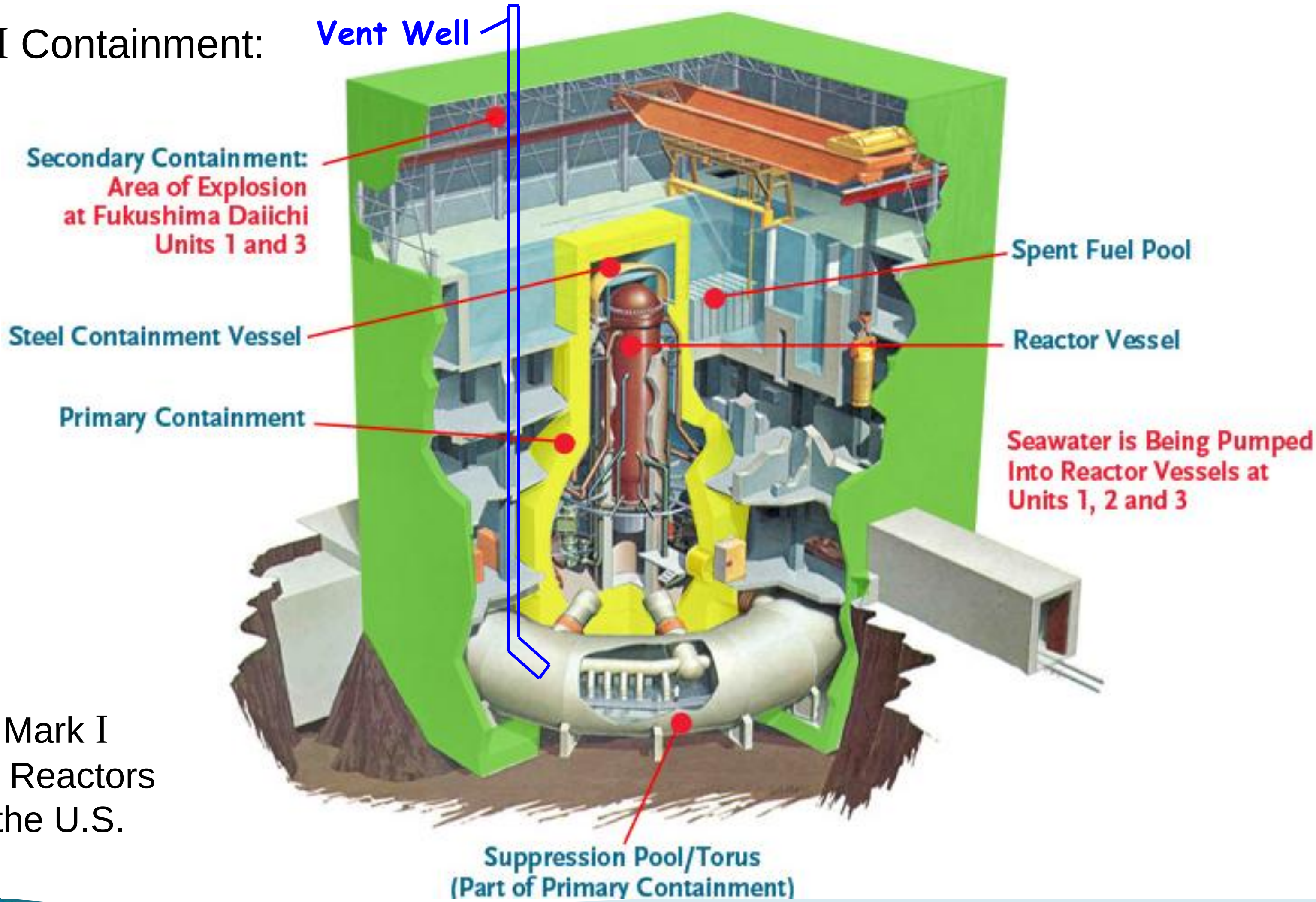
In the U.S., extensive modifications of Mark I containment buildings have been performed in the last 40 years, the most important being:

- Quenchers were installed in Torus to distribute the steam bubbles
- Deflectors were installed in Torus to break up the pressure wave
- Primary Containment, Torus, and Internal Piping (especially of the Emergency Core Cooling System) were structurally fortified
- Most importantly, the NRC required 1989 that all Mark I containments have a Hardened Wetwell Vent installed (NRC Generic Letter 89-16) (like the barrel on a rifle, strong enough to withstand explosion within)

Japan's Nuclear Safety Commission rejected requirement of Hardened Wetwell Vent in 1992 – it should be left to the plant operators to decide

Sources: GE “Mark I Containment Report” (Revision 1, 3/19/2011), Reuters

BWR Mark I Containment:



There are 23 Mark I Boiling Water Reactors Operating in the U.S.

Source: Adapted from Nuclear Energy Institute (NEI, updated 3/23/2011)

Additional Resources:

Japan Atomic Industrial Forum (JAIF) Daily Updated Information about Reactors
http://www.jaif.or.jp/english/

Stanford Center for International Studies "The Fukushima Daiichi Incident"
(Technical Slide Presentation based on Slides of Dr. Matthias Braun, AREVA NP)
http://iis-db.stanford.edu/evnts/6615/March21_JapanSeminar.pdf

General Electric "The Mark I Containment System in BWR Reactors"
http://www.gereports.com/the-mark-i-containment-system-in-bwr-reactors/

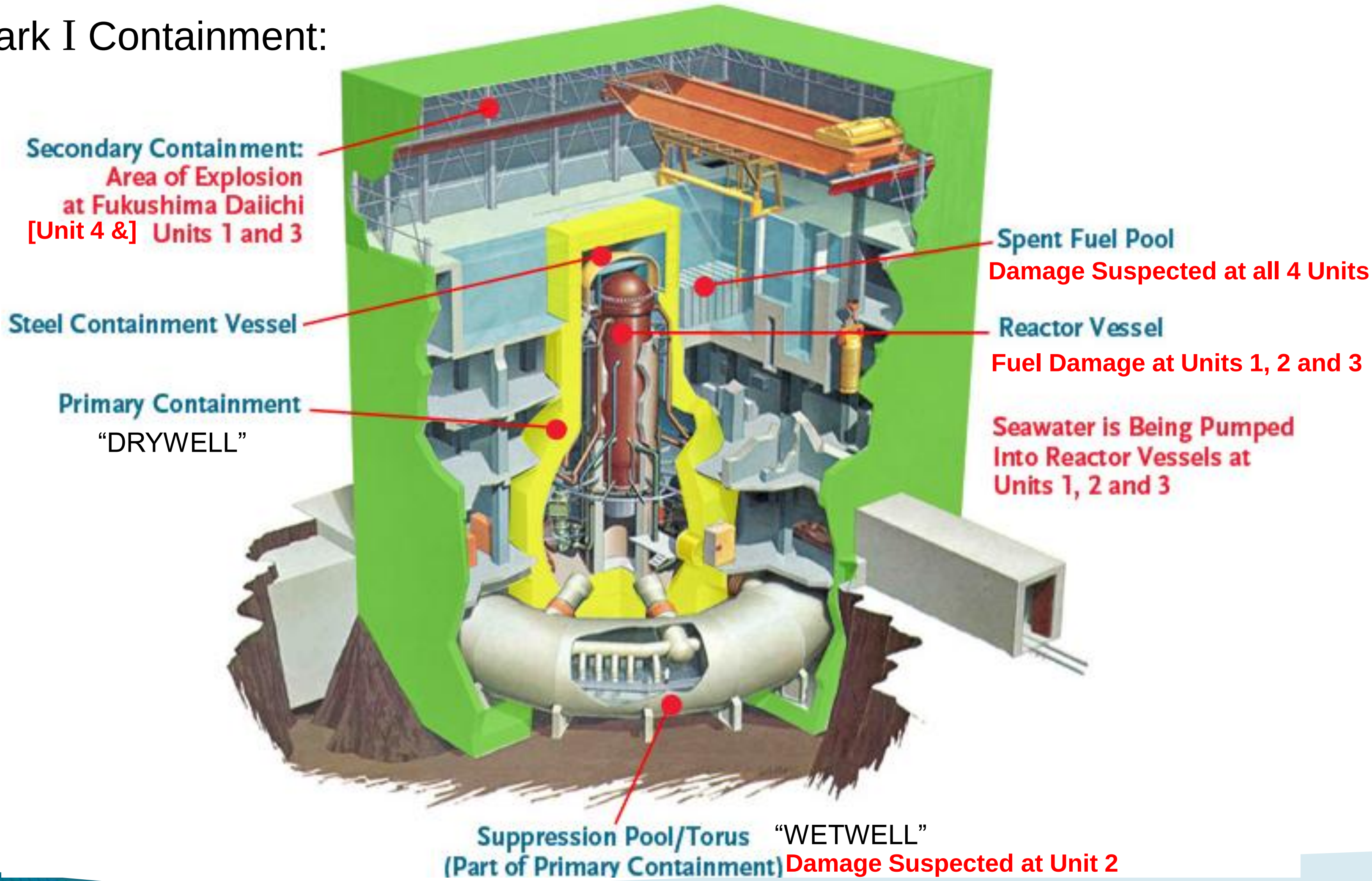
EETD Seminar Presentation by Robert Budnitz, April 15, 2011
"Recent Progress in U.S. Nuclear Power Plant Safety"
http://eetd-seminars.lbl.gov/seminar/recent-progress-us-nuclear-power-plant-safety

Status of nuclear power plants in Fukushima as of 10:00, April 5th (Estimated by JAIF)

Power Station	Fukushima Dai-ichi Nuclear Power Station			
Unit	1	2	3	4
Electric / Thermal Power output (MW)	460 / 1380	784 / 2381	784 / 2381	784 / 2381
Type of Reactor	BWR-3	BWR-4	BWR-4	BWR-4
Operation Status at the earthquake occurred	In Service -> Shutdown	In Service -> Shutdown	In Service -> Shutdown	Outage
Fuel assemblies loaded in Core	400	548	548	No fuel rods
Core and Fuel Integrity (Loaded fuel assemblies)	Damaged	Damaged	Damaged	No fuel rods
Reactor Pressure Vessel structural integrity	Unknown	Unknown	Unknown	Not Damaged
Containment Vessel structural integrity	Not Damaged (estimation)	Damage and Leakage Suspected	Not damaged (estimation)	Not Damaged
Core cooling requiring AC power 1 (Large volumetric freshwater injection)	Not Functional	Not Functional	Not Functional	Not necessary
Core cooling requiring AC power 2 (Cooling through Heat Exchangers)	Not Functional	Not Functional	Not Functional	Not necessary
Building Integrity	Severely Damaged (Hydrogen Explosion)	Slightly Damaged	Severely Damaged (Hydrogen Explosion)	Severely Damaged (Hydrogen Explosion)
Water Level of the Rector Pressure Vessel	Fuel exposed partially or fully	Fuel exposed partially or fully	Fuel exposed partially or fully	Safe
Pressure / Temperature of the Reactor Pressure Vessel	Gradually increasing / Decreased a little after increasing over 400℃ on Mar. 24th	Unknown / Stable	Unknown	Safe
Containment Vessel Pressure	Decreased a little after increasing up to 0.4Mpa on Mar. 24th	Stable	Stable	Safe
Water injection to core (Accident Management)	Continuing (Switch from seawater to freshwater)	Continuing (Switch from seawater to freshwater)	Continuing (Switch from seawater to freshwater)	Not necessary
Water injection to Containment Vessel (AM)	(To be confirmed)	to be decided (Seawater)	(To be confirmed)	Not necessary
Containment Venting (AM)	Temporally stopped	Temporally stopped	Temporally stopped	Not necessary
Fuel assemblies stored in Spent Fuel Pool	292	587	514	1331
Fuel Integrity in the spent fuel pool	Unknown	Unknown	Damage Suspected	Possibly damaged
Cooling of the spent fuel pool	Water spray started (ffreshwater)	Continued water injection (Switch from seawater to freshwater)	Continued water spray and injection (Switch from seawater to freshwater)	Continued water spray and injection (Switch from seawater to freshwater) Hydrogen from the pool exploded on Mar. 15t
Main Control Room Habitability & Operability	Poor due to loss of AC power (Lighting working in the control room at Unit 1 and 2.)		Poor due to loss of AC power (Lighting working in the control room at Unit 3 and 4.)	
INES (estimated by NISA)	Level 5	Level 5	Level 5	Level 3
Remarks	●Progress of the work to recover injection function Water injection to the reactor pressure vessel by temporally installed pumps were switched from seawater to freshwater at Unit 1, 2 and 3. High radiation circumstance hampering the work to restore originally installed pumps for injection. Discharging radioactive water in the basement of the buildings of Unit transfer work is being made to secure a place the water to go. Lighting in the turbine buildings became partly available at Unit 1through 4. ●Function of containing radioactive material It is presumed that radioactive material inside the reactor vessel may leaked outside at Unit 1, 2 and Unit 3, based on radioactive material found outside. NISA announce			

Source: Japan Atomic Industrial Forum (JAIF) Updated April 5, 2011

BWR Mark I Containment:



Source: Adapted from Nuclear Energy Institute (NEI, updated 3/23/2011)