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Earthquake and Tsunami in Japan on March 11, 2011 and Consequences for Fukushima and other Nuclear Power Plants

Status: April 15, 2011

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Tohoku-Taiheiyou-Oki Earthquake

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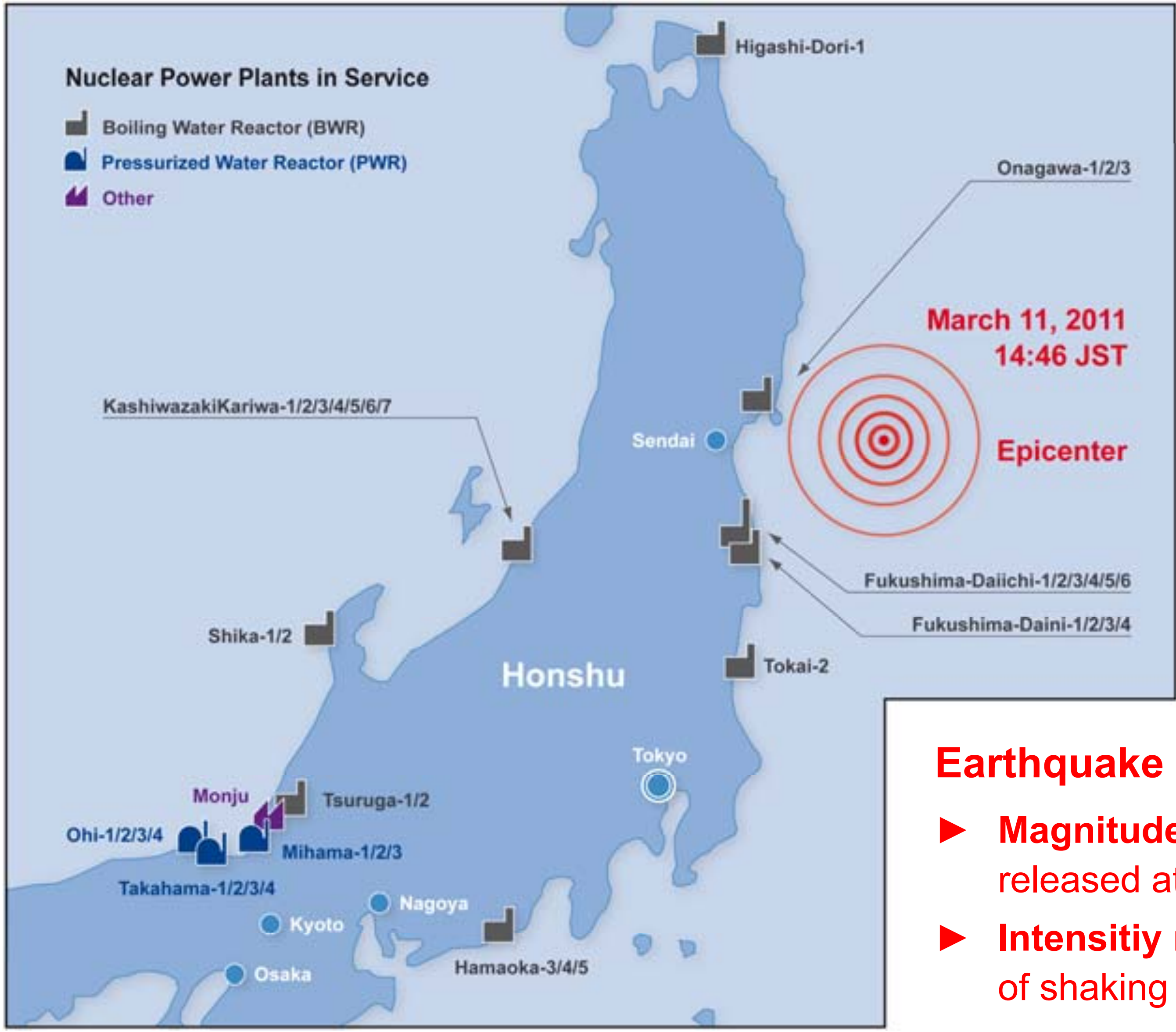


Epicenter Location

38.3 °N, 142.4 °E

Epicenter Distance

- ► Onagawa ≈ 90 km
- ► F-Daiichi ≈ 160 km
- ► F-Daini ≈ 170 km
- ► Tokai ≈ 260 km

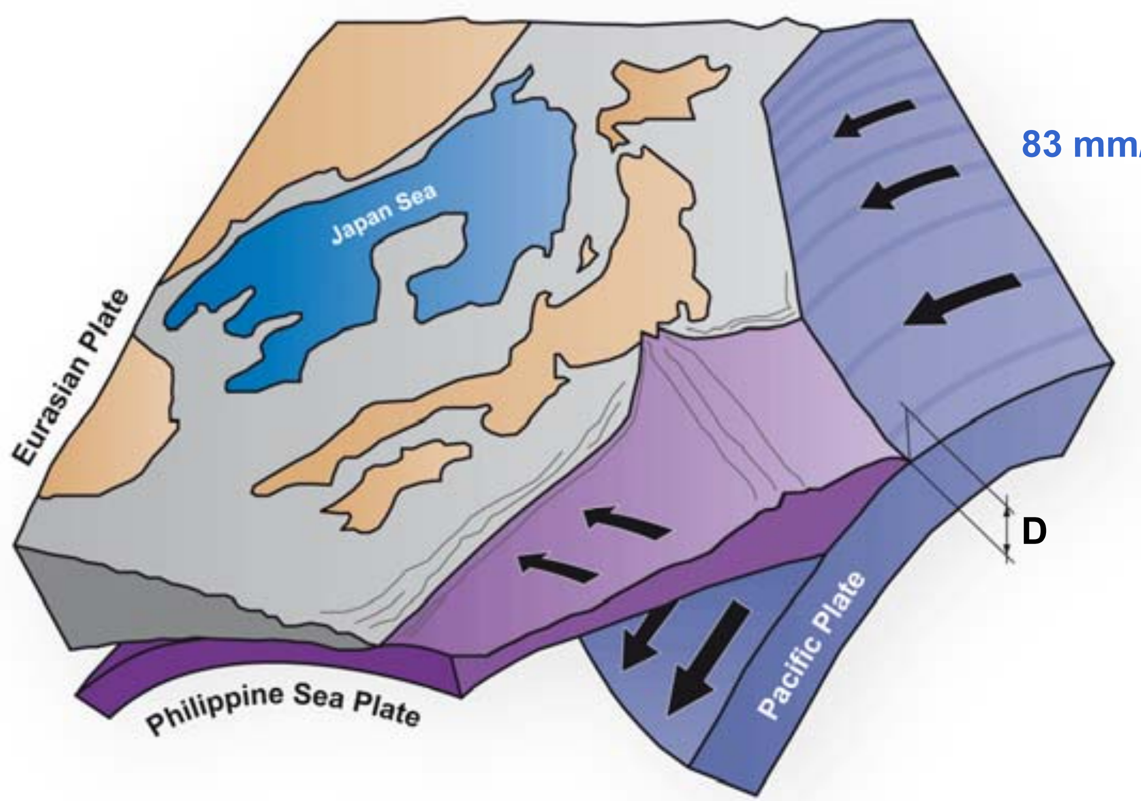
- ► Sendai ≈ 150 km

Earthquake Parameters

- ► **Magnitude** measures the energy released at the epicenter.
- ► **Intensitiy** measures the strength of shaking at a certain location.

Source: GRS, 2011 F: Fukushima JST: Japan Standard Time

Tohoku-Taiheiyou-Oki Earthquake



- **Vertical Displacement**
  D ≈ 7 to 10 m
- **Peak Displacement**
  D_{max} ≈ 17 to 25 m [1])
- **Rupture Zone**
  A ≈ 500 km x 100 km
- **Hypo Center Depth**
  Z_H ≈ 20 to 25 km
- **Crack Velocity**
  v ≈ 2 km/s
- **Water Depth**
  Z ≈ 8 km

- **Rough Estimate of Water Volume Involved**
  $V \approx A \cdot \frac{1}{4} D \approx 500\ km \cdot 100\ km \cdot 2{,}5\ m = 125\ km^3$
- **Consequence:** Sudden displacement of a huge water volume ► **Tsunami.**

Source: Dr. Hein Meidow, Cologne, 2011   JST: Japan Standard Time   UTC: Coordinated Universal Time   [1]) in deep underground

Topographic Effects

- **Relative horizontal displacement of Japan, based on GPS data:**

  ≈ 5.2 m (maximum)

- **Displacement on rupture surface:**

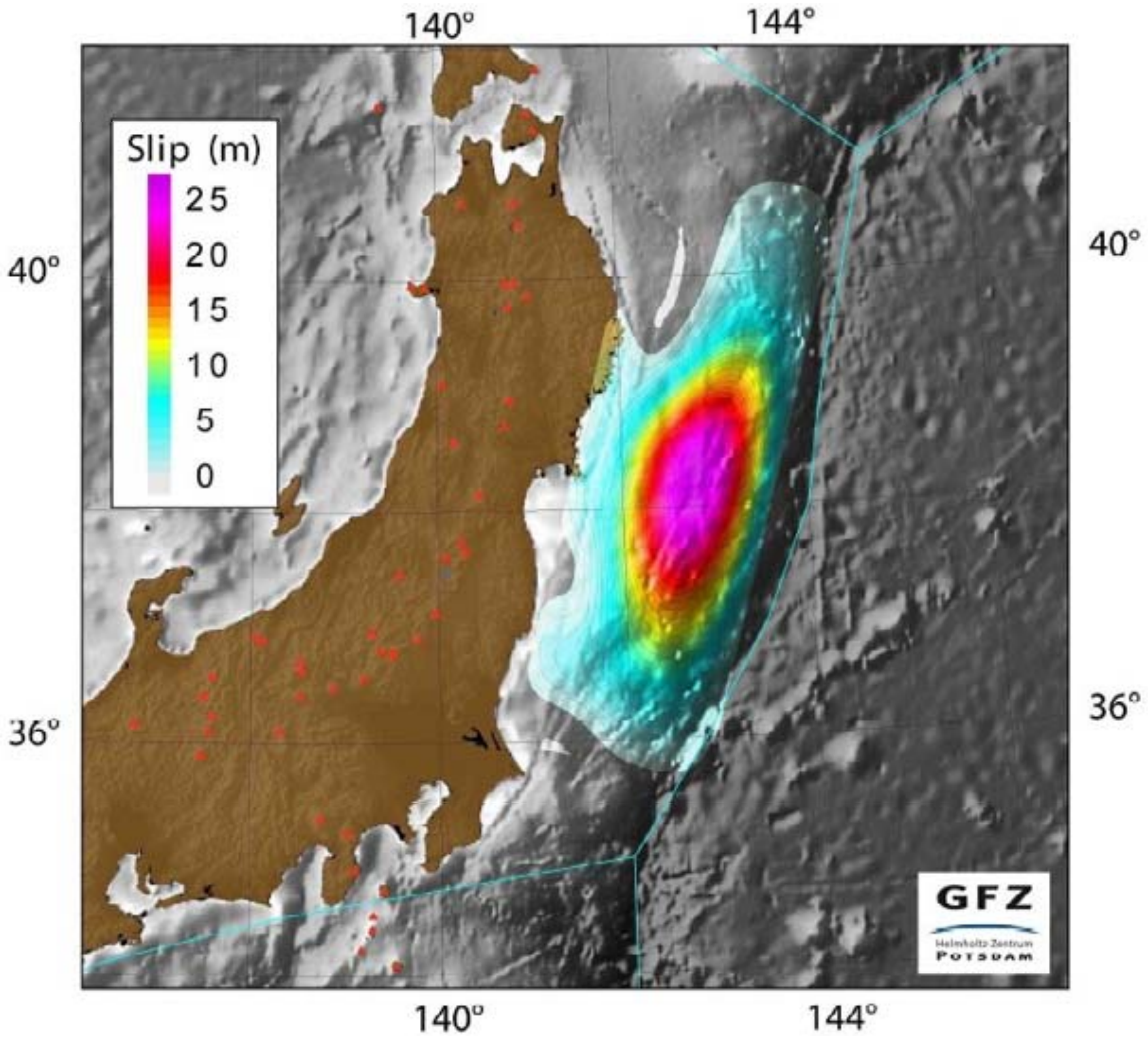
  ≈ 25 to 27 m

- **Rupture length (aftershock):**

  ≈ 400 km

- **Sea bed lifting:**

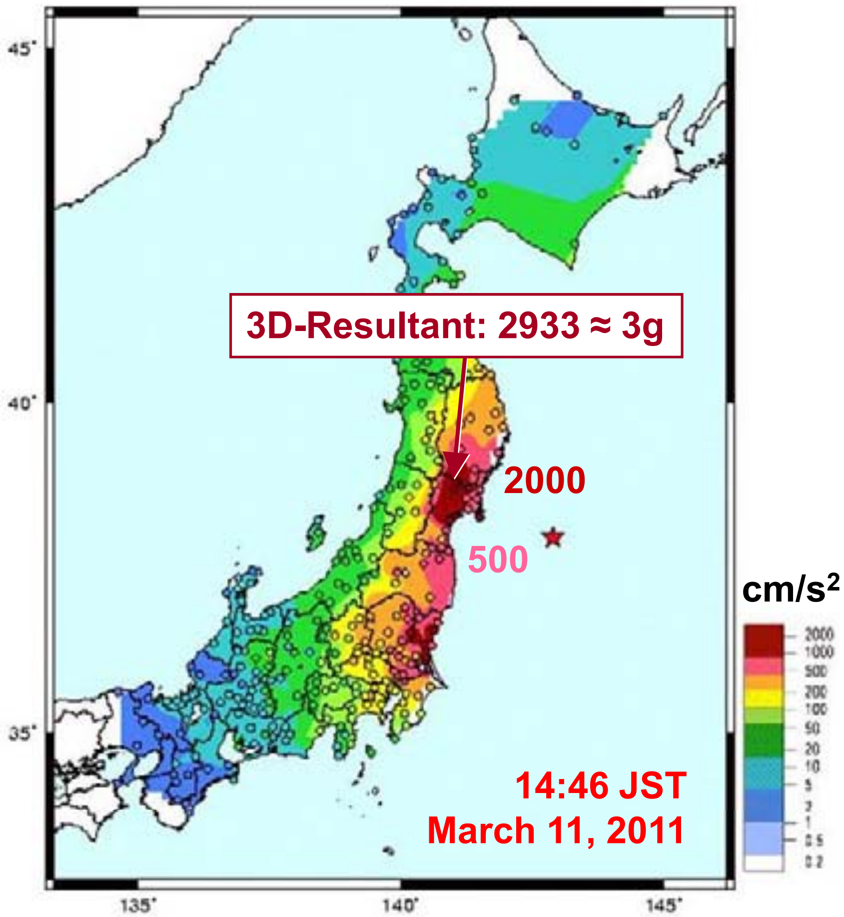
  up to 7 m



Sources: Dr. Hein Meidow, Cologne, GFZ Potsdam, 2011

Tohoku-Taiheiyou-Oki Earthquake

Peak Accelerations Contour Map



Fukushima	Acceleration 1) in cm/s^2		
	Horizontal		Vertical
	N-S	E-W	
Daiichi-1	460	447	258
Daiichi-2	348	550	302
Daiichi-3	322	507	231
Daiichi-4	281	319	200
Daiichi-5	311	548	256
Daiichi-6	298	444	244
Design Basis	441	438	412
Daini-1	254	230	305
Daini-2	243	196	232
Daini-3	277	216	208
Daini-4	210	205	288
Design Basis	415	415	504
Shutdown 2)	135 to 150		100

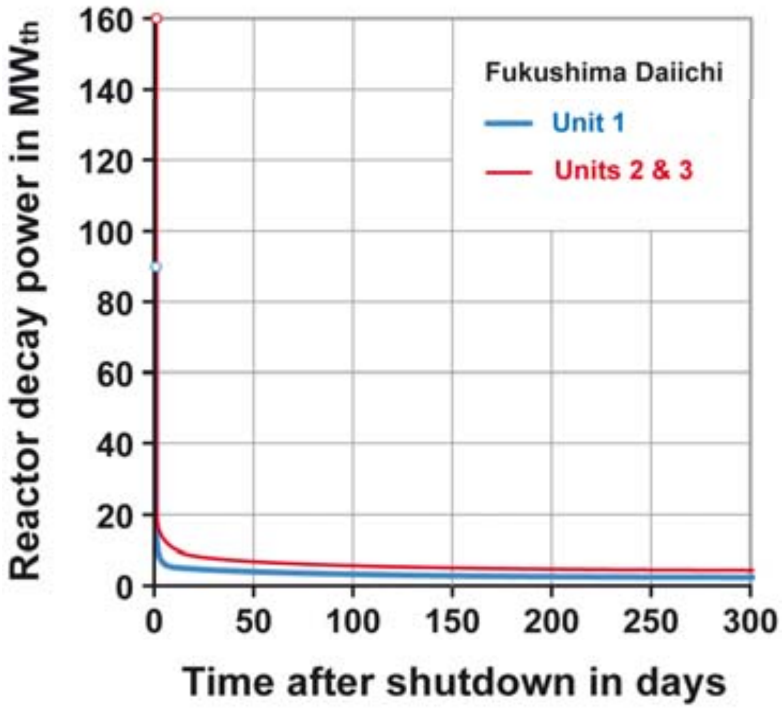
► **Measured accelerations were up to 26 % higher than earthquake design basis values for Fukushima Daiichi (≈ 10 % for Onagawa).**

Sources: Nied, Wano Tokyo, Tepco, 2011 E-W: East-West N-S: North-South 1) maximum response, preliminary data 2) threshold for reactor scram

Initial Response to Earthquake

March 11, 2011, 14:46 JST ► Seconds later

- ► Automatic shutdown (scram) of all operating reactor units within seconds at Onagawa (3), Fukushima Daiichi (3), Fukushima Daiini (4) and Tokai (1).
- ► Start of the cooling systems to remove residual heat, with an initial value of 6 to 7 % of previous core power and decreasing steadily to less than 0.5 % after some days.
- ► Turbine room fire at Onagawa-1 (exstinguished hours later).
- ► Earthquake-induced loss of offsite power at Fukushima-Daiichi.
- ► Start of some emergency diesel generators as well as relevant cooling systems.
- ► Typical redundancy: 2 + 1 per unit.



Sources: FPL, KIT, 2011 JST: Japan Standard Time

Initial Response to Tsunami

About 55 minutes later

► At least Fukushima Daiichi is struck by the tsunami, with a wave height (≈ 14 m) far beyond levee design height (5.7 m) taking out all multiple sets of backup emergency diesel generators (common mode failure).

► Reactor cooling by steam-driven emergency pumps, referred to as reactor core isolation pumps. The relevant auxiliary systems require emergency battery power (8 h).

Tsunami Arrival at Fukushima Daiichi

► Operators follow:

- abnormal operating procedures,
- emergency operating procedures, later
- severe accident management guidelines (SAMGs).

Sources: FPL, AFP, JIJI Press, 2011

Tsunami Impact at Fukushima Daiichi

Source: Tepco, 2011

Tsunami Impact at Fukushima Daini

2 to 3 m inundation height on the side of unit 1 building.

Source: Tepco, 2011

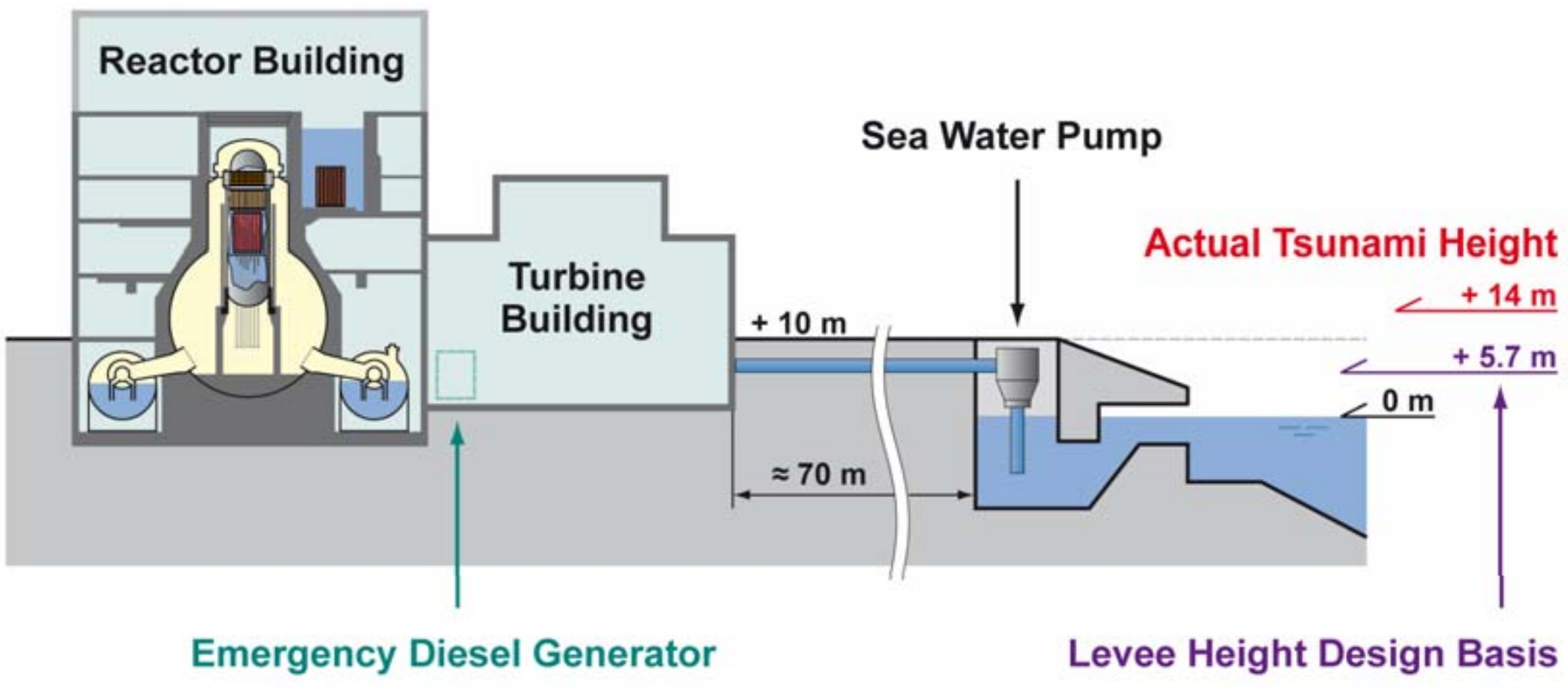
Tsunami

- **Maximum Wave Height** 1) ≈ 23 m
- **Travel Time** from
  - Epicenter to Shore 15 min
  - Epicenter to Fukushima 55 min
- **Arrival** at Fukushima Daiichi 15:41 JST
- **Wave Height** 2)
  - at Fukushima Daiichi ≈ 14 m
  - at Fukushima Daini ≈ 10 m
- **Protecting Levee Height**
  - Fukushima Daiichi 5.7 m
  - Fukushima Daini 5.2 m
- **Ground Level of Reactor Buildings**
  - Fukushima Daiichi ≈ 10 m
  - Fukushima Daini (minimum) ≈ 7 m
  - Onagawa ≈ 20 m

- **Practically all damages at Fukushima Daiichi were caused by the tsunami.**

Sources: AFP, GRS, 2011 1) calculations and GPS-data 2) according to Janti, related to the base level of Onahama Bay

Tsunami and Fukushima Daiichi Heights



- ► At Fukushima Daiichi, countermeasures for tsunamis had been established with a design basis height of **5.7 m** above the lowest Osaka Bay water level.
- ► As additional safety margin, the ground level had been set to as + 10 m.

Source: Janti, 2011 All levels are related to the base level of Onahama Bay

Design of Fukushima Daiichi Unit 1

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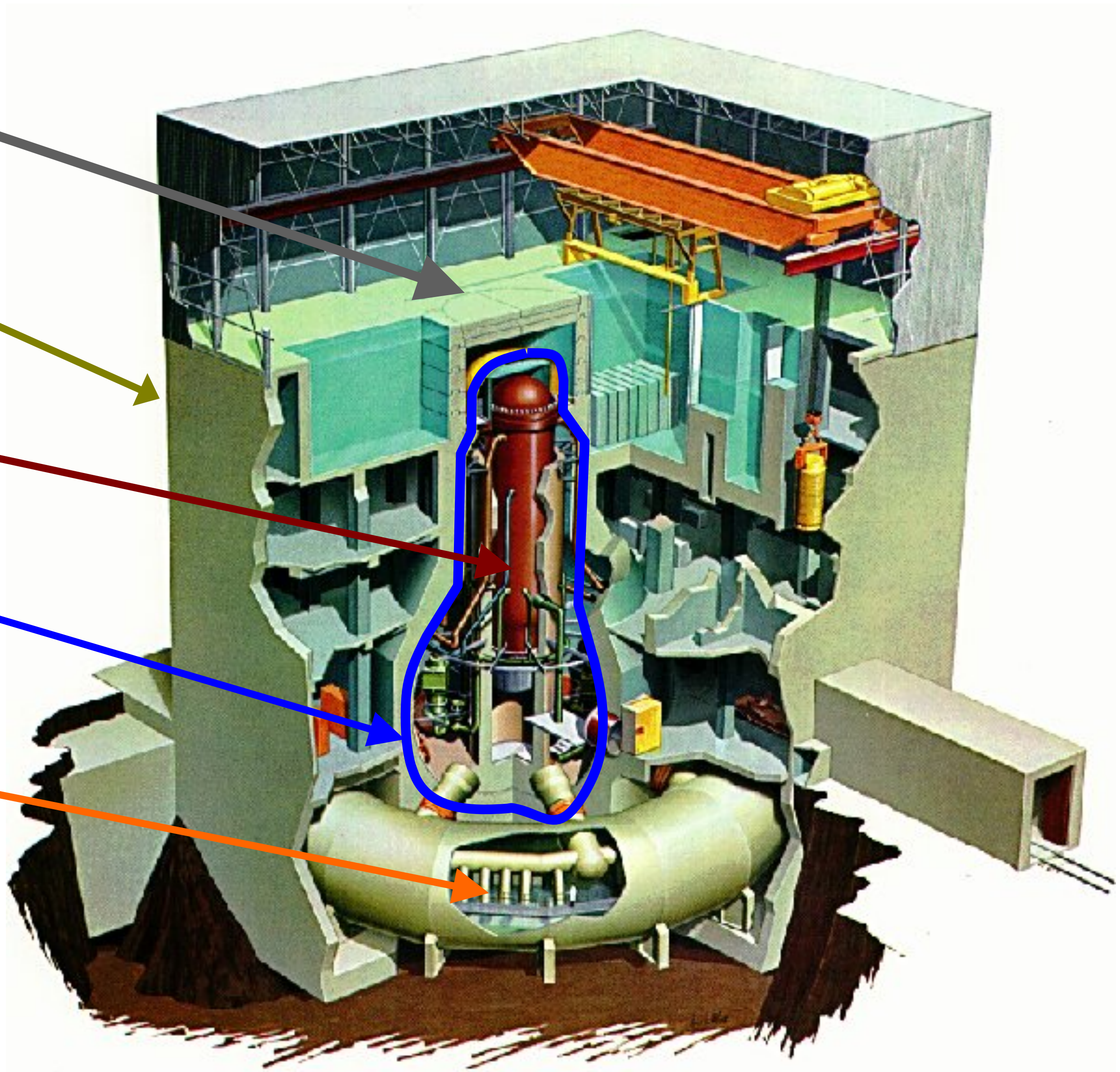
Reactor Service Floor (Steel Construction)

Concrete Reactor Building (Secondary Containment)

Reactor Pressure Vessel

Primary Containment (Drywell)

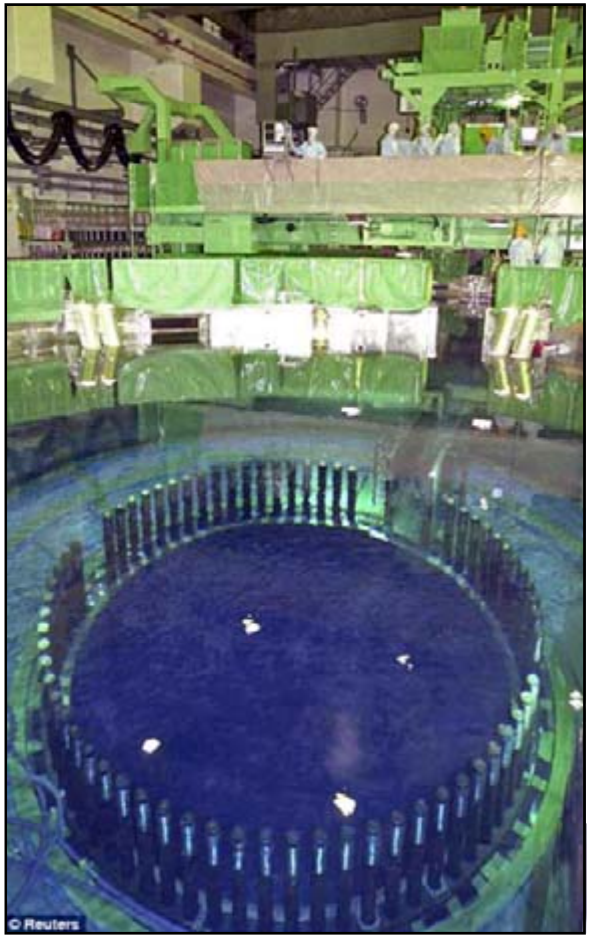
Pressure Suppression Pool (Wetwell)



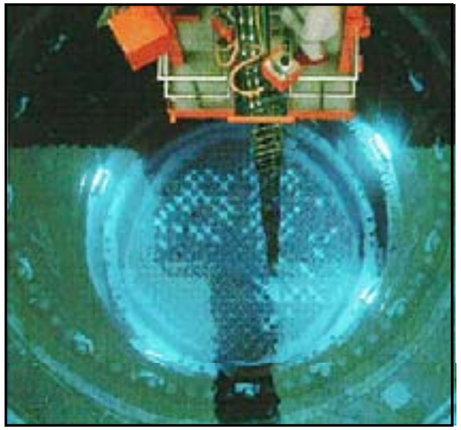
- **Reactor:** BWR-3
- **Containment:** Mark-I

Sources: NRC, General Electric, www.nucleartourist.com

Boiling Water Reactor Internals



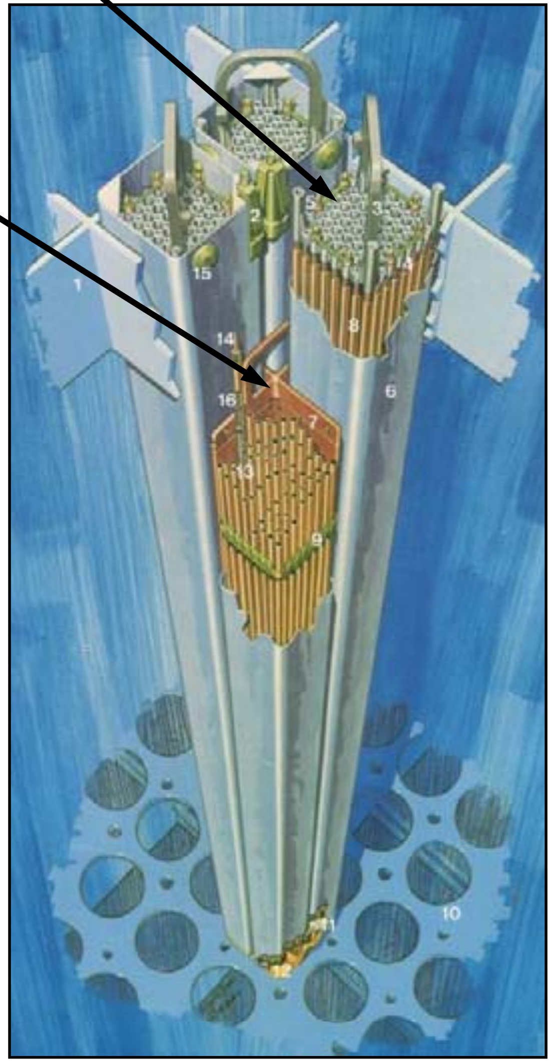
Reactor Building Internal View



Reactor Core

Fuel Assembly

Control Rod



Fuel Assemblies (4)

Source: www.nucleartourist.com

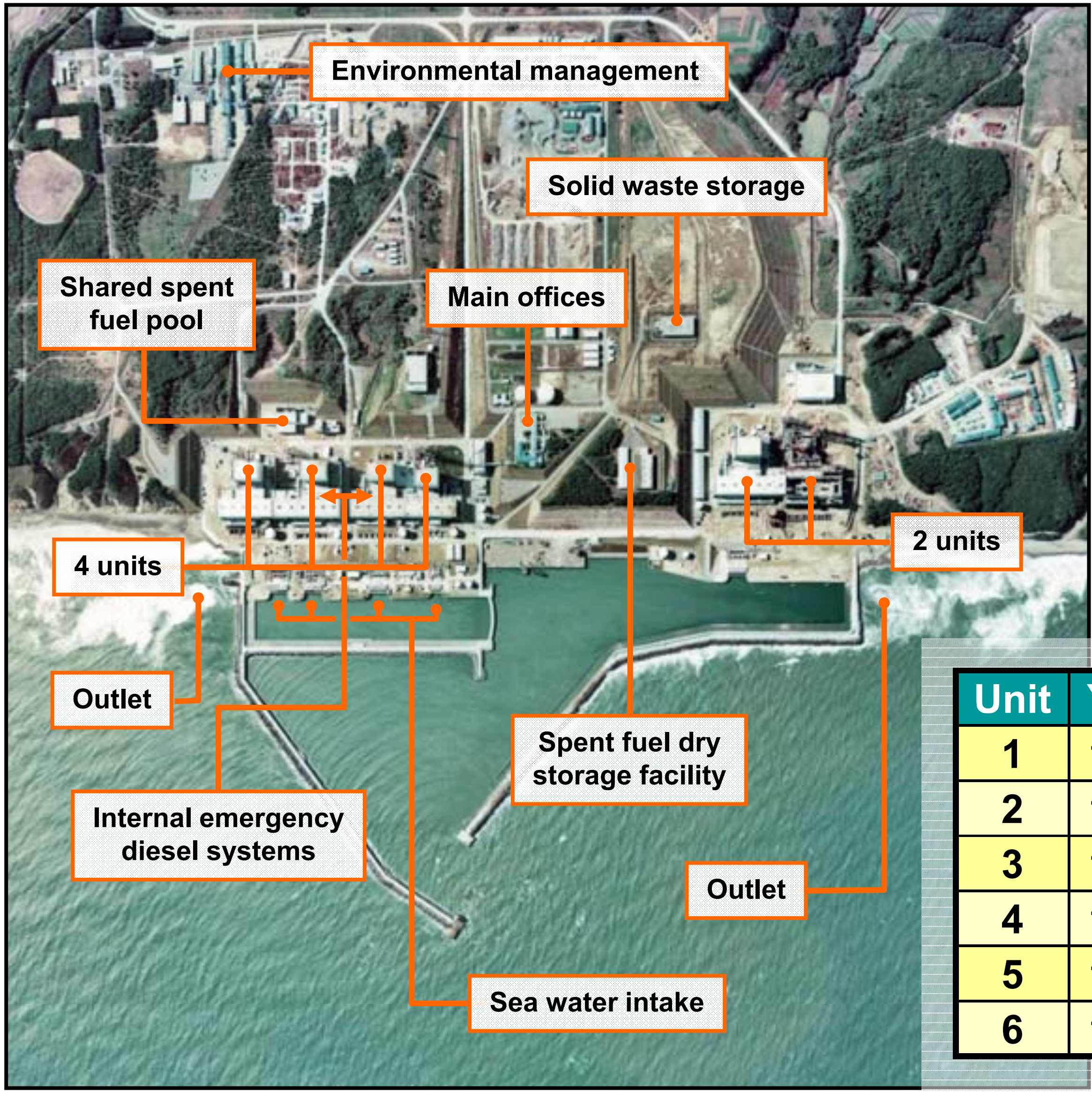
Fukushima Daiichi Aerial View

Unit	Power	Status [1])
1	439 MWe	Operating
2	760 MWe	Operating
3	760 MWe	Operating
4	760 MWe	Outage
5	760 MWe	Outage
6	1067 MWe	Outage

[1]) before earthquake

Source: Nuclear Engineering Handbook, 2010

Fukushima Daiichi Site Layout

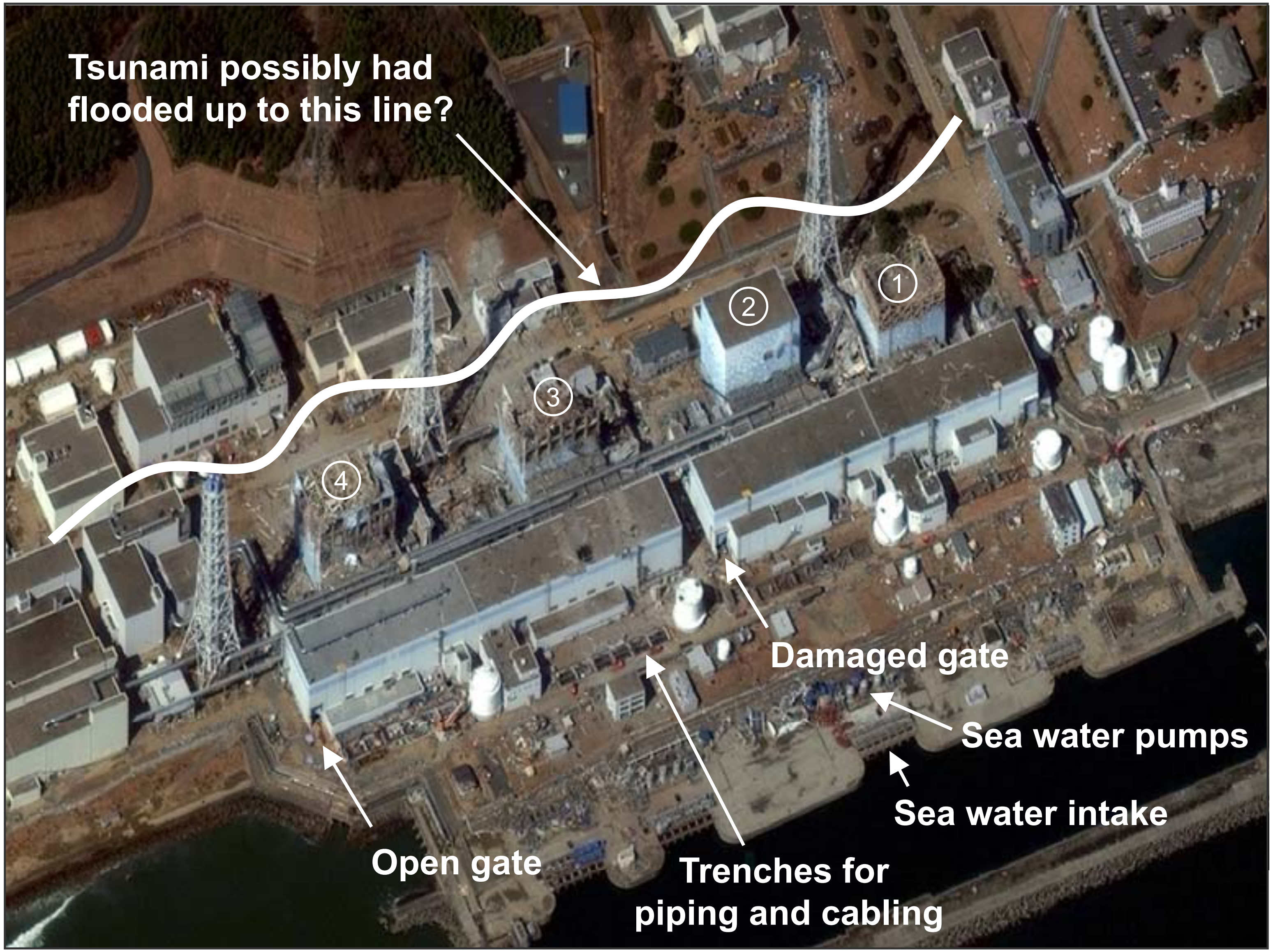


„Bird‘s Eye Views“

Unit	Year	Reactor	Containment
1	1971	BWR-3	Mark I
2	1974	BWR-4	Mark I
3	1976	BWR-4	Mark I
4	1978	BWR-4	Mark I
5	1978	BWR-4	Mark I
6	1979	BWR-5	Mark II

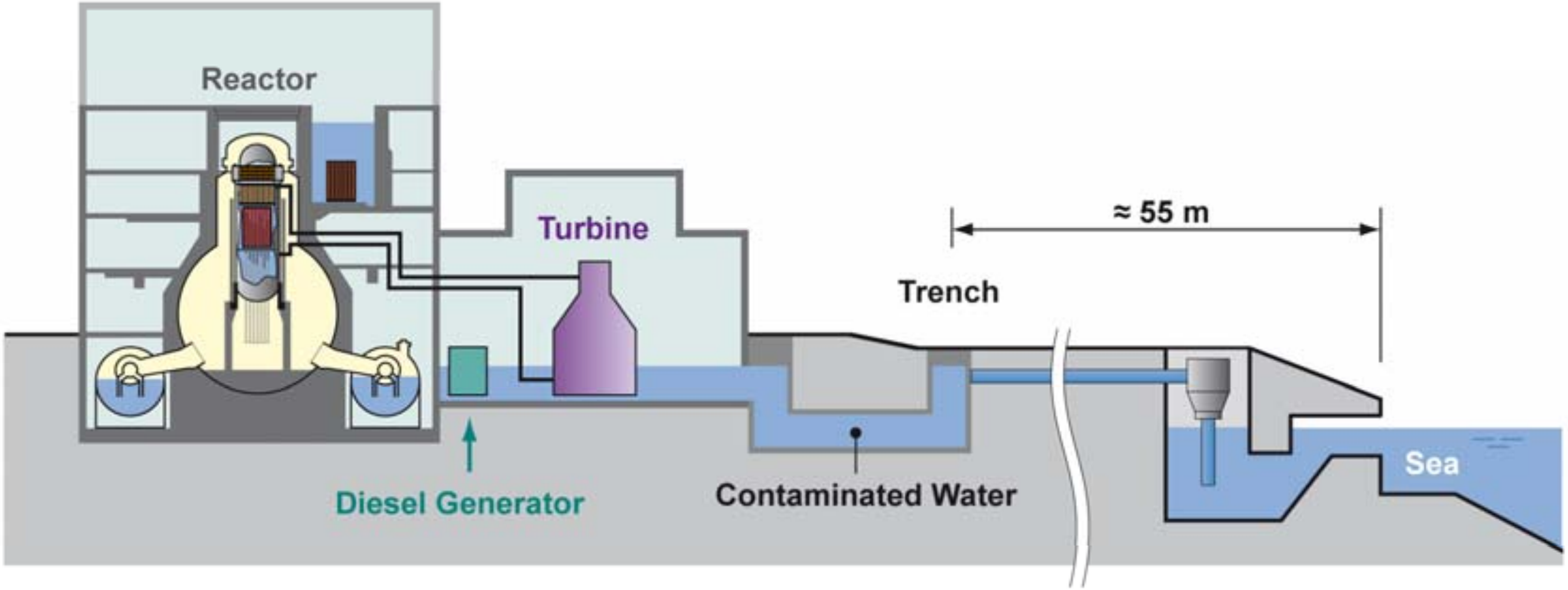
Sources: Florida Power & Light, AFP, Jiji Press, 2011

Fukushima-Daiichi After Tsunami



Sources: Janti, Digital Globe, 2011

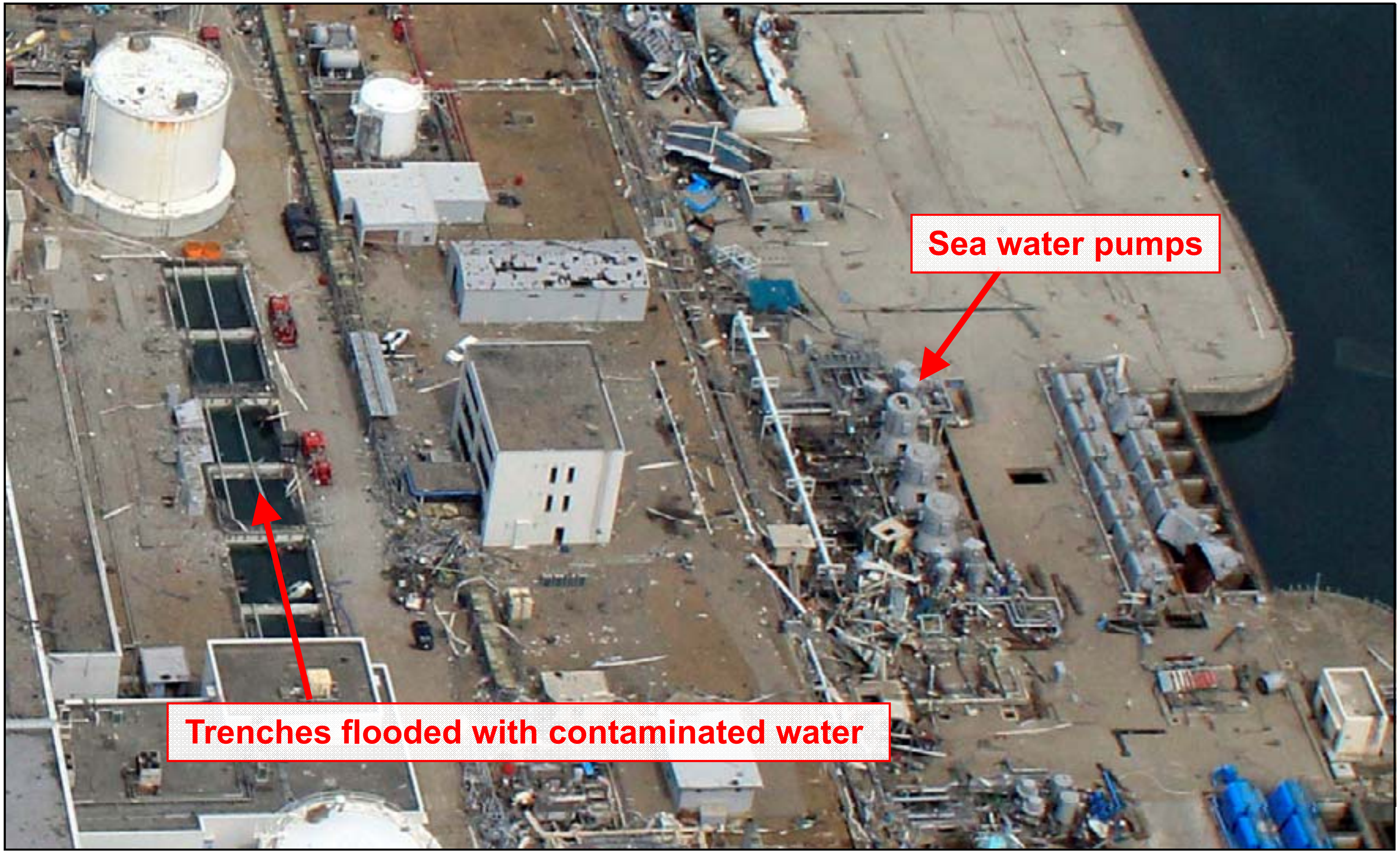
Flooded Trenches for Piping and Cabling



- Each unit has an underground trench for piping and cabling that runs from the basement of the turbine building.
- These trenches were separately found to be flooded.
- Direct results of the tsunami that overwhelmed the power plant.

Sources: IAEA,, WNN, 2011

Flooded Trenches for Piping and Cabling



Sources: Janti, www.cryptome.org, 2011

The Fukushima Daiichi Accident

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► **Question: Is this accident a matter of residual risk of nuclear energy?**

History data of earthquake-induced tsunamis with maximum amplitudes above 10 m hitting the coasts of Japan and the Kuril Islands (Russia) over the past 513 years					
Date and Country		Affected Region	Earthquake [1]	Tsunami [2]	Victims
11.03.2011	Japan	Japan	M = 9.0	23 m	> 10 000
04.10.1994	Russia	Kuril Islands	M = 8.3	11 m	Not specified
12.07.1993	Japan	Sea of Japan	M = 7.7	31.7 m	330
26.05.1983	Japan	Noshiro	M = 7.7	14.5 m	103
07.12.1944	Japan	Kii Peninsula	M = 8.1	10 m	40
02.03.1933	Japan	Sanriku	M = 8.4	30 m	3 000
01.09.1923	Japan	Tokaido	M = 7.9	12 m	2 144
07.09.1918	Russia	Kuril Islands	M = 8.2	12 m	50
15.06.1896	Japan	Sanriku	M = 7.6	38 m	26 360
24.12.1854	Japan	Nankaido	M = 8.4	28 m	3 000
29.06.1780	Russia	Kuril Islands	M = 7.5	12 m	12
24.04.1771	Japan	Ryukyu Islands	M = 7.4	85 m	13 500
28.10.1707	Japan	Japan	M = 8.4	11 m	30 000
31.12.1703	Japan	Tokaido-Kashima	M = 8.2	10,5 m	5 200
02.12.1611	Japan	Sanriku	M = 8.0	25 m	5 000
20.09.1498	Japan	Nankaido	M = 8.6	17 m	200

► **Simple Estimation:**

Within the past 513 years 16 tsunamis with maximum amplitudes above 10 m and induced by earthquakes of magnitudes between 7.4 and 9.2 have been recorded for Japan and the adjacent Kuril Islands (Russia).

► **Experienced Frequency:**

$f = 16/513\ a \approx 0.0312\ a^{-1}$

Thus, within a **thirty** years period one severe tsunami with a maximum amplitude of more than 10 m has to be expected in Japan!

► **No, it is rather a matter of obviously having ignored a high specific risk!**

Sources: Dr. Johannis Nöggerath, Swiss Nuclear Society, March 28, 2011, www.tsunami-alarm-system.com [1]) magnitude [2]) maximum amplitude

Severe Accident Management Measures

March 11, 2011, 14:46 JST ► Some hours later at Fukushima-Daiichi

► No restoration of offsite power possible, delays in obtaining and connecting portable diesel generators.

► After running out of batteries, loss of heat sink for residual heat.

► Reactor temperatures increase and reactor water levels decrease, eventually uncovering and overheating the reactor cores of units 1 to 3.

► Hydrogen production due to oxidation processes in the reactor cores, with main contributions from fuel cladding (Zircaloy) steam reactions at temperatures above ≈ 850 °C (exothermal reaction reinforces the reactor core heatup from radioactive decay power).

► Primary leaks or operator-initiated venting of the reactor cooling systems to relieve the steam pressure (design: 70 bar).

► Release of energy and hydrogen into the inertised primary containment (Drywell) causing primary containment temperatures and pressures to increase (Fukushima Daiichi units 1 to 3).

Source: FPL, 2011 JST: Japan Standard Time

Event Sequence – Accident Progression

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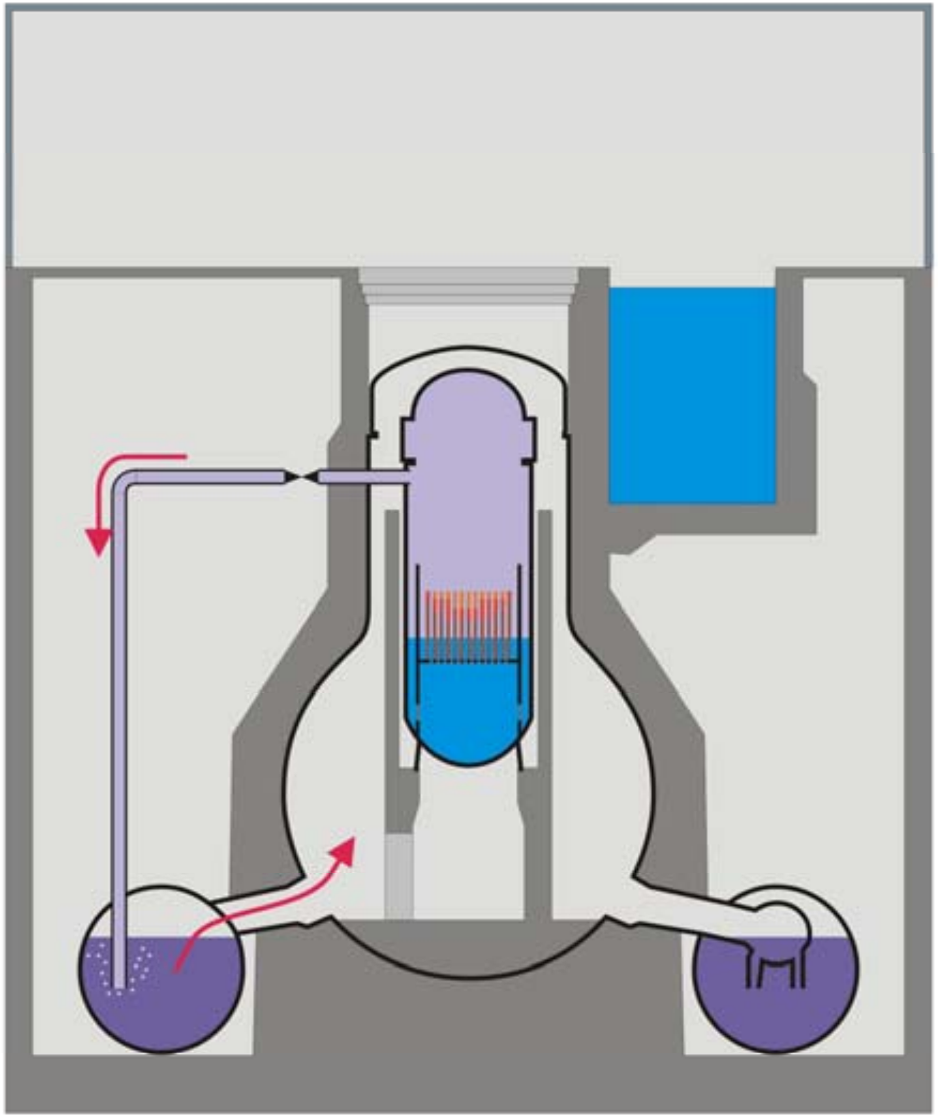
Temperature Escalation Phase

- ► About 75 % of the core cooled by steam only.
  - Cladding temperatures exceed ≈ 1200 °C.
  - Start of significant zirconium oxidation in steam atmosphere.

    $Zr + 2\ H_20$ ► $ZrO_2 + 2\ H_2$ + Heat
  - Exothermal reaction leads to an additional core heatup.
  - Oxidation of 1 kg of zirconium generates ≈ 44.2 g of hydrogen.
  - Hydrogen production:

    ► ≈ 300 to 600 kg in unit 1,

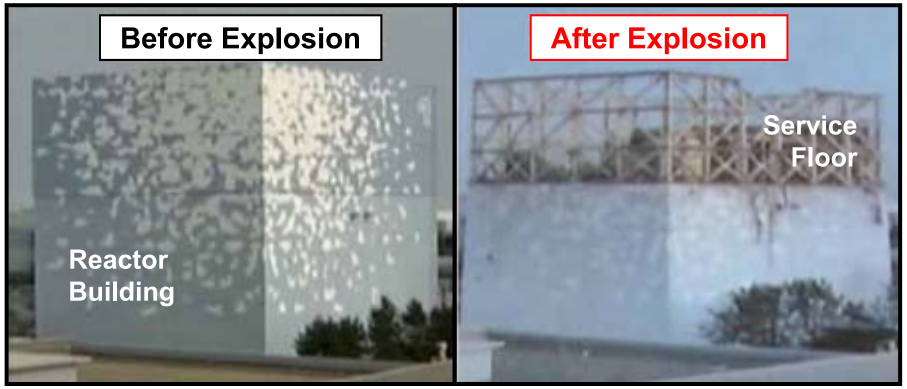
    ► ≈ 300 to 1000 kg in units 2 & 3.
- ► Produced Hydrogen is pushed via the wetwell into the drywell.



Source: AREVA NP, March 24, 2011

Severe Accident Management Measures

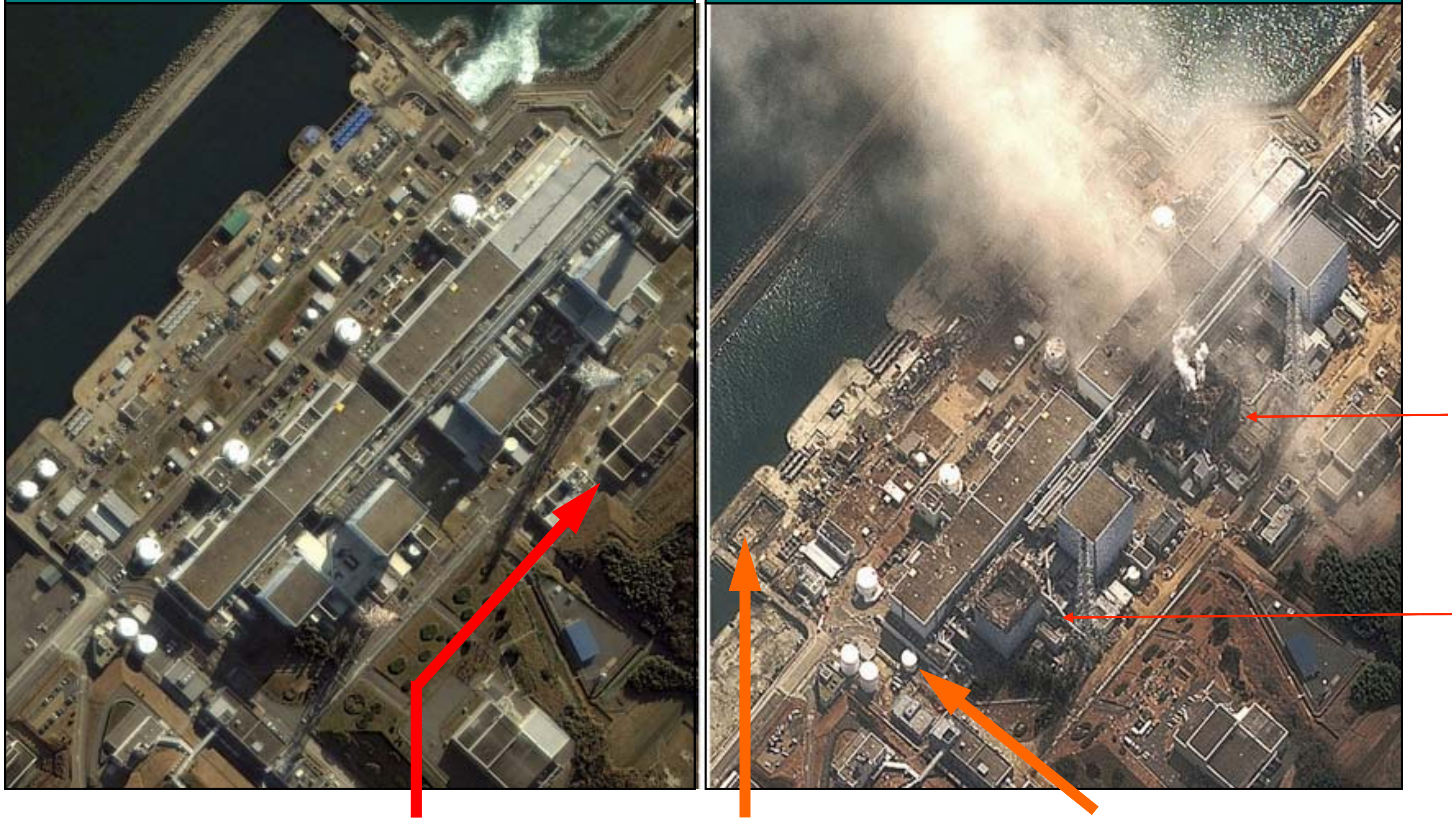
- **Fukushima Daiichi Units 1 to 3:** Operator actions to vent the primary containments and to control primary containment pressures and hydrogen levels (required to protect the primary containments from failure).
- Primary containment venting through a filtered (?) path that travels through a duct work in the secondary containment to an elevated release point on the service (refuel) floor on top of the reactor building.
- Hydrogen explosions on service floor of units 1 and 3. Basic requirement: hydrogen concentrations above the lower flammable limit of hydrogen in air (i.e. above 4 volume percent) and activating spark (unit 2 reactor building had eventually been damaged by hydrogen detonation at unit 3).



Source: FPL, 2011

Aerial Views at Fukushima Daiichi

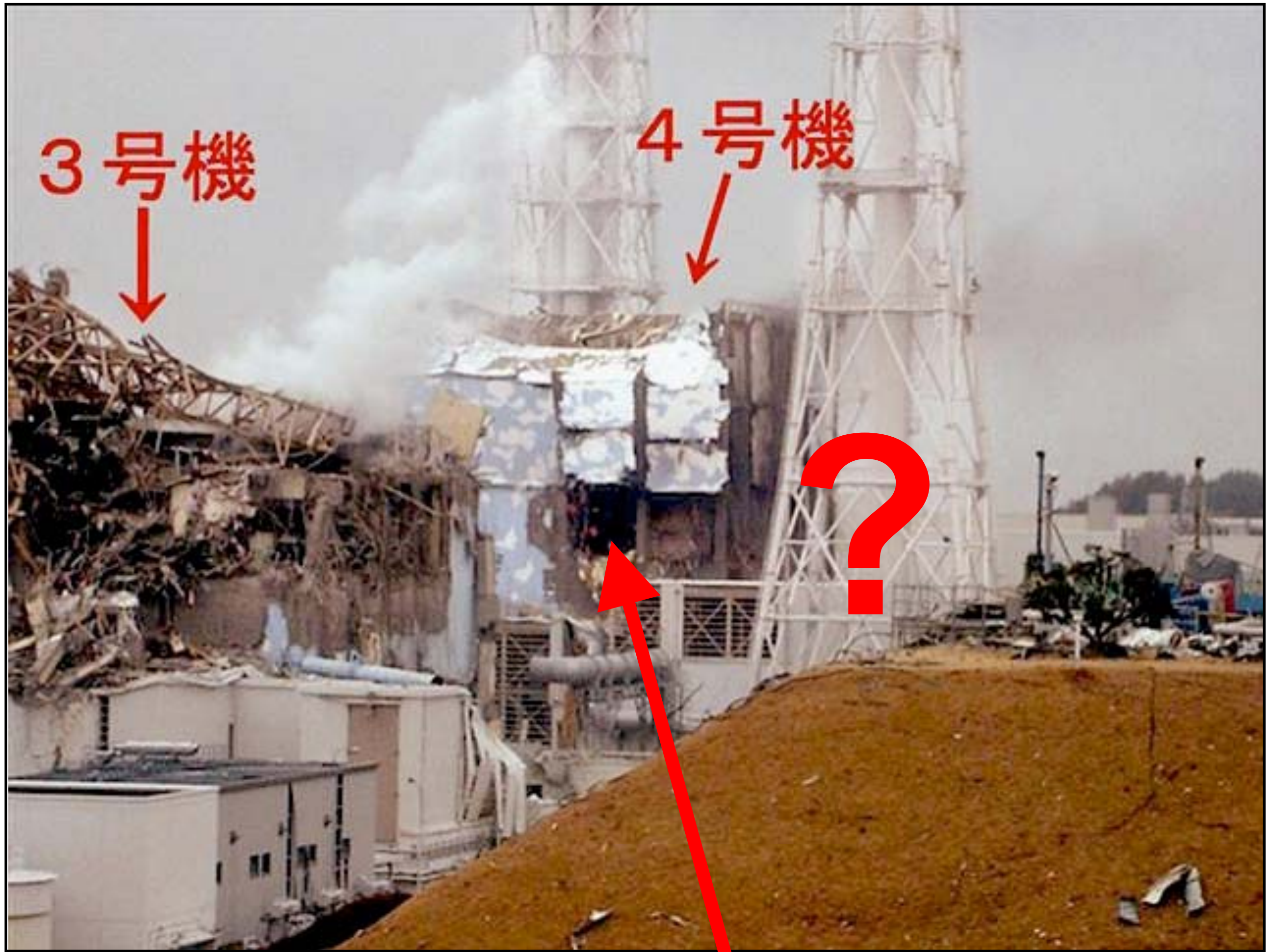
Before Tsunami	After Tsunami and Detonation in Unit 3



Shared spent fuel pool building | Missing heavy oil tanks | Displaced oil tank?

Source: Wano PC, Barrwood, 2011

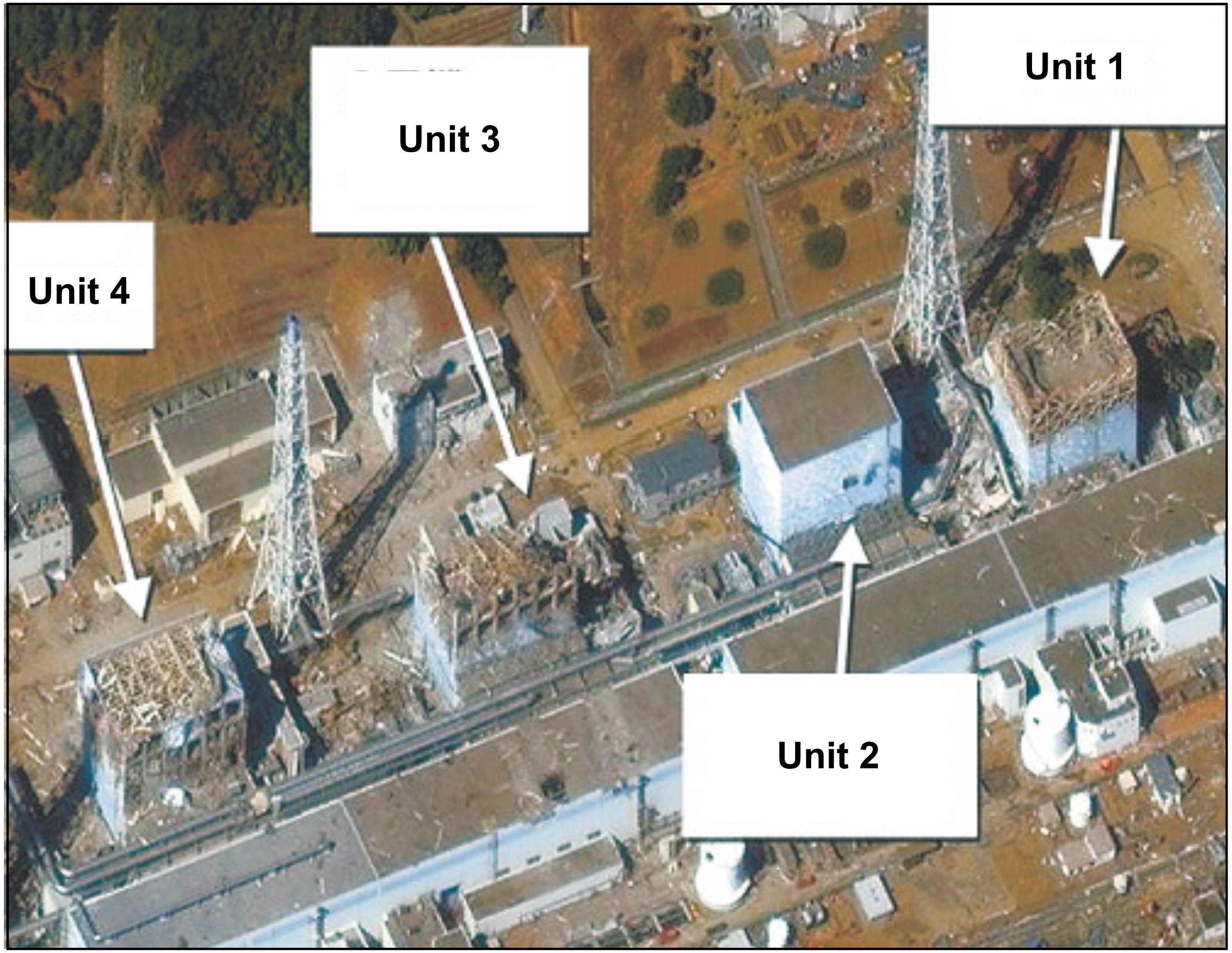
Unit 3 and Unit 4 after Hydrogen Explosions



Explosion in concrete part of the reactor building of unit 4, although no fuel inside of reactor!

Source: WANO PC, Barnwood, 2011

Units 1 to 4 after Hydrogen Explosions



Sources: Areva NP, www.niirs.org

Aerial View after Hydrogen Explosions

Source: www.cryptome.org, 2011

Aerial View after Hydrogen Explosions

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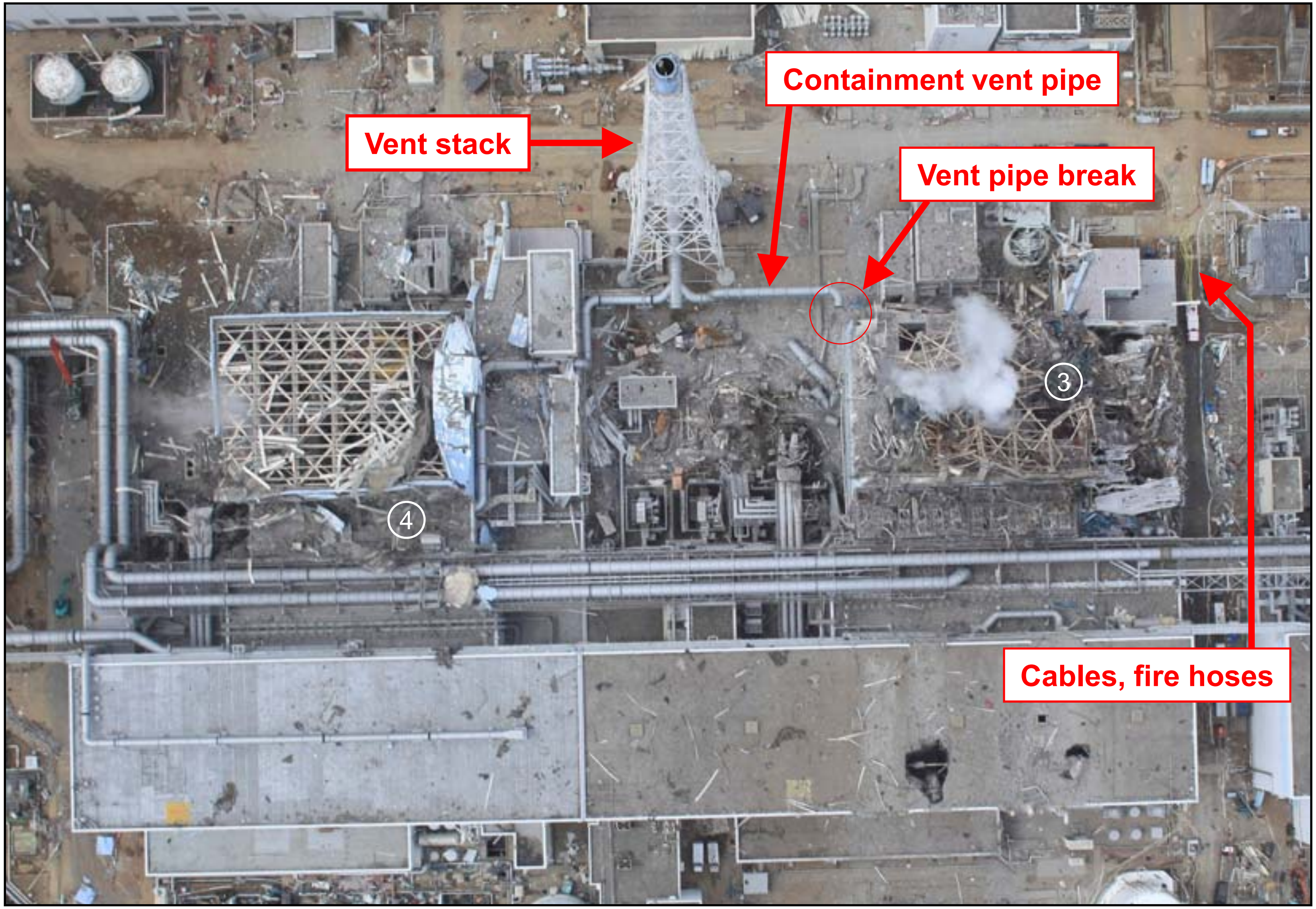

Source: www.cryptome.org, 2011

Nuclear Power in Japan

(Updated December 2015)

- **Japan needs to import about 84% of its energy requirements.**
- **Its first commercial nuclear power reactor began operating in mid-1966, and nuclear energy has been a national strategic priority since 1973. This came under review following the 2011 Fukushima accident but has been confirmed.**
- **The country's 50+ main reactors have provided some 30% of the country's electricity and this was expected to increase to at least 40% by 2017. The prospect now is for two thirds of this, from a depleted fleet.**
- **Currently 43 reactors are operable and potentially able to restart, and 24 of these are in the process of restart approvals. The first two restarted in August and October 2015.**

Despite being the only country to have suffered the devastating effects of nuclear weapons in wartime, with over 100,000 deaths, Japan embraced the peaceful use of nuclear technology to provide a substantial portion of its electricity. However, following the tsunami which killed 19,000 people and which triggered the Fukushima nuclear accident (which killed no-one), public sentiment shifted markedly so that there were wide public protests calling for nuclear power to be abandoned. The balance between this populist sentiment and the continuation of reliable and affordable electricity supplies is being worked out politically.

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Japan's energy situation and international dependence

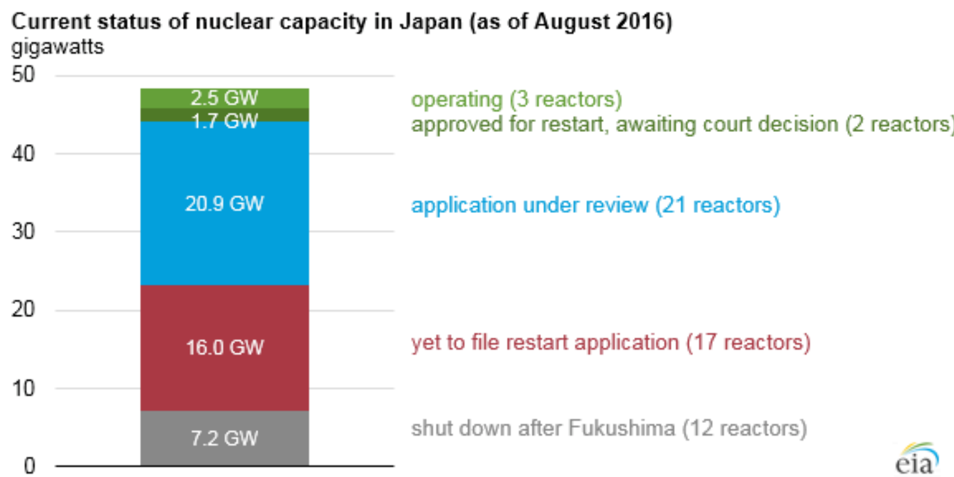
Japan's shortage of minerals and energy was a powerful influence on its politics and history in the 20th century. Today it depends on imports for over 90% of its primary energy needs. As it recovered from World War II and rapidly expanded its industrial base it was dependent on fossil fuel imports, particularly oil from the Middle East (oil fuelled 66% of the electricity in 1974). This geographical and commodity vulnerability became critical due to the oil shock in 1973. At this time, Japan already had a growing nuclear industry, with five operating reactors. Re-evaluation of domestic energy policy resulted in diversification and in particular, a major nuclear construction program. A high priority was given to reducing the country's dependence on oil imports. A closed fuel cycle was adopted to gain maximum benefit from imported uranium.

Nuclear power has been expected to play an even bigger role in Japan's future. In the context of the Ministry of Economy, Trade and Industry (METI) Cool Earth 50 energy innovative technology plan in 2008, the Japan Atomic Energy Agency (JAEA) modelled a 54% reduction in CO_2 emissions (from 2000 levels) by 2050 leading on to a 90% reduction by 2100. This would lead to nuclear energy contributing about 60% of primary energy in 2100 (compared with 10% in 2008), 10% from renewables (from 5%) and 30% fossil fuels (from 85%). This would mean that nuclear contributed 51% of the emission reduction: 38% from power generation and 13% from hydrogen production and process heat.

TODAY IN ENERGY

SEPTEMBER 13, 2016

Five and a half years after Fukushima, 3 of Japan's 54 nuclear reactors are operating



Source: U.S. Energy Information Administration, based on Institute of Energy Economics, Japan, and IAEA Power Reactor Information System

Since the accident at Fukushima Daiichi in March 2011 and the subsequent shutdown of nuclear reactors in Japan, five reactors have received approval to restart operations under the new safety standards imposed by Japan's Nuclear Regulation Authority (NRA). Only three of those reactors are currently operating. Applications for the restart of 21 other reactors, including 1 under construction, are under review by the NRA. Some reactors that meet the new NRA safety standards and have been approved to restart continue to face legal or political opposition that may delay or forestall their restart.

After the Fukushima accident, all 54 of Japan's reactors were shut down. Twelve reactors totaling 7.2 gigawatts (GW) were permanently closed. Restart applications for 20 previously operating reactors (totaling 19.5 GW) and 1 new reactor under construction (the 1.4 GW Oma Nuclear Power Station) have been filed with the NRA. The remaining 17 reactors (16 GW) have yet to submit restart applications. There is still uncertainty about whether some of these reactors can meet the new NRA safety regulations, particularly regulations regarding the ability to

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- **Currently 42 reactors are operable and potentially able to restart, and 24 of these are in the process of restart approvals. The first two restarted in August and October 2015, with three more since.**

Despite being the only country to have suffered the devastating effects of nuclear weapons in wartime, with over 100,000 deaths, Japan embraced the peaceful use of nuclear technology to provide a substantial portion of its electricity. However, following the tsunami which killed 19,000 people and which triggered the Fukushima nuclear accident (which killed no-one), public sentiment shifted markedly so that there were wide public protests calling for nuclear power to be abandoned. The balance between this populist sentiment and the continuation of reliable and affordable electricity supplies is being worked out politically.

WORLD NUCLEAR ASSOCIATION

Nuclear Power in Japan

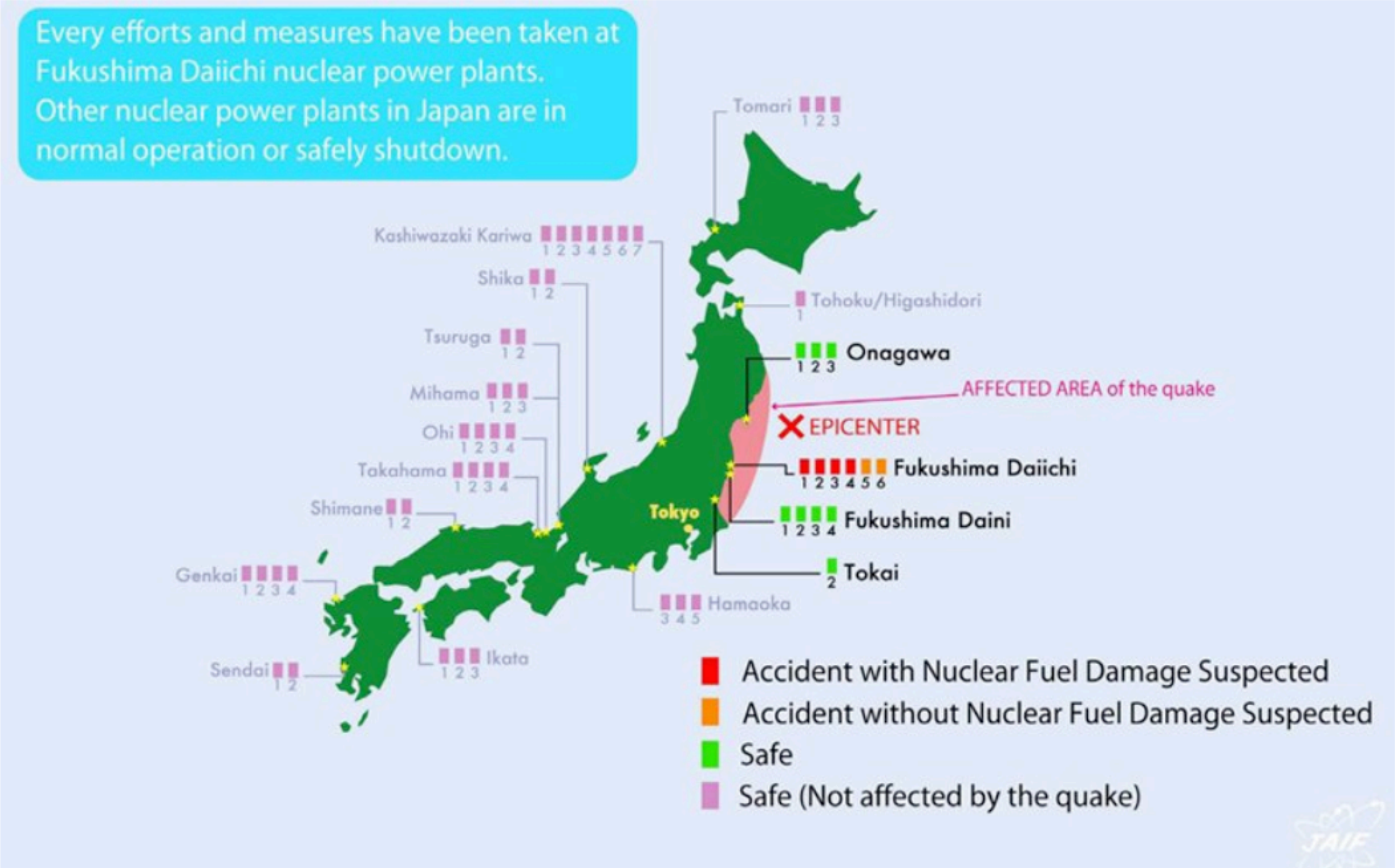
(Updated January 2019)

- **Japan needs to import about 90% of its energy requirements.**
- **Its first commercial nuclear power reactor began operating in mid-1966, and nuclear energy has been a national strategic priority since 1973. This came under review following the 2011 Fukushima accident but has been confirmed.**
- **Up until 2011, Japan was generating some 30% of electricity from its reactors and this was expected to increase to at least 40% by 2017. The prospect now is for two-thirds of this, from a depleted fleet.**
- **Currently 42 reactors are operable. The first two restarted in August and October 2015, with a further seven having restarted since. 17 reactors are currently in the process of restart approval.**

Japan in 2016 produced 1058 TWh of electricity, 407 TWh (38%) from natural gas, 349 TWh (33%) from coal, 85 TWh (8%) from oil, 85 TWh (8%) from hydro, 57 TWh (5%) from solar and wind, 34 TWh (3%) from biofuels and waste, and 18 TWh (1.7%) from nuclear. There were no imports or exports, and final consumption in 2016 was 967 TWh or about 7600 kWh per capita on average. Total installed capacity was about 336 GWe at the end of December 2016[1].

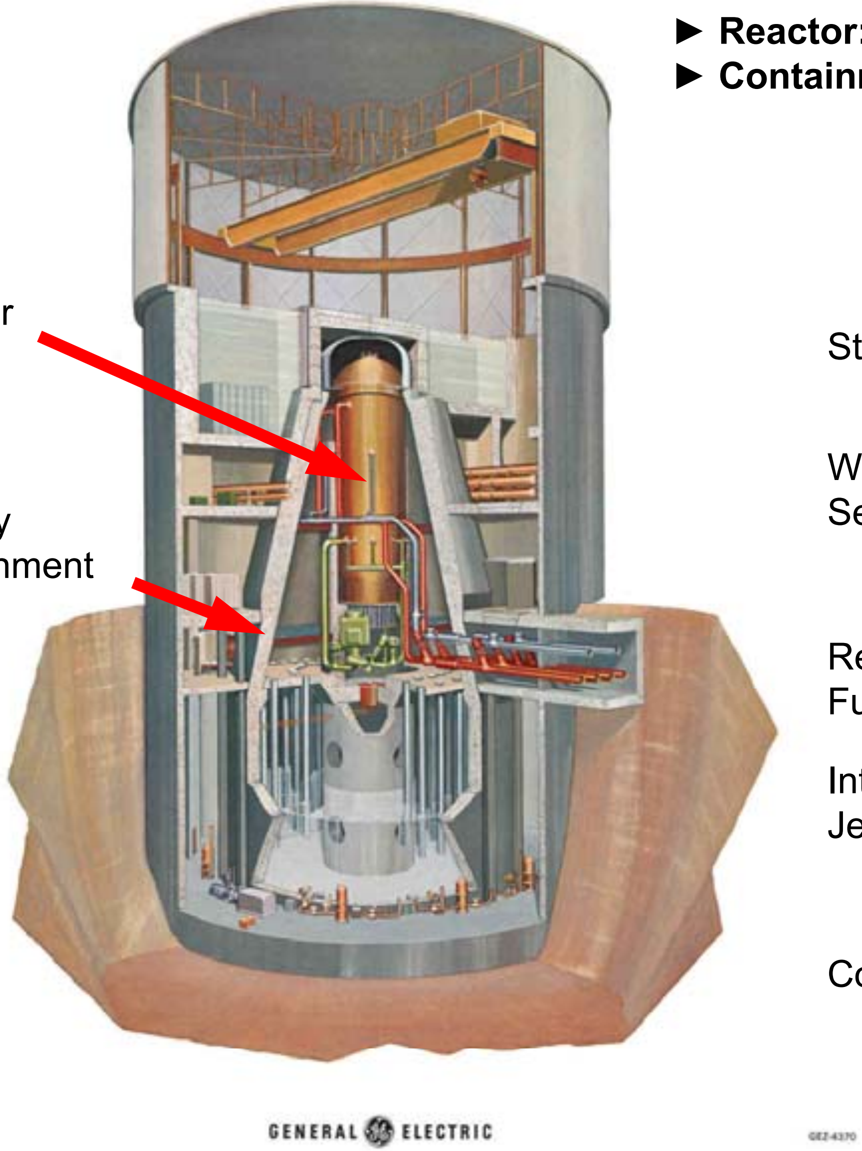
Despite being the only country to have suffered the devastating effects of nuclear weapons in wartime, with over 100,000 deaths, Japan embraced the peaceful use of nuclear technology to provide a substantial portion of its electricity. However, following the tsunami which killed 19,000 people and which triggered the Fukushima nuclear accident (which killed no-one) in March 2011, public sentiment shifted markedly so that there were widespread public protests calling for nuclear power to be abandoned. The balance between this populist sentiment and the continuation of reliable and affordable electricity supplies is being worked out politically.

Map reveals status of Japan's 54 nuclear reactors



Design of Fukushima Daiichi Unit 6

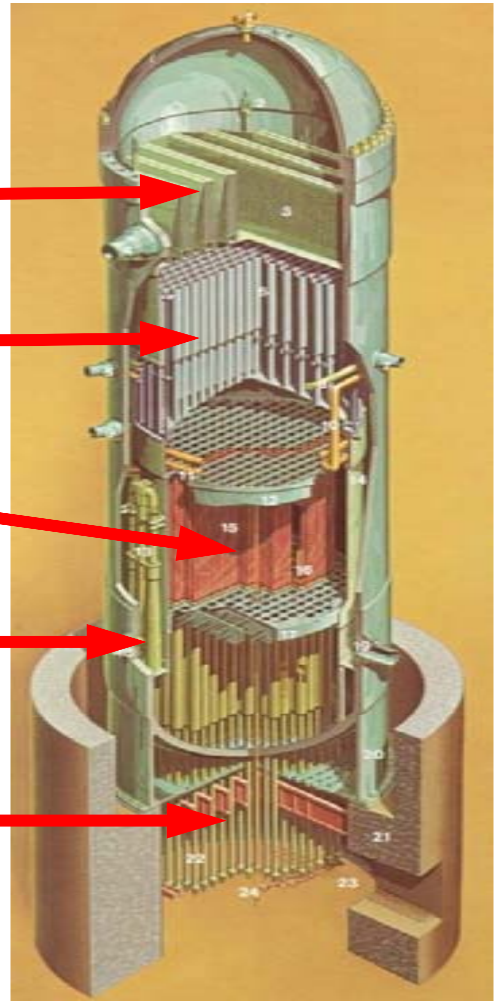
- ► **Reactor:** BWR-5
- ► **Containment:** Mark-II



Reactor

Primary Containment

Reactor Pressure Vessel



Steam Dryer

Water/Steam-Separator

Reactor Core Fuel Assemblies

Internal Jet Pumps

Control Rods

Sources: NRC, General Electric

Service Floor of Fukushima Daiichi Unit 1

Source: www.nucleartourist.com

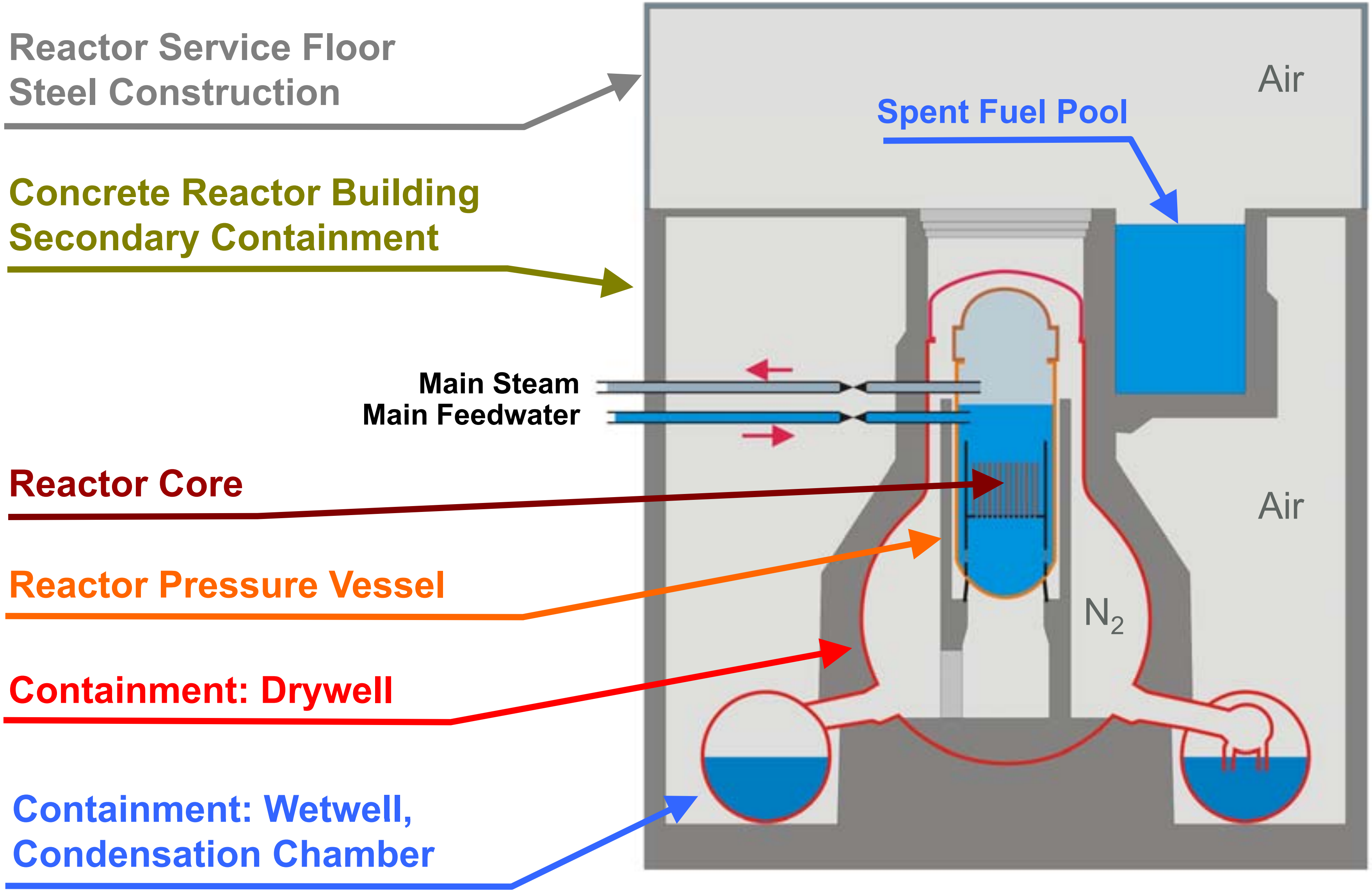
Service Floor with Primary Containment Head

Source: www.nucleartourist.com

Reactor Pressure Vessel Head

Source: www.zwentendorf.com

Plant Design



Source: AREVA NP, March 24, 2011

Primary Containment Construction Phase

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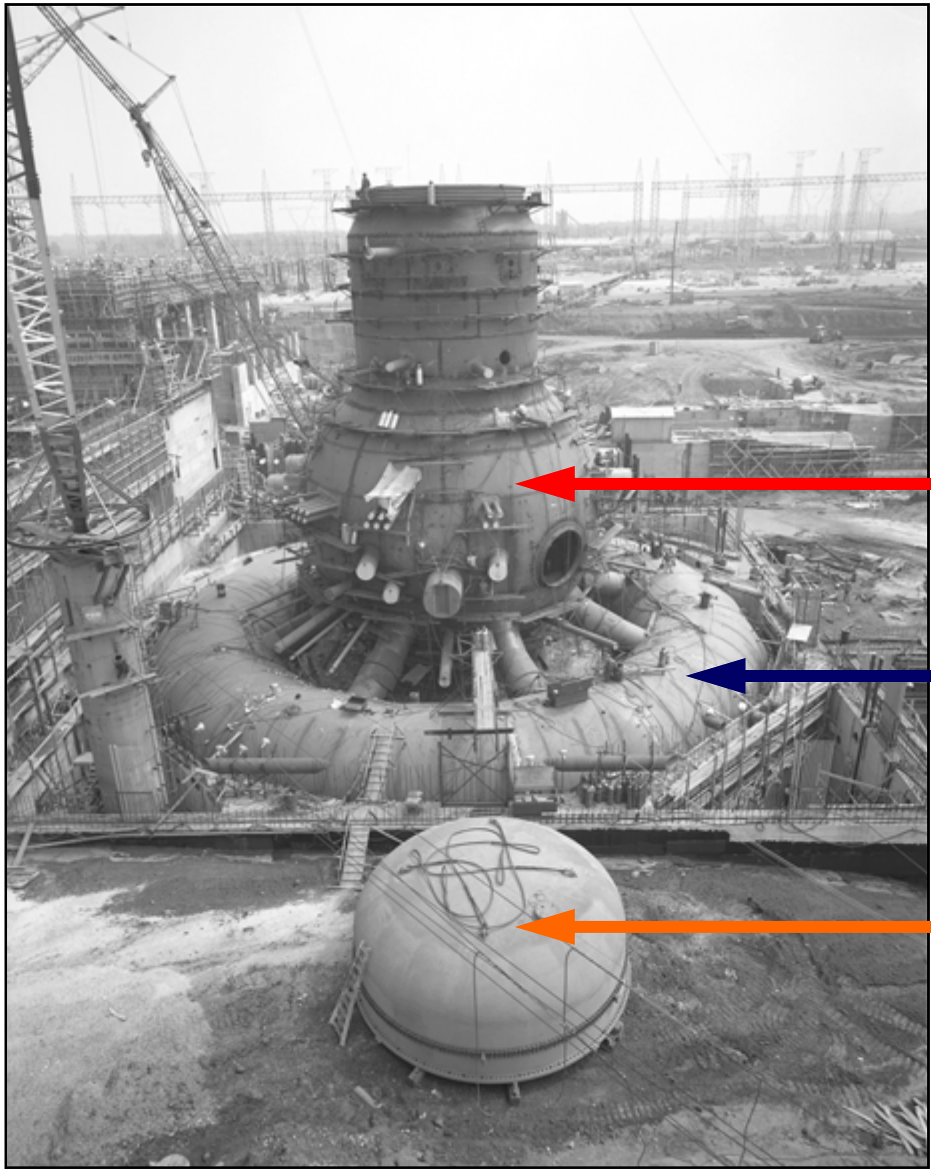


Design: Mark-I

Primary containment

Pressure suppression pool

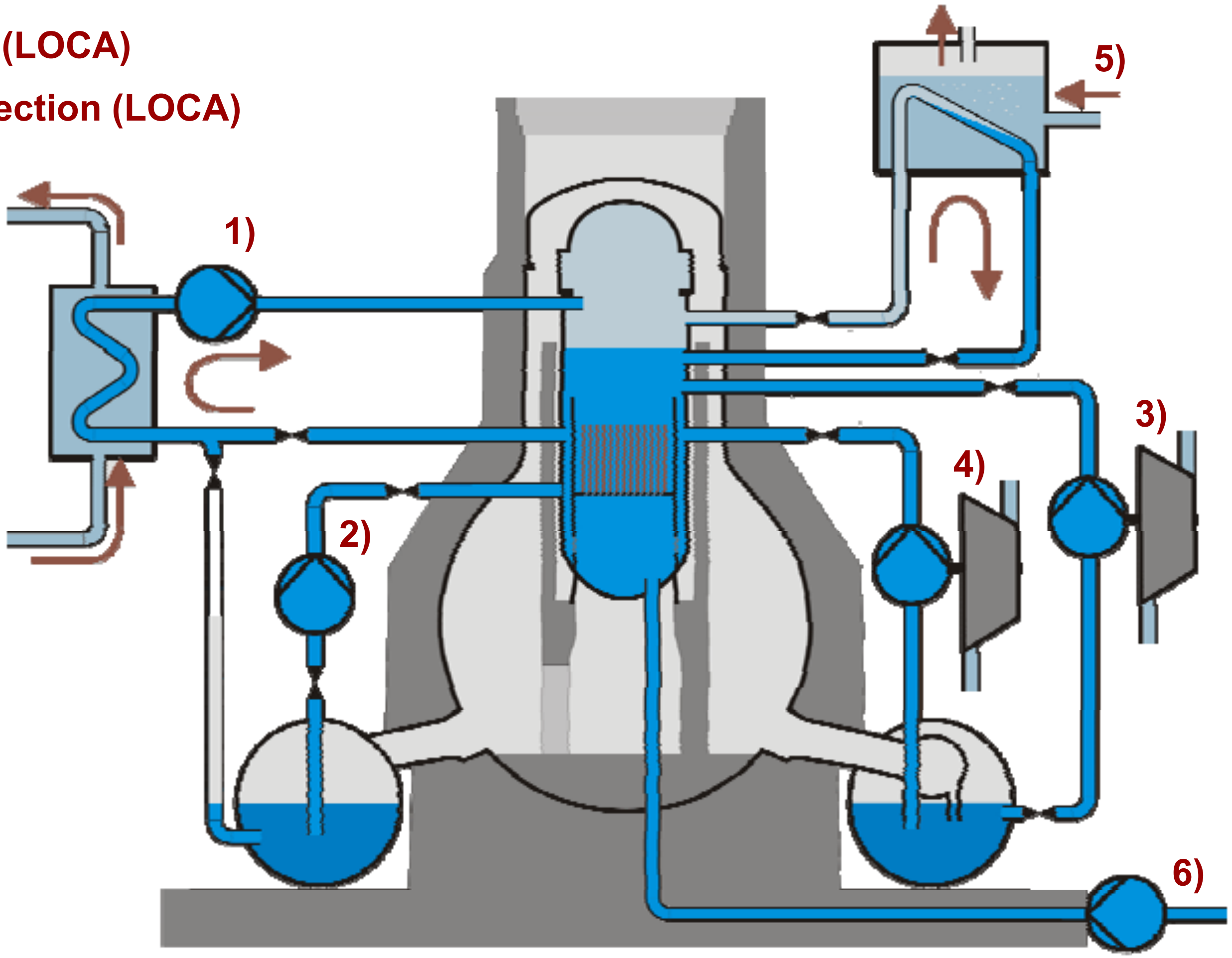
Containment closure head

Source: Browns Ferry, USA, http://en.wikipedia.org/wiki

Plant Design

Emergency Core Cooling Systems of Different Units at Fukushima Daiichi

1) Residual Heat Removal System
2) Low-Pressure Core Spray (LOCA)
3) High-Pressure Coolant Injection (LOCA)
4) Reactor Core Isolation Cooling (Unit 2/3: BWR-4)
5) Isolation Condenser (Unit 1: BWR-3)
6) Borating System



Source: AREVA NP, March 24, 2011 LOCA: Loss of Coolant Accident

Event Sequence – Accident Progression

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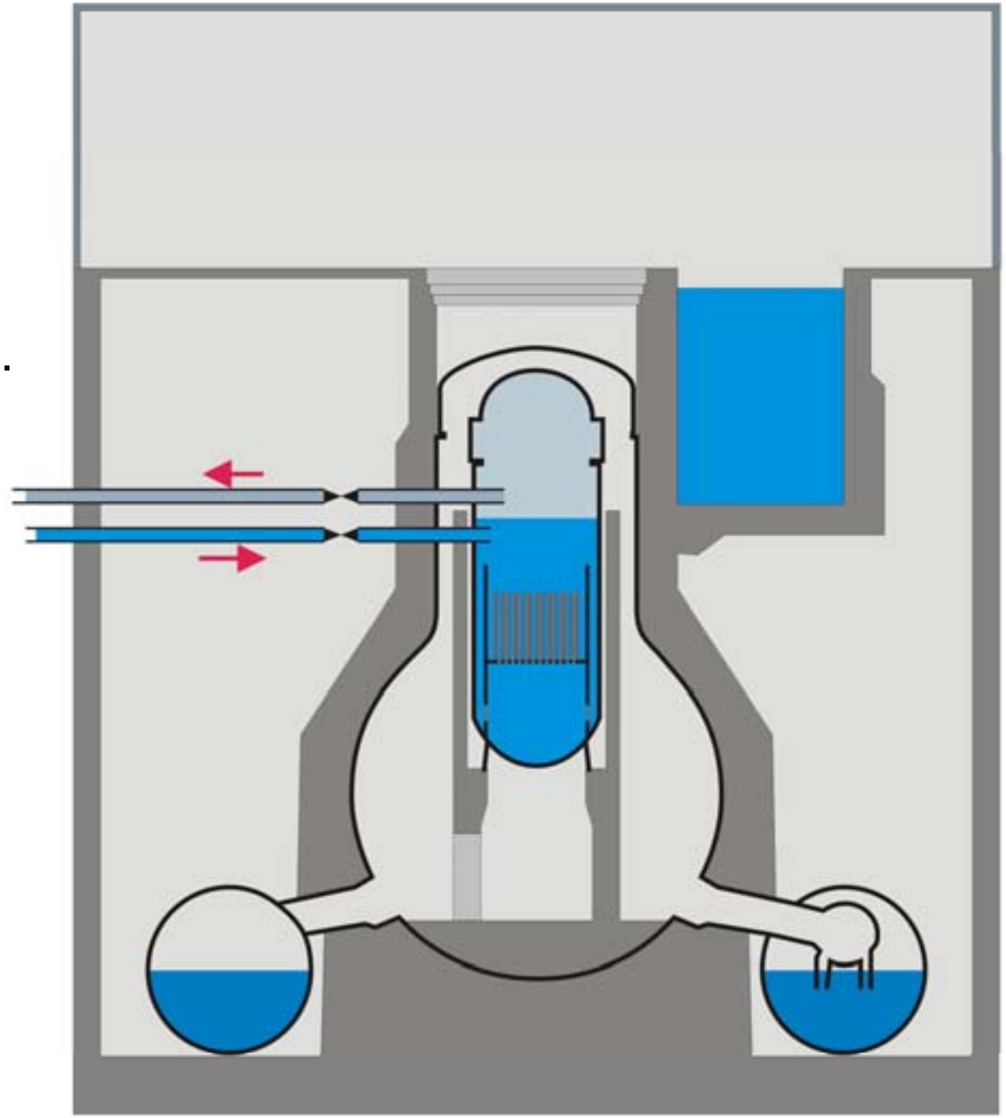
► **March 11, 2011, 14:46 JST**

- **Earthquake of magnitude 9.**
- The power grid in the northern part of Honshu (Japan) fails.
- Reactors are mainly undamaged.

► **Automatic Scram**

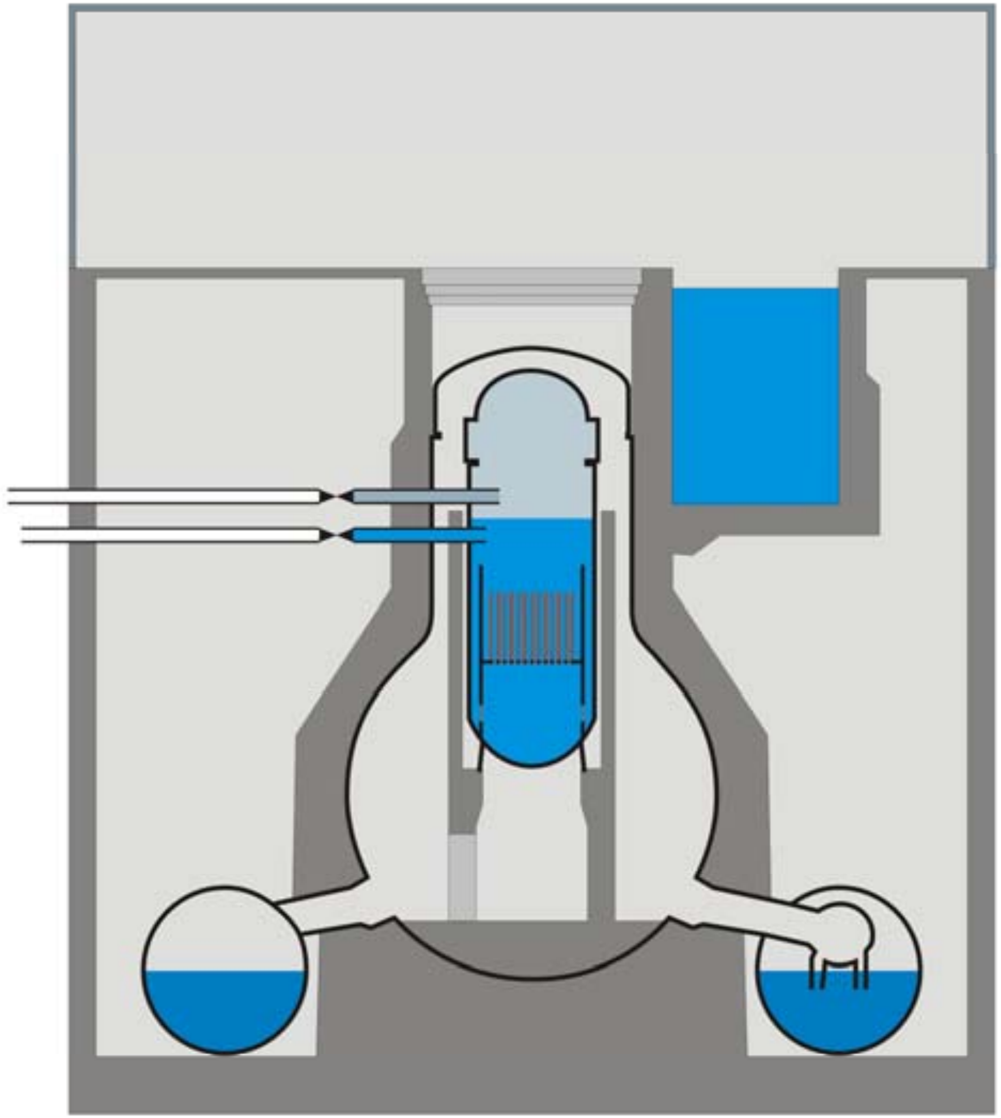
- Stop of power generation due to fission reaction.
- Further heat generation due to radioactive decay of fission products:
  - ► after scram ≈ 6 %
  - ► after 1 day ≈ 1 %
  - ► after 5 days ≈ 0.5 %



Source: AREVA NP, March 24, 2011 JST: Japan Standard Time

Event Sequence – Accident Progression

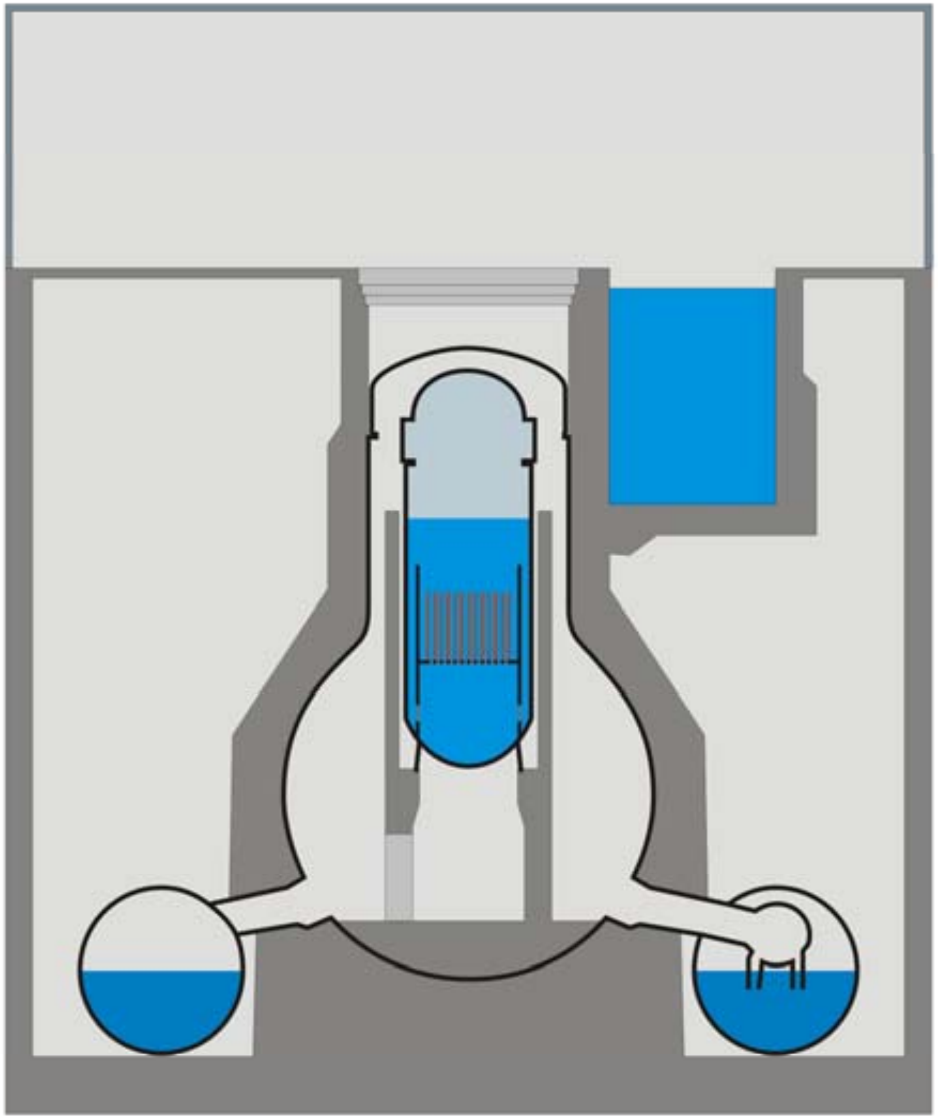
- **Containment Isolation**
  - Closing of all non-safety related penetrations of the containment.
  - Turbine hall cut off.
  - If containment isolation succeeds, an early large release of fission products is highly unlikely.
- **Start of Diesel Generators**
  - Emergency core cooling systems are supplied with electricity.
- **Stable Plant State**



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

- **March 11, 2011, 15:41**
  - **Tsunami hits the plant site.**
  - Plant levee design for tsunami wave heights: 5.7 m
  - Actual tsunami height: ≈ 14 m
  - Flooding of diesel generators and/or essential service water buildings.
- **Station Blackout**
  - Common cause failure of power supply.
  - Only batteries are still available.
  - Loss of all emergency core cooling systems, only the pump directly mechanically driven by a steam-turbine is available.



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

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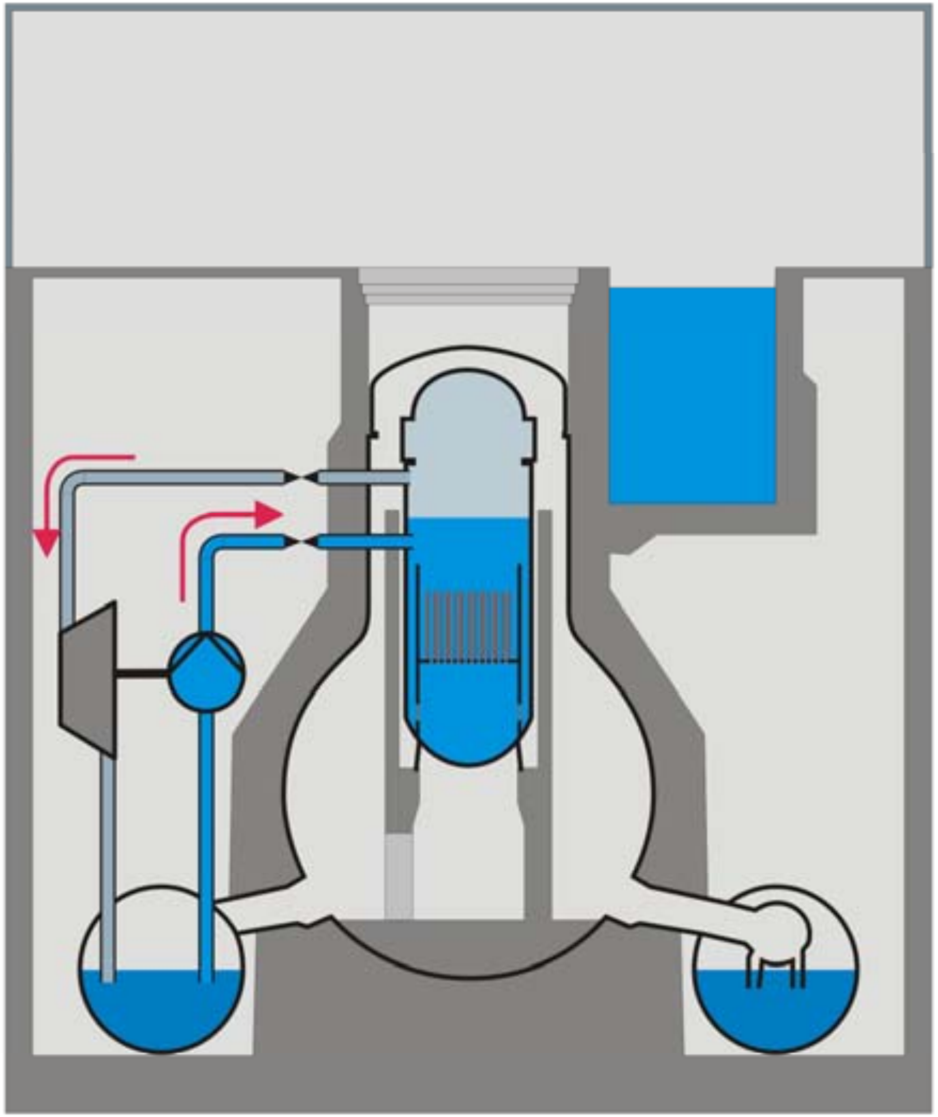
- **Reactor Core Isolation Pump**
  - Steam from the reactor core drives a turbine,
  - the turbine drives a pump,
  - steam condensation in the wetwell,
  - water from the wetwell is pumped into the reactor core.
  - Requirements:
    - Battery power for steam turbine auxiliaries,
    - the temperature in the wetwell must be lower than 100 °C.
- As there is no heat removal from the reactor building, the work of the reactor core isolation pump is limited.



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

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► **Reactor Core Isolation Pump Stop**

Unit 1: March 11, 16:36, batteries empty,

Unit 2: March 14, 13:25, pump failure,

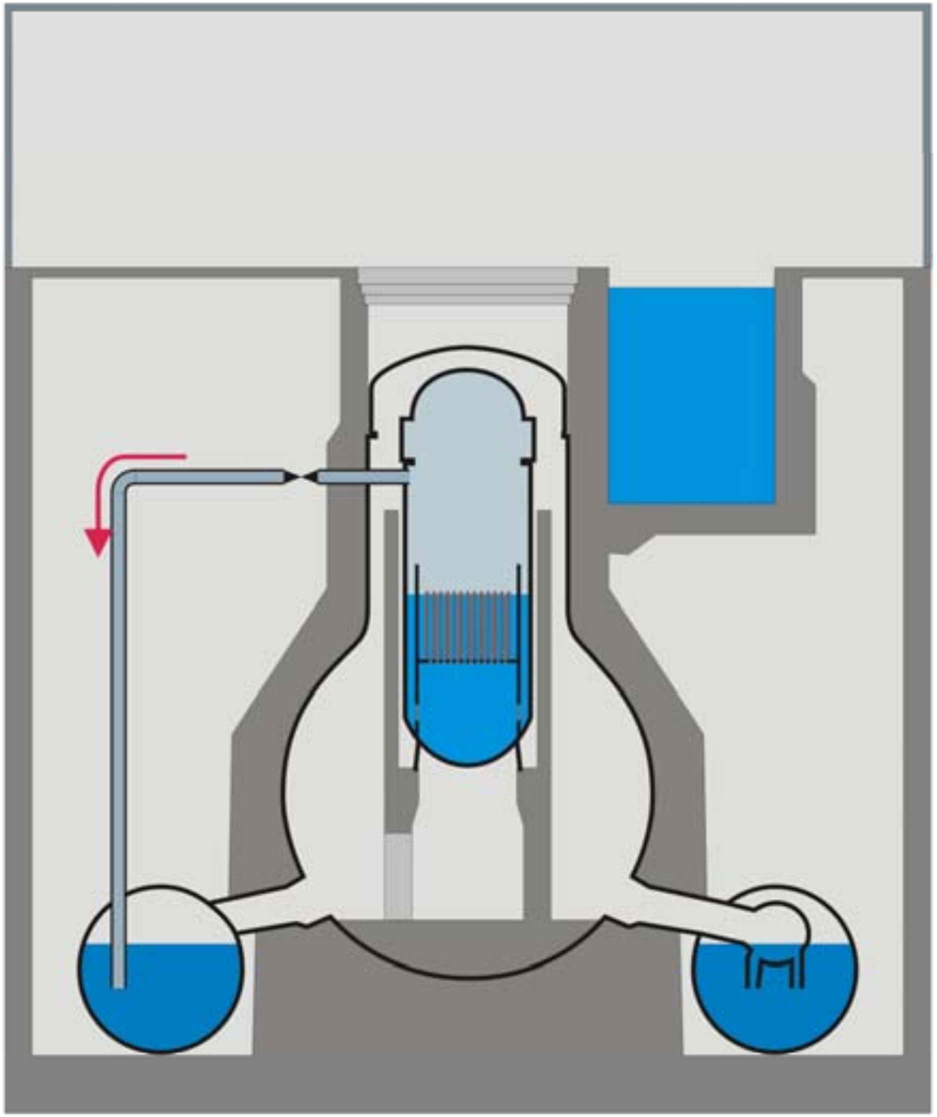
Unit 3: March 13, 02:44, batteries empty.

► **Decay heat** still produces steam in the reactor pressure vessel, leading to a pressure rise.

► **Steam discharge** into the wetwell due to steam relieve valve opening.

► **Decreasing liquid level** within the reactor pressure vessel.

► The measured liquid level is the „static" level. The actual swell level is higher due to steam bubbles in the liquid phase.

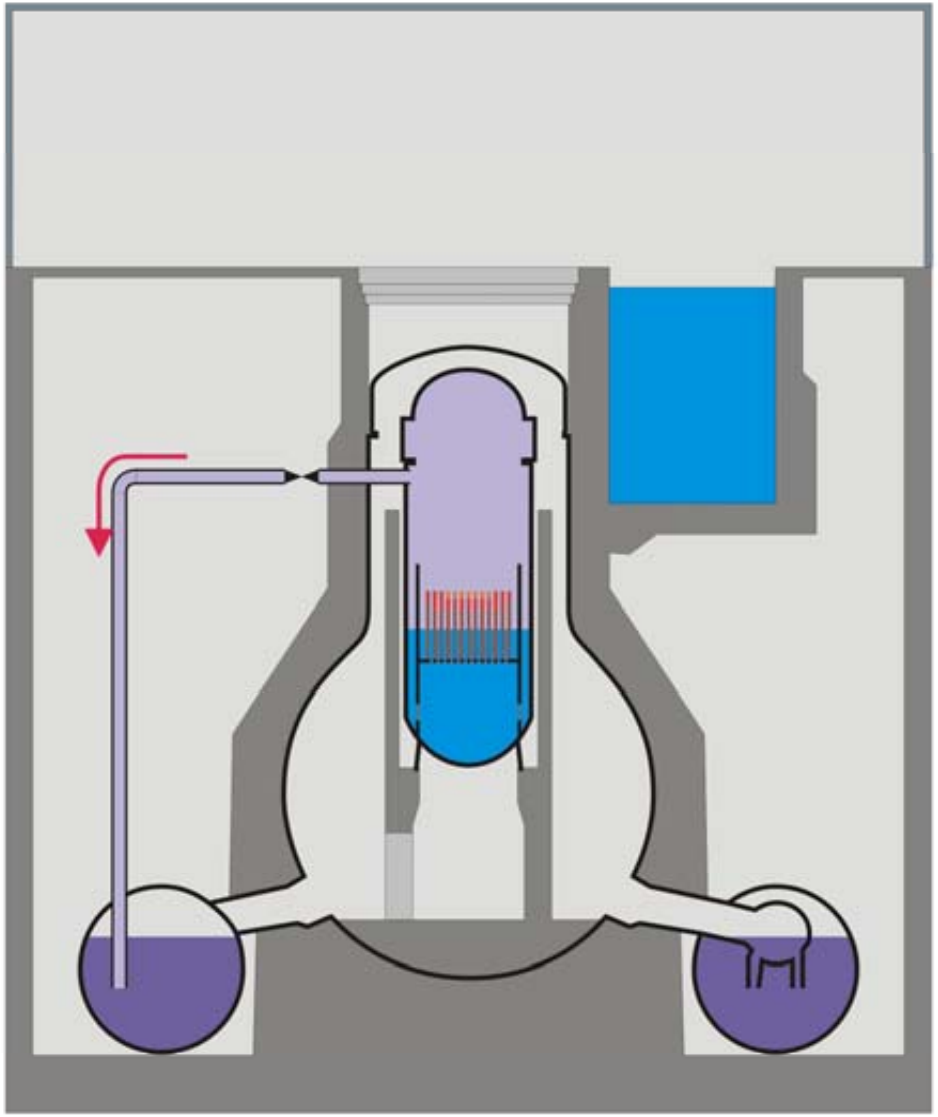


Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

Core Heatup Phase

- About 50 % of the core cooled by steam only.
- Cladding temperatures rise, but still no significant core damage.
- About 67 % of the core cooled by steam only.
  - Cladding temperatures exceed ≈ 900 °C.
  - Ballooning and/or bursting of claddings (local damages).
  - Release of volatile fission products (noble gases) from internal gaps between fuel pellets and claddings.



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

Temperature Escalation Phase

► About 75 % of the core cooled by steam only.

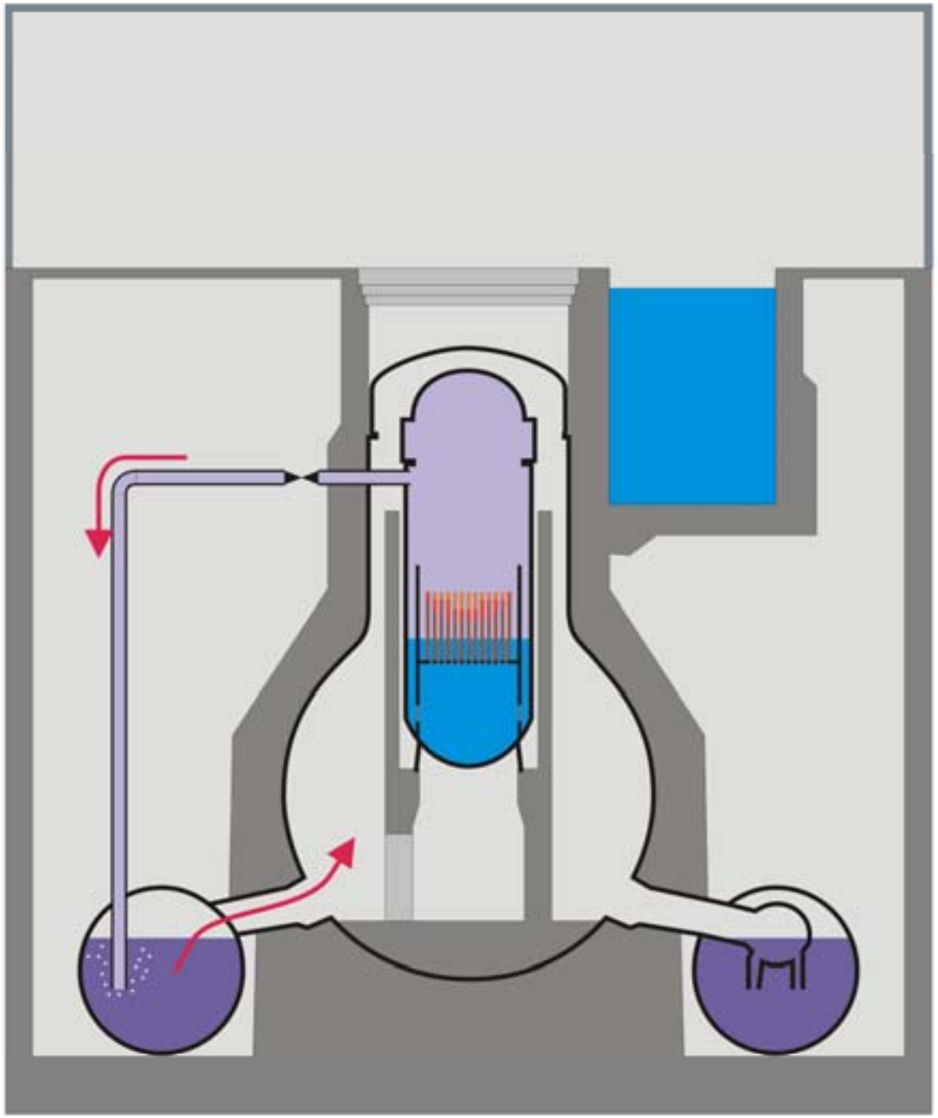
- Cladding temperatures exceed ≈ 1200 °C.
- Start of significant zirconium oxidation in steam atmosphere.

  $Zr + 2\ H_20$ ► $ZrO_2 + 2\ H_2$ + Heat
- Exothermal reaction leads to an additional core heatup.
- Oxidation of 1 kg of zirconium generates ≈ 44.2 g of hydrogen.
- Hydrogen production:

  ► ≈ 300 to 600 kg in unit 1,

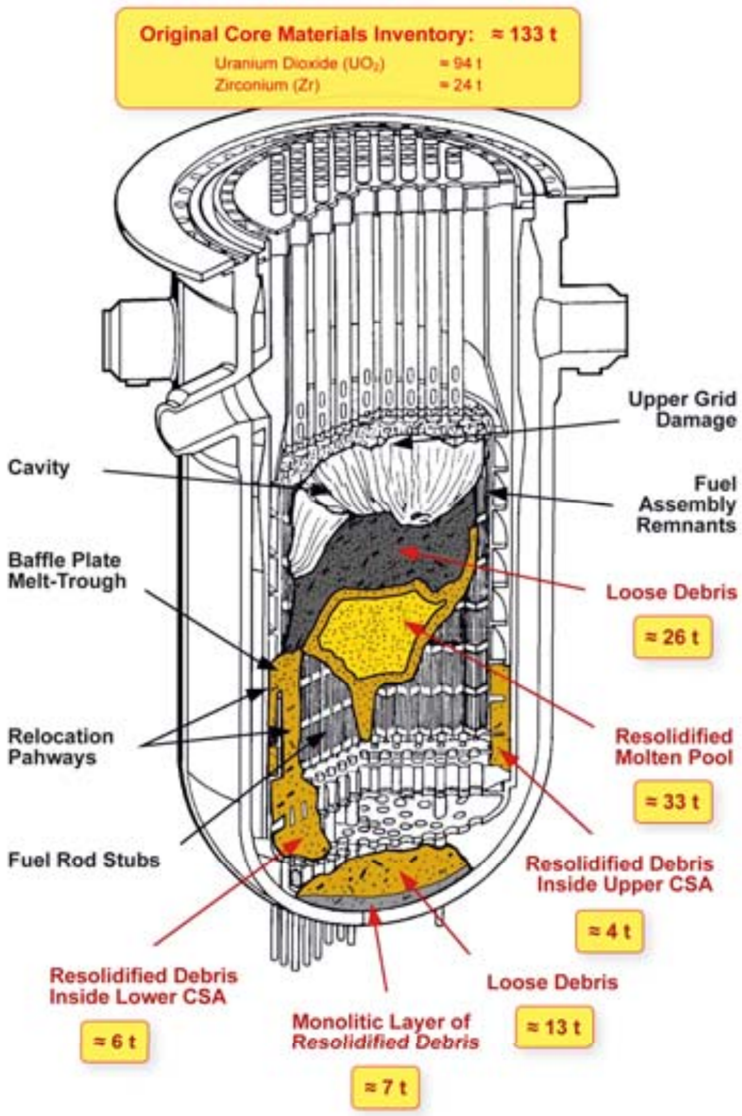
  ► ≈ 300 to 1000 kg in units 2 & 3.

► Produced Hydrogen is pushed via the wetwell into the drywell.



Source: AREVA NP, March 24, 2011

TMI-2 Reactor Core Endstate Configuration



- **Post-accident analyses** indicated that ≈ 70 % of core materials had been displaced or damaged.
- **Total hydrogen mass** produced:

  m ≈ 459 kg

  This corresponds to a hydrogen volume of about 5500 to 6000 m^3 at temperatures between 20 and 50 °C and atmospheric pressure according to the equation of state for an ideal gas:

  $$V = \frac{m \cdot R \cdot T}{p \cdot M}$$

  with

m	mass
M	molar mass
p	pressure
R	universal gas constant
T	absolut temperature in K
V	volume

- **Complete oxidation** of the zirconium inventory would have led to a hydrogen mass of ≈ 1061 kg.

Sources: D. W. Akers et al., 1989   CSA: Core Support Assembly   TMI-2: Three Mile Island Unit 2, Pressurized Water Reactor, 900 MW

Core Materials Liquefaction Regimes

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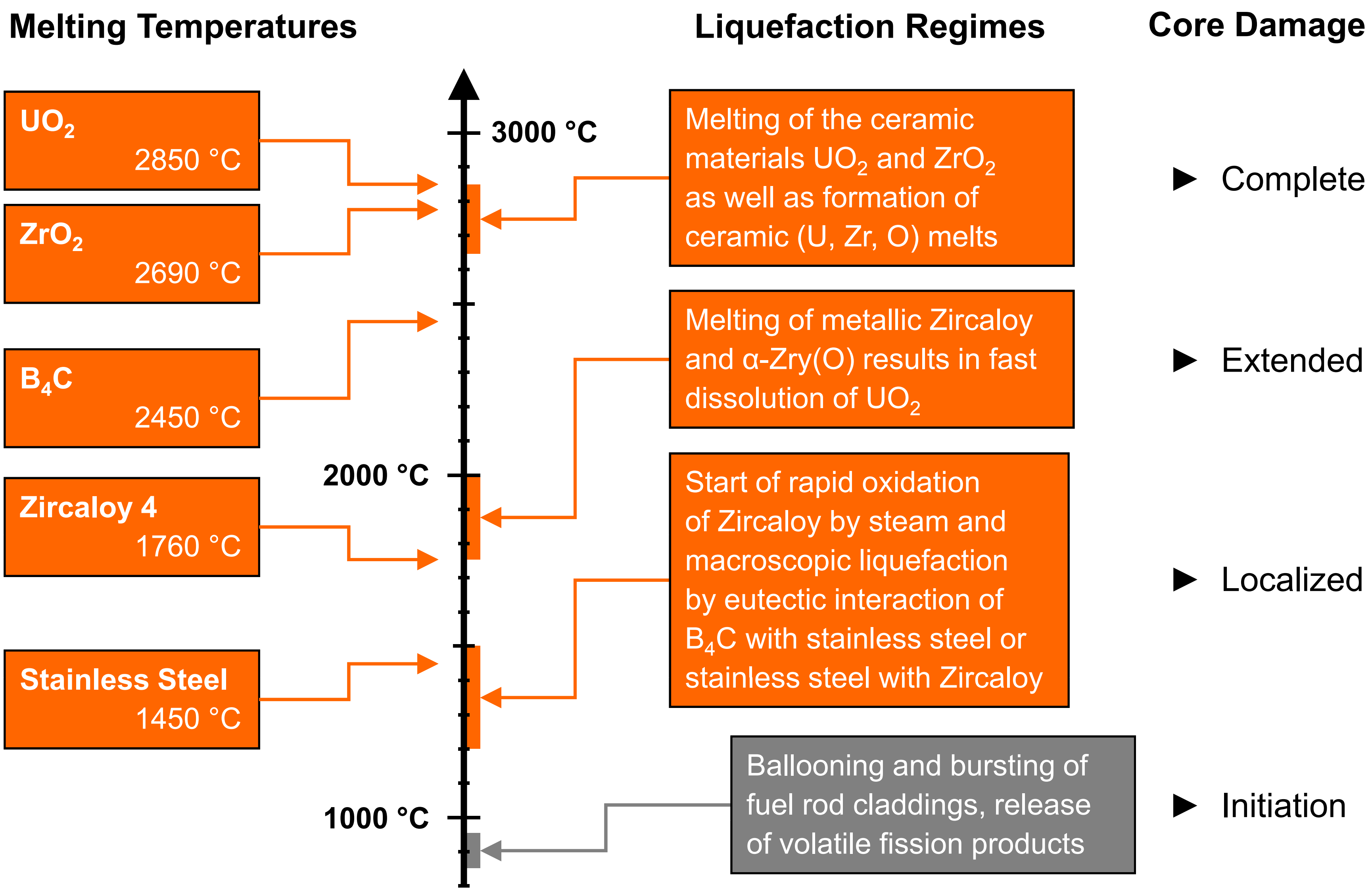


Source: KIT, GRS, 2011

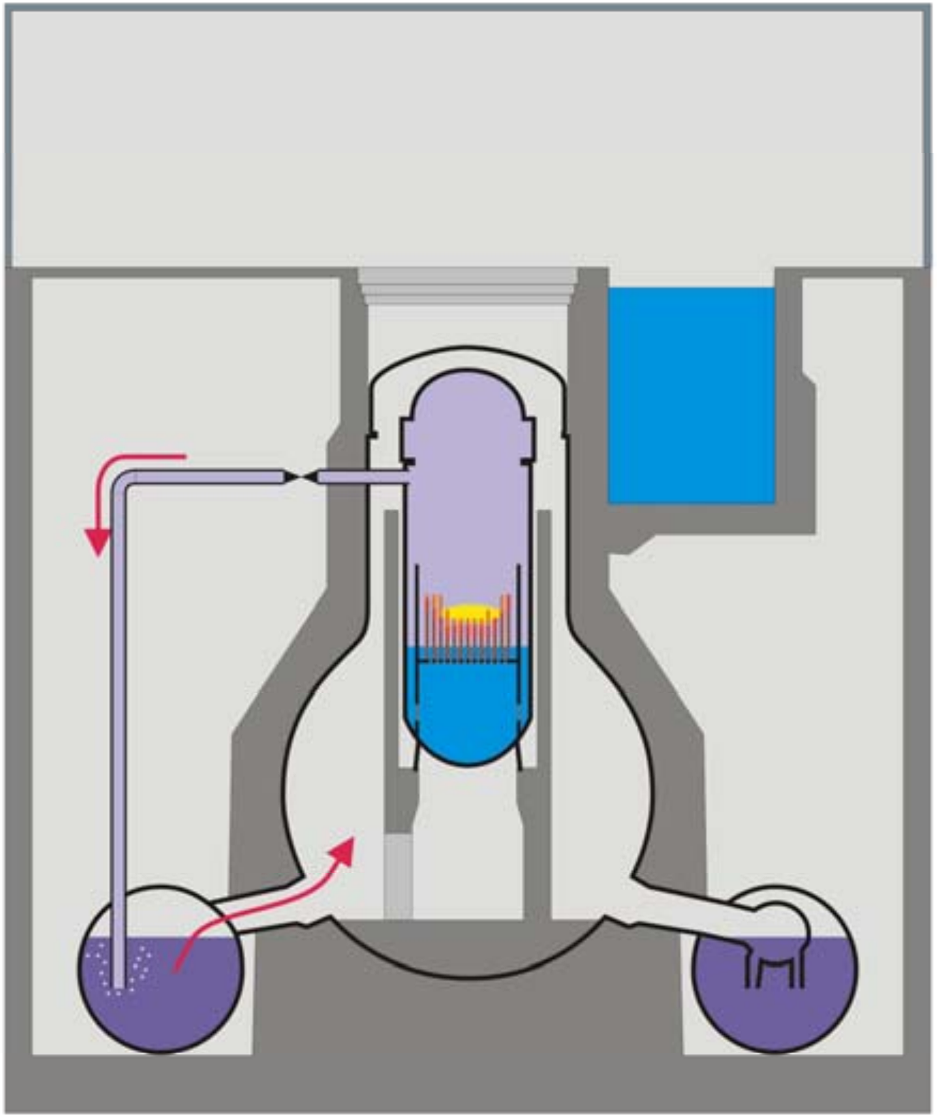
Event Sequence – Accident Progression

Core Melt Progression

- ► **At about 1800 °C (Units 1, 2, 3)**
  - Melting of metallic cladding remnants and steel structures.
- ► **At about 2500 °C (Units 1, 2)**
  - Breakdown of fuel rods,
  - inside core debris bed formation.
- ► **At about 2700 °C (Unit 1)**
  - Melting of (U, Zr)O_2 eutectics.

Reflood Phase

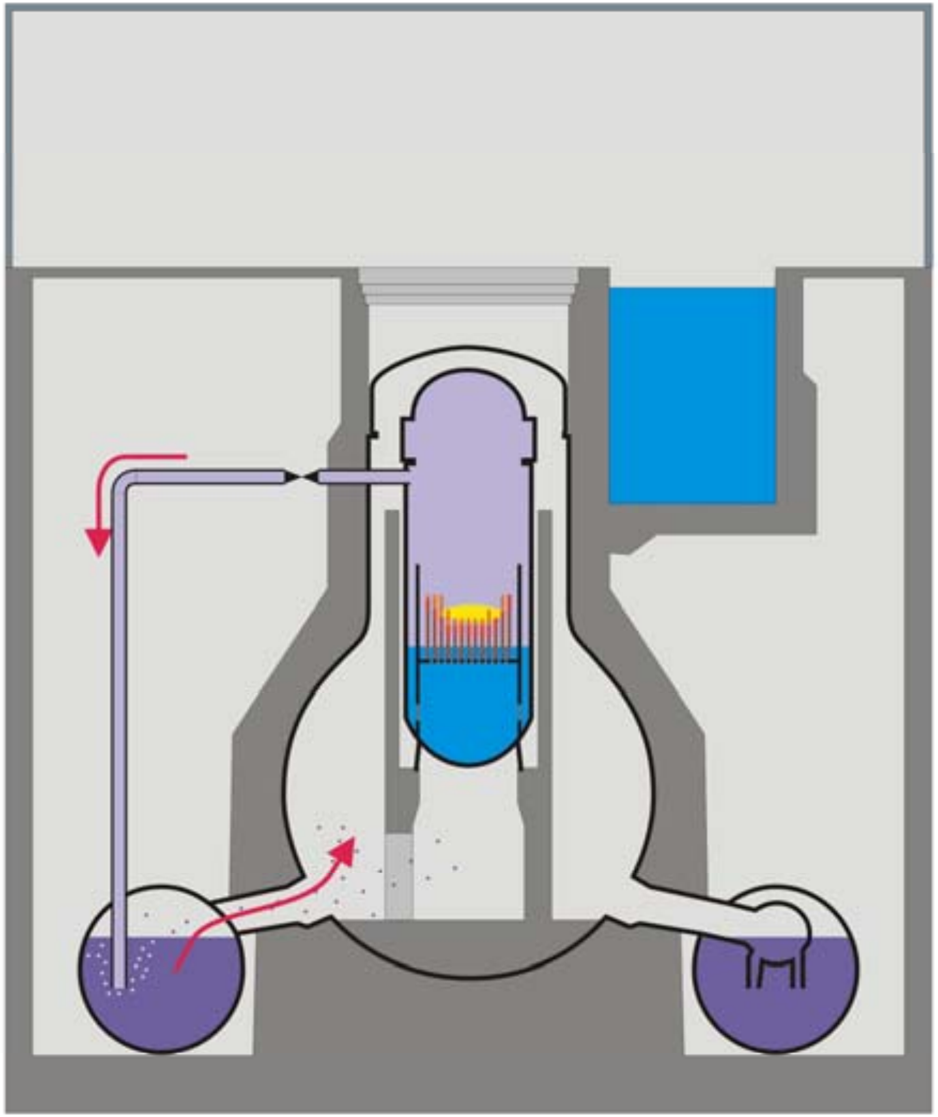
- ► **Seawater** supply stops the core melt progression in the three units.
  - ► **Unit 1:** March 12, 20:20 ► 27 h without water.
  - ► **Unit 2:** March 14, 20:33 ► 7 h without water.
  - ► **Unit 3:** March 13, 09:38 ► 7 h without water.



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

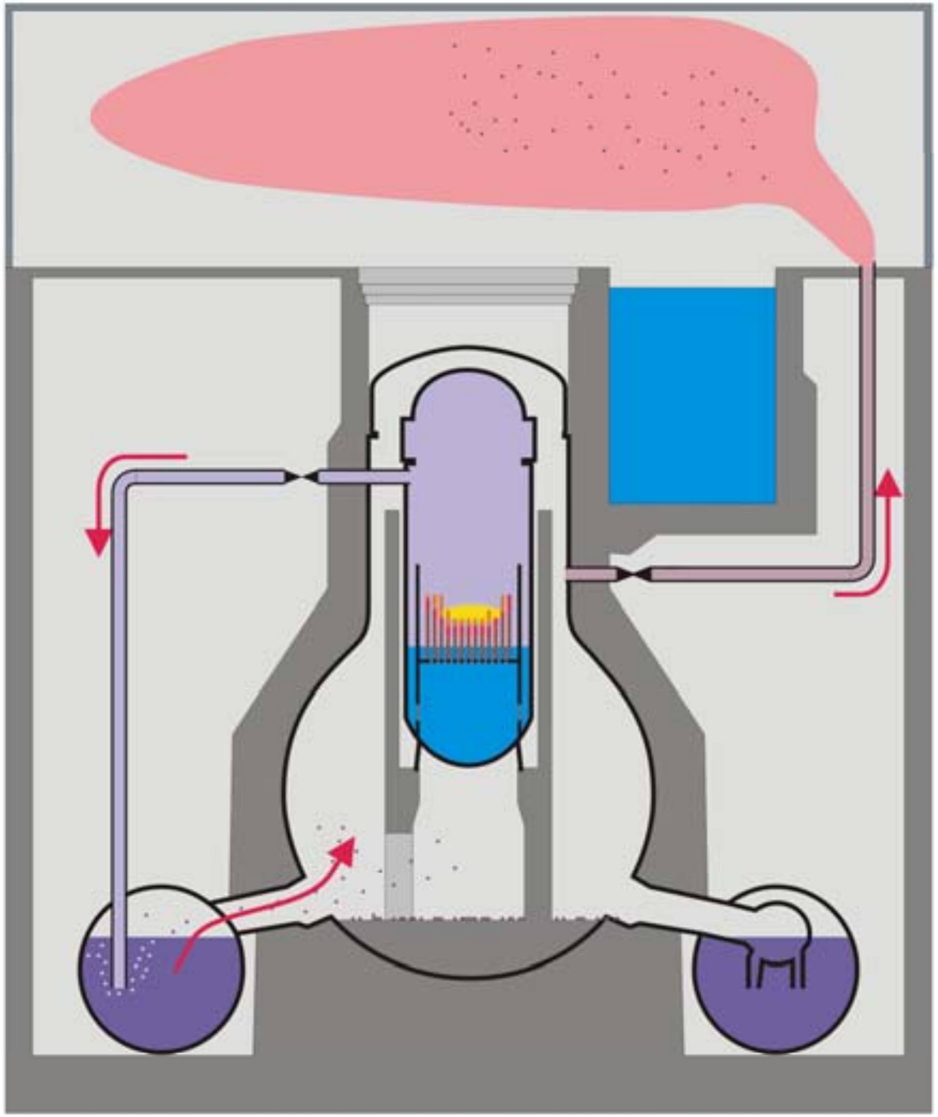
- **Release of fission products during core melt progression:**
  - Xenon, cesium, iodine, …
  - Uranium and plutonium remain in the core.
  - Condensation of some fission products to airborne aerosols.
- **Discharge through valves into the wetwell:**
  - Pool scrubbing leads to partial aerosol capture in the water.
- **Xenon and remaining aerosols enter the drywell:**
  - Deposition of aerosols on surfaces leads to further air decontamination.



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

- **Containment Safety Function**
  - Last barrier between fission products and environment.
  - Wall thickness: ≈ 3 cm.
  - Design pressure: 4 to 5 bar.
- **Actual Pressures up to 8 bar**
  - Inert gas filling (nitrogen),
  - hydrogen from core oxidation,
  - boiling condensation chamber (like a pressure cooker).
- **Containment Depressurization**
  - **Unit 1:** March 12, 04:00,
  - **Unit 2:** March 13, 00:00,
  - **Unit 3:** March 13, 08:41.

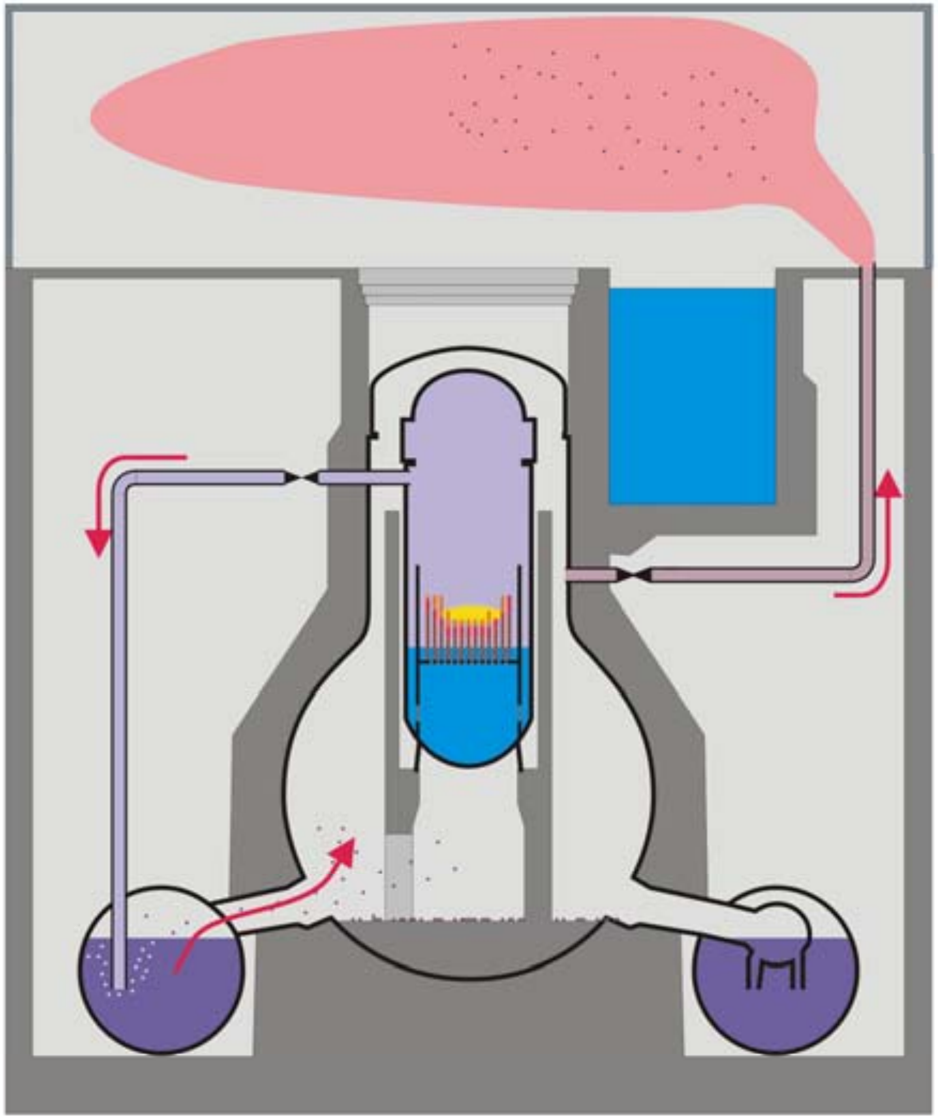


Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

Containment Depressurization

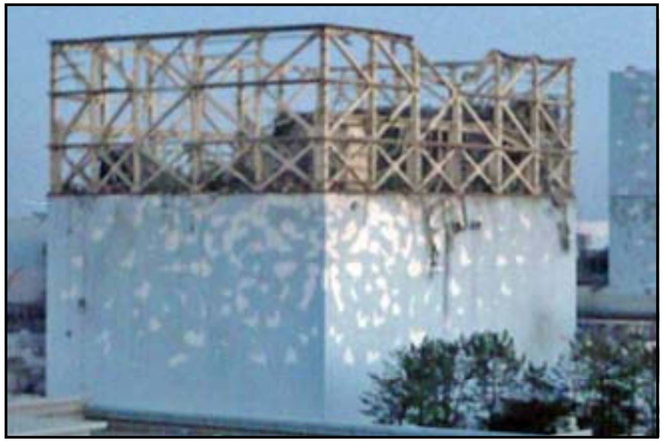
- ► Positive and negative aspects:
  - Removes energy from the containment (only way left),
  - reduces pressure to ≈ 4 bar,
  - release of
    - ► small amounts of aerosols (iodine, cesium ≈ 0.1 %),
    - ► all noble gases,
    - ► hydrogen.
- ► The gas mixture is released onto the reactor service floor.

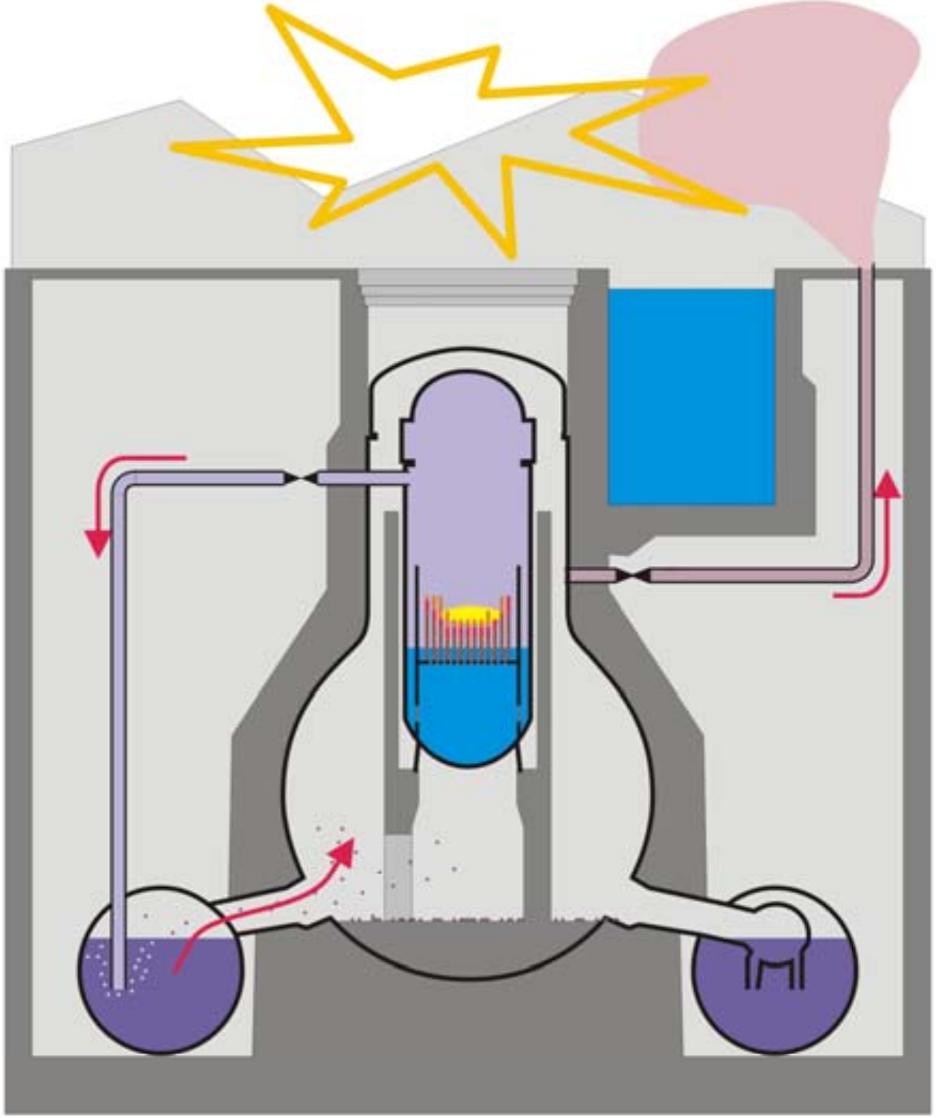


Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

- **Units 1 and 3:**
  - No recombiners (?).
  - Hydrogen explosion inside the reactor service floor.
  - This leads to destruction of the steel-frame construction.
  - Reinforced concrete reactor building remains undamaged.



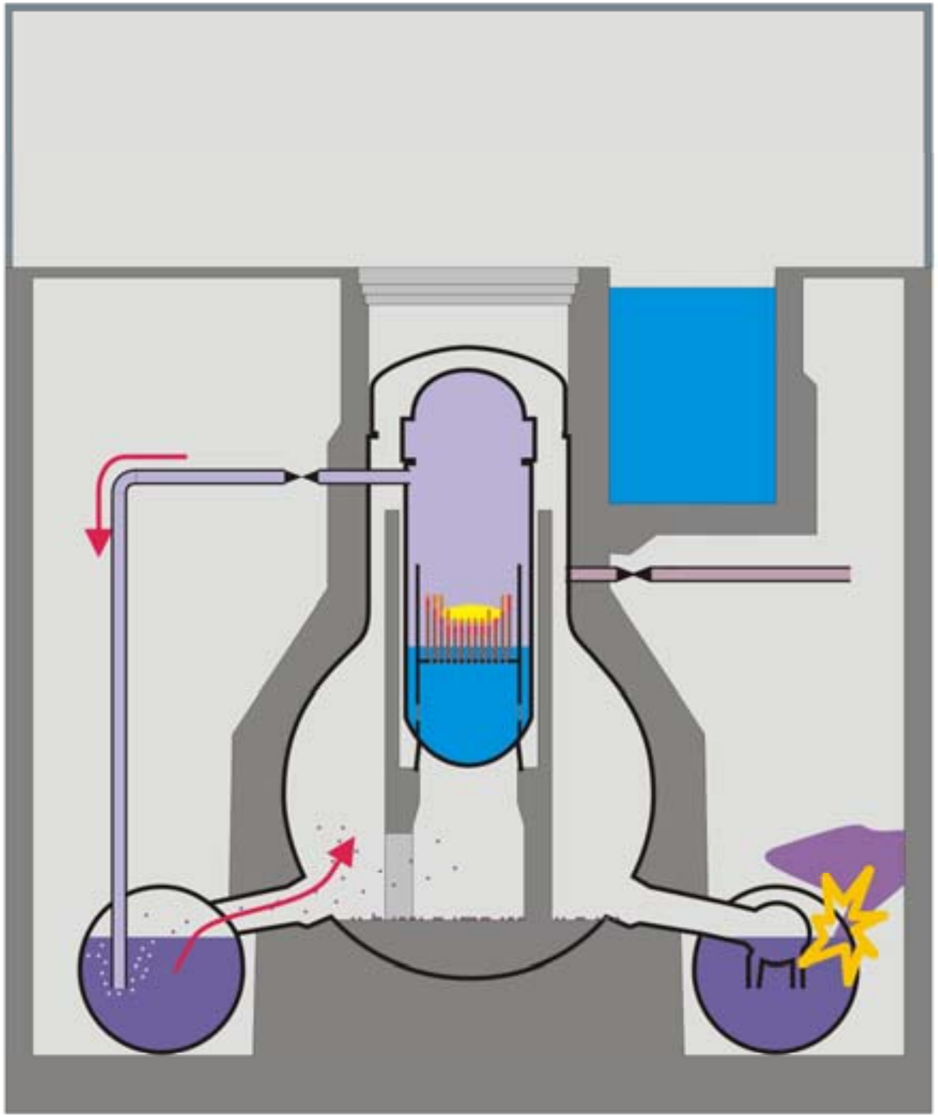


Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

► **Unit 2:**

- Probable damage of drywell following a pressure increase within the reactor pressure vessel and containment.
- Highly contaminated water.
- Uncontrolled release of gas from the containment.
- Release of fission products.
- Temporary plant evacuation due to high local dose rates on the plant site.



Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

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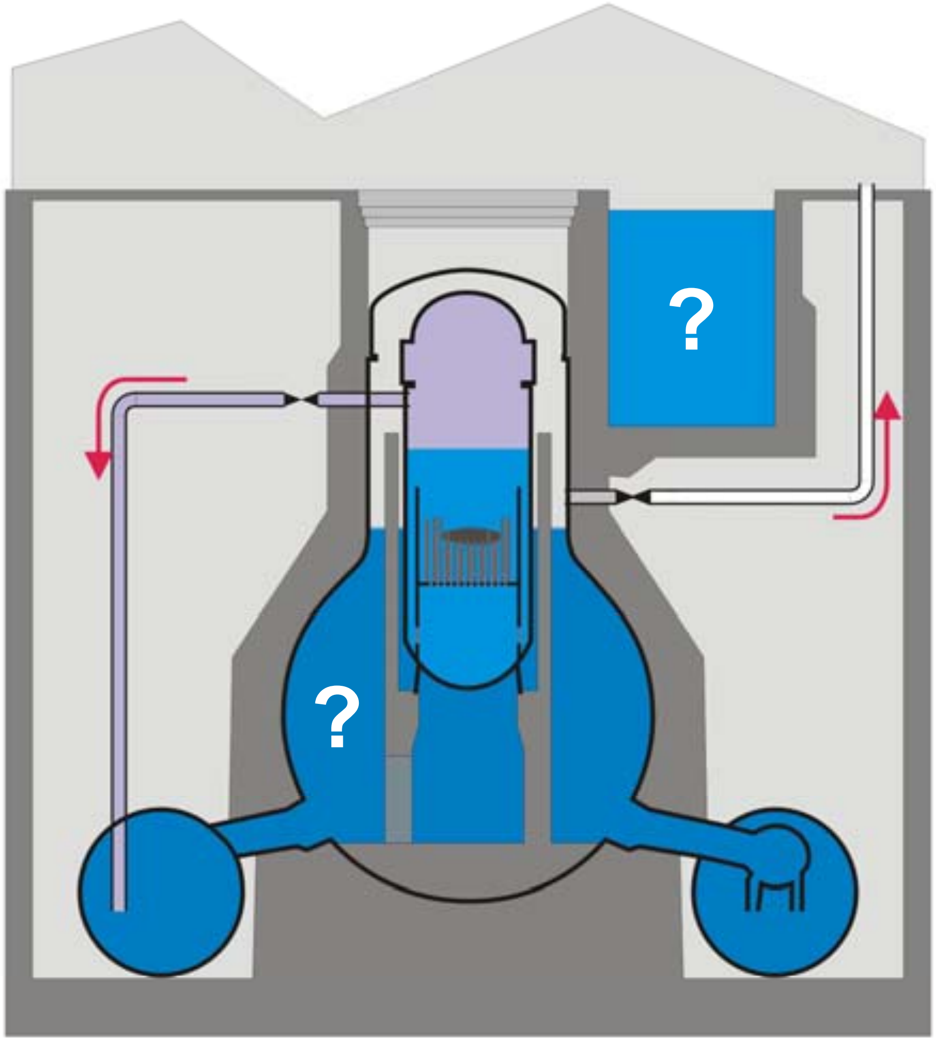
- **Reactor Status as of March 24:**
  - Core damage in units 1, 2, 3.
  - Damaged reactor buildings of units 1 to 4.
  - Reactor pressure vessels of all units are fed with seawater or sweet water by mobile pumps.
  - Estimates of General Electric indicate that about 45 tonnes of salt could have been injected into the reactor cores so far, with possible impacts on the reactor core coolability.

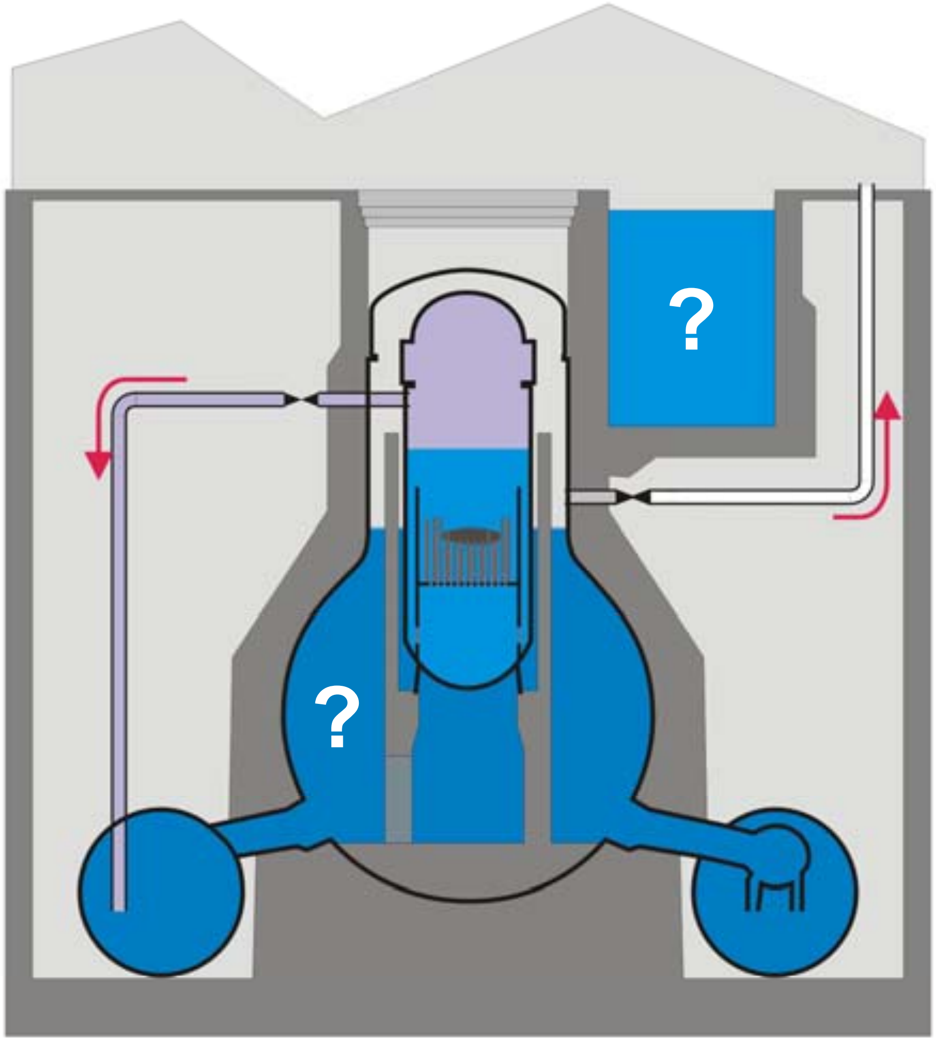


Source: AREVA NP, March 24, 2011

Event Sequence – Accident Progression

► **Changes as of March 29:**

- External power supply has been recovered for all reactors.
- Control rooms of units 1 and 3 have lighting, technicians test the functionality of the existing emergency feedwater pumps and will replace damaged pumps in the short term.
- Fresh water is supplied from some nearby hydro-reservoirs (tanks?), thus banning dangers of reduced cooling by salt crusts on the fuel rod surfaces and of reduced heat transfer in fuel ponds due to salt after sea water intrusion.



Source: AREVA NP, March 24, 2011

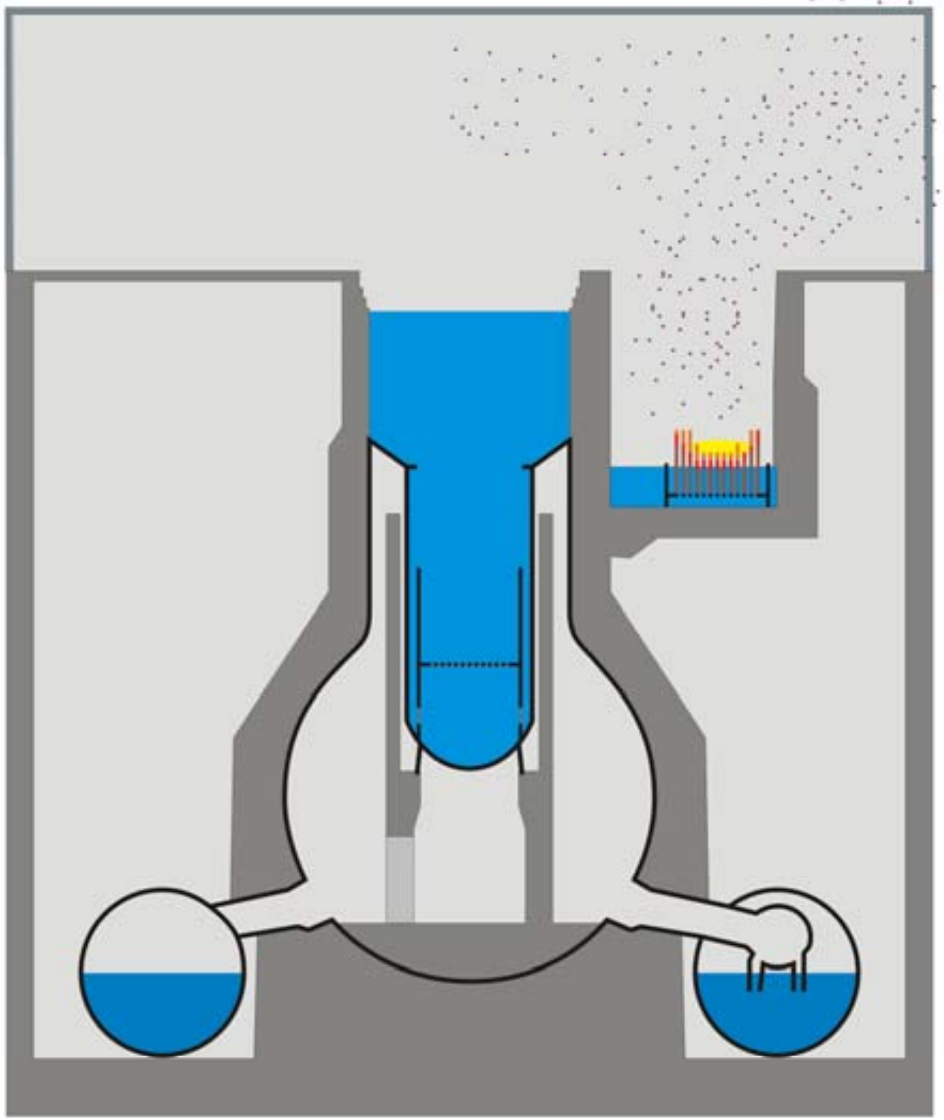
Fukushima-Daiichi-1

Central control room after lighting has been restored on March 25, 2011.

Source: Tepco, 2011

Spent Fuel Transfer Pools

- **Spent Fuel Stored in Pool on the Reactor Service Floor:**
  - The entire core of unit 4 had been stored in the spent fuel pool for maintenance reasons before the earthquake.
  - Dry-out of spent fuel pools:
    - unit 4 in ten days,
    - other units in a few weeks.
  - Leakage of the spent fuel pools due to earthquake?
- **Consequences:**
  - Fuel melting „on fresh air“,
  - nearly no retention of fission products within the plant,
  - possible large release.



Source: AREVA NP, March 24, 2011

Spent Fuel Transfer Pools & Shared Pool

Unit	Number of Assemblies	Water m^3	Power MW	Fresh Core	Cooling	Fuel Damage
1	292	1020	0.3	No	?	?
2	587	1425	1.0	No	Steam Plume	?
3	514	1425	0.7	No	Boiling	?
4	1331	1425	3.0	Yes	Pump Car	Major
5	946	1425	4.5	Probably	Diesel [2])	No
6	876	1497	1.5	Probably	Diesel	No
S	6291 [1])	?	?	No	Working	No

Fukushima-Daiichi

- **Unit 1:** 400 fuel rod assemblies,
- **Units 2 to 5:** 548 fuel rod assemblies,
- **Unit 6:** 764 fuel rod assemblies.

- **Unit 3:** Small number (32) of ten years old old mixed oxide (MOX) fuel assemblies in spent fuel pool. No significant difference of plutonium inventory compared to other pools, since uranium fuel also contains plutonium, but old MOX fuel contains higher amounts of Americium (more volatile than plutonium).

S: site shared spent fuel pool [1]) total number on the site in November 2010, overall capacity: 6840 assemblies [2]) unit 6

Unit 4 Spent Fuel Transfer Pool Cooling

VGB PowerTech

- **150 tonnes of sea water** were poured into the spent fuel pool of unit 4 using a **concrete pump car** on March 22. This action took about **three hours** and was repeated over hours later.

- The concrete pump has a maximum capacity of 120 t/h, is equipped with an **arm** of 58 m maximum length and operated by **12 persons** (remotely).

Source: TEPCO, March 22, 2011

Unit 4 Spent Fuel Transfer Pool Cooling

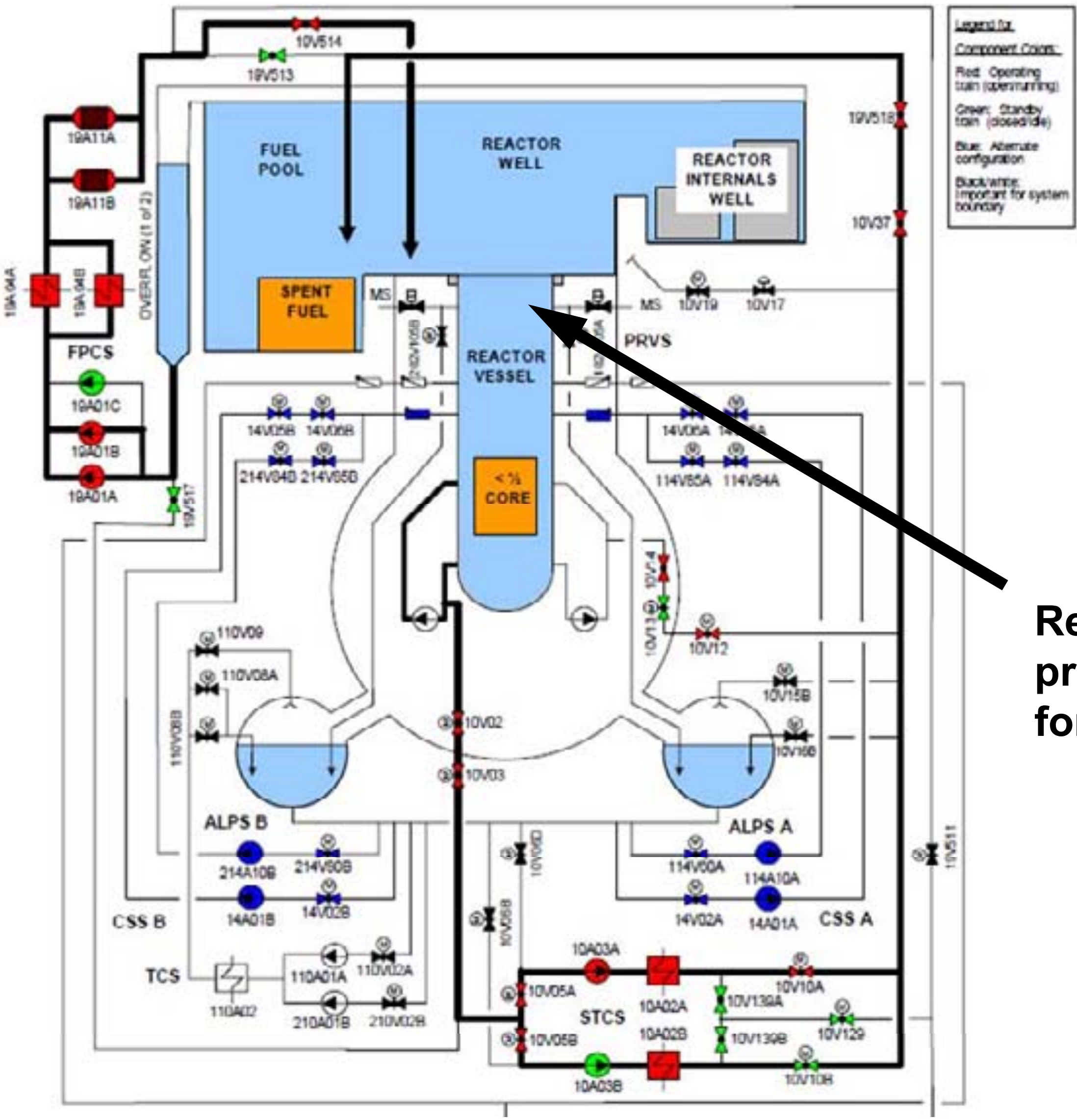
Source: www.cryptome.org, 2011

Unit 4 Spent Fuel Transfer Pool Cooling

April 4, 2011:
Four additional concrete pumps (62 m, 70m) are underway by Antonov airlift from Germany and USA.

Source: www.cryptome.org, 2011

Fukushima Daiichi Refueling Cooling System



Reactor pressure vessel and primary containment are open for refueling.

Source: FPL, 2011

Dose Rates at Fukushima Daiichi

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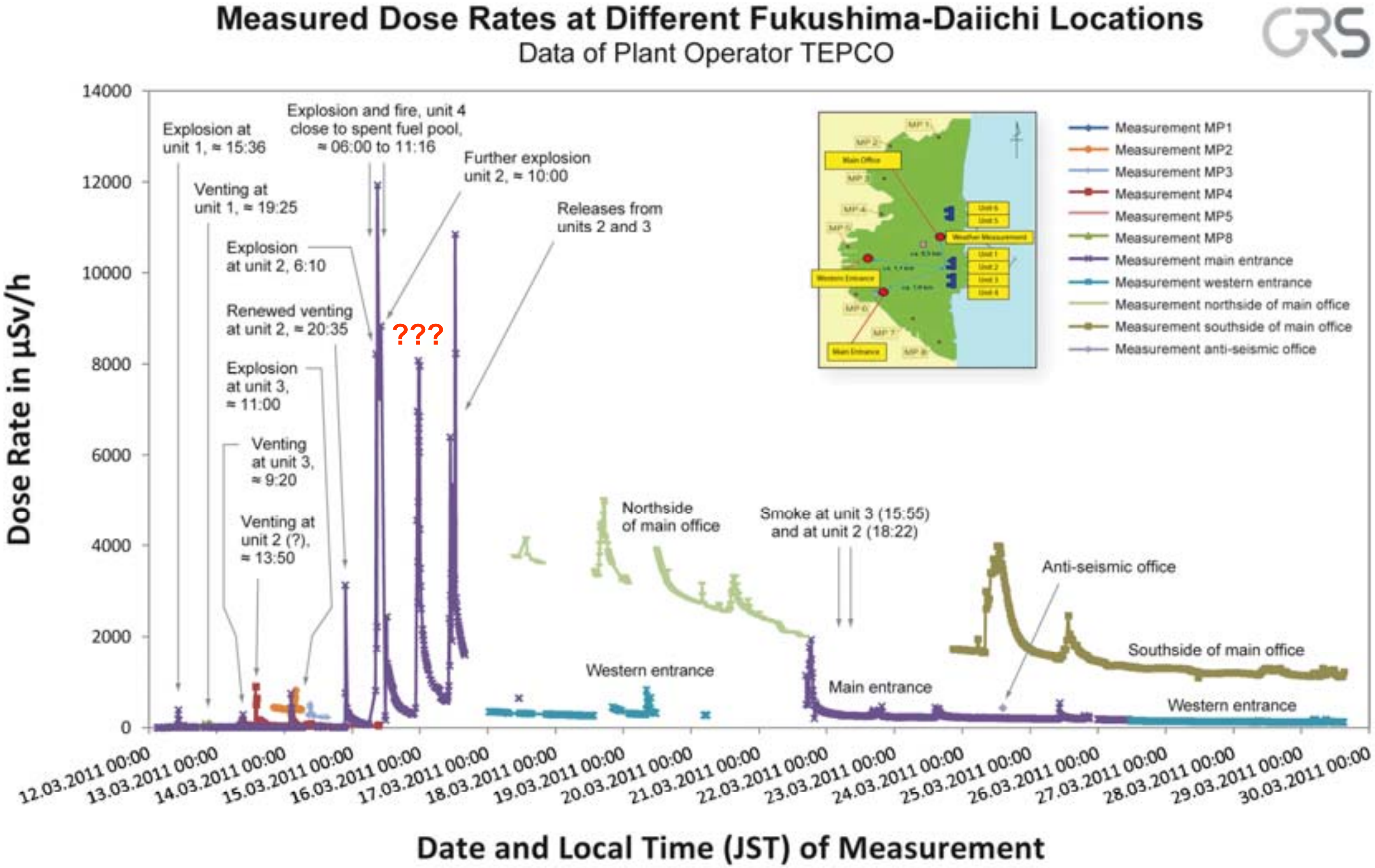
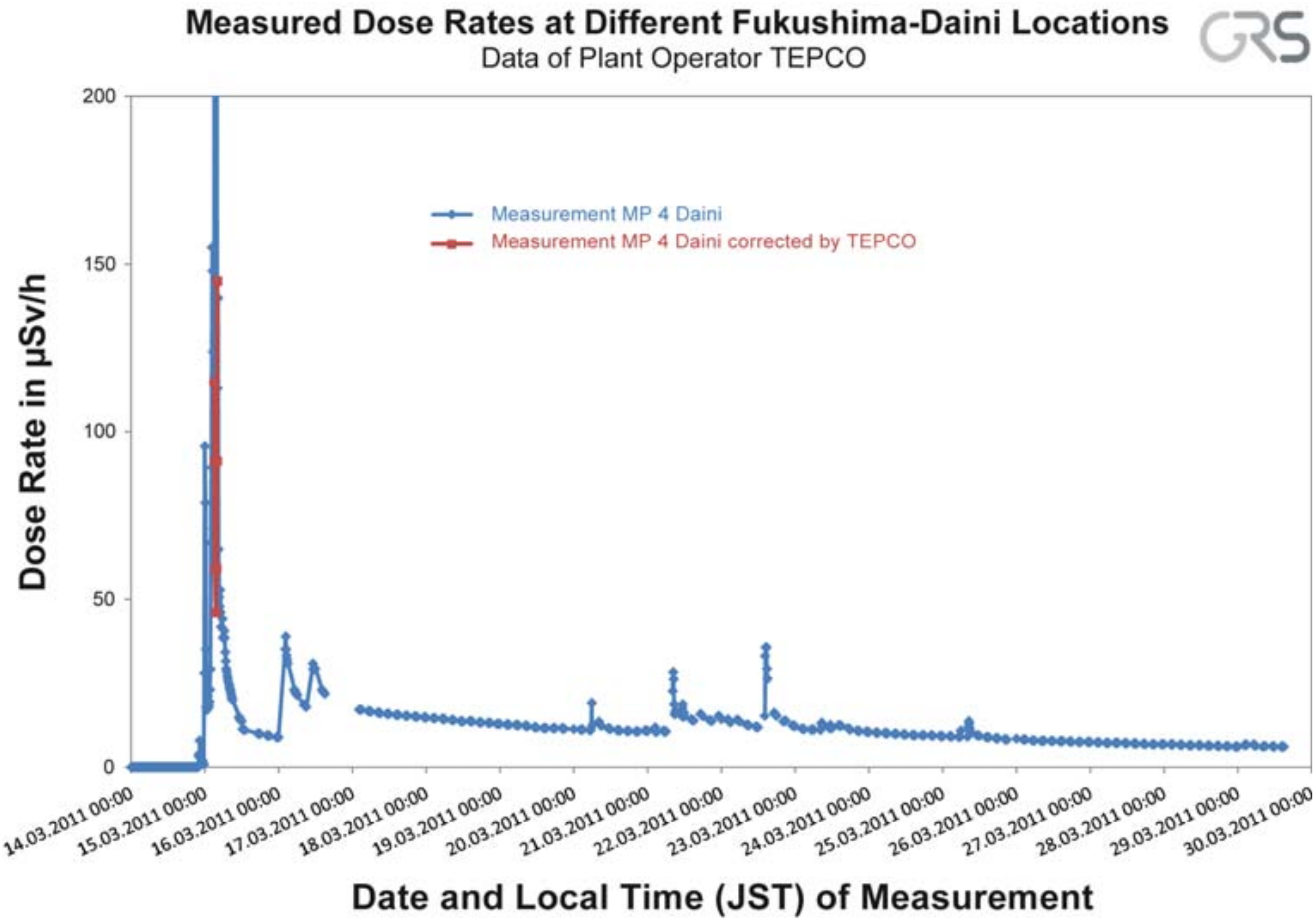


Source: GRS, March 30, 2011 JST: Japan Standard Time

Dose Rates at Fukushima Daini



Source: GRS, March 30, 2011 JST: Japan Standard Time

Measures to Minimize Radiological Impacts

From Start of Emergency Procedures

► **Evacuations** according to risk within a 20 km radius.

► **Core cooling recovery** as far as possible by flooding of reactor cores based on

- mobile diesel pumps and/or
- recovery of external power supply,
  - ► successful for units 1 and 2 on March 20,
  - ► units 3 and 4 following.

► **Spent fuel pool cooling recovery** by helicopters and/or water cannons for unit 4.

- Mobile diesel pumps and concrete pump cars for other units (?) and/or
- recovery of external power supply,
  - ► successful for unit 1 on March 20,
  - ► units 2 to 4 following.

Source: GRS, March 24, 2011

Fukushima Daiichi, Status as of March 19, 2011

Unit	1	2	3	4	5	6
Core and fuel integrity	Damaged	Damaged	Damaged	No fuel in the reactor	Not Damaged	Not Damaged
Reactor Pressure Vessel Integrity	Unknown	Unknown	Unknown			
Containment Integrity	Not Damaged	Damage Suspected	Might be not damaged	Not Damaged	Not Damaged	Not Damaged
Reactor building integrity	Severely Damaged	Slightly Damaged	Severely Damaged	Severely Damaged	Open a vent hole on the rooftop for avoiding hydrogen explosion	Open a vent hole on the rooftop for avoiding hydrogen explosion
Water injection to core	Continuing (Seawater)	Continuing (Seawater)	Continuing (Seawater)	Not necessary	Not necessary	Not necessary
Water injection to Containment Vessel	Continuing (Seawater)	to be decided (Seawater)	Continuing (Seawater)	Not necessary	Not necessary	Not necessary
Fuel integrity in the spent fuel pool	Water injection to be considered	no info	level low - water injection	level low - preparing water injection	Pool temperature increasing	Pool temperature increasing

Quelle: AREVA NP, March 19, 2011

Fukushima Daiichi, Status as of April 2, 2011

Unit	1	2	3	4	5	6
Reactor Type	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-G
Thermal Power	1380 MW_{th}	2381 MW_{th}	2381 MW_{th}	2381 MW_{th}	2381 MW_{th}	3293 MW_{th}
Electric Power	460 MW_e	784 MW_e	784 MW_e	784 MW_e	784 MW_e	1100 MW_e
Status before earthquake	In service ► auto shutdown	In service ► auto shutdown	In service ► auto shutdown	Outage	Outage	Outage
Core and fuel integrity	Damaged	Severe Damage	Damaged	No fuel in reactor	**Cold Shutdown** Being maintained by existing plant equipment and offsite electrical power	
Reactor outside temperatures	250 °C 128 °C	**180 °C** **450 °C**	90 °C (?) 150 °C	Not applicable due to outage plant status		
Containment integrity	Pressure of 2 bar, flooded?	Pressure of 1 bar, damage suspected	Pressure of 1 bar, damage suspected			
AC Power	Yes plus control room light	Yes plus control room light	Yes plus control room light	Yes plus control room light		
Building	Severe damage	Slight damage	Severe damage	Severe damage		
Reactor water level	40 % of fuel uncovered	30 % of fuel uncovered	50 % of fuel uncovered	Not applicable due to outage plant status		
Reactor pressure	About 5 bar, decreasing	Less than 1 bar (?)	1 bar			
Status of spent fuel pool	Fresh water by concrete pump car	58 °C, sea water and fresh water by pool cooling	Sea water and fresh water by concrete pump car	Sea water and fresh water by concrete pump car	32 ° C, pump repaired	24 °C

Quelle: IAEA, April 2, 2011 ■ Severe condition ■ Concern ■ No immediate concern

INES-Classification as of April 12, 2011

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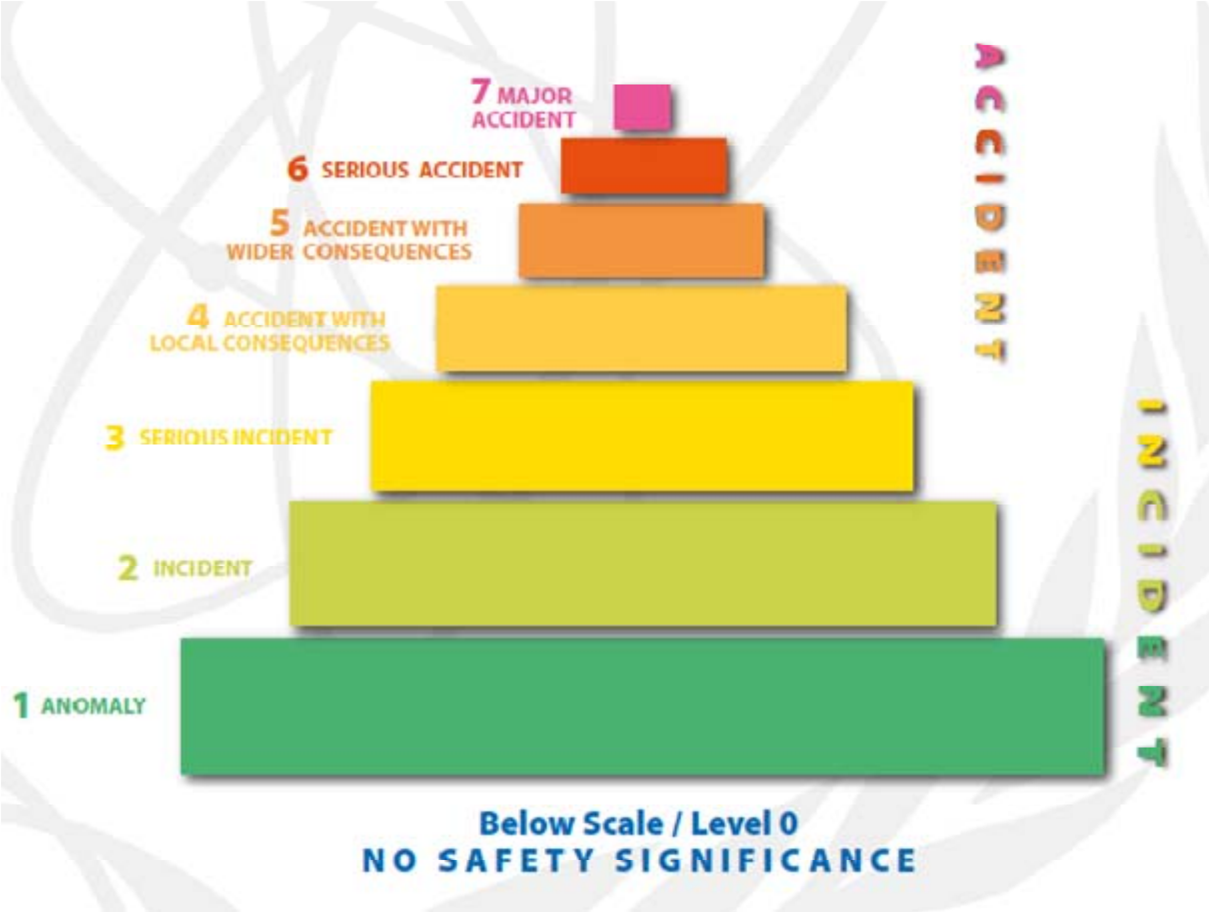
Fukushima Daiichi

Unit	INES-Level
1	7
2	7
3	7
4	3
5	not specified
6	not specified

Fukushima Daini

Unit	INES-Level
1	3
2	3
3	not specified
4	3



Sources: IAEA, GRS, April 12, 2011

Radiology

Lethal Dose [1]): 5000 mSv

Extended Tepco Limit: 250 mSv

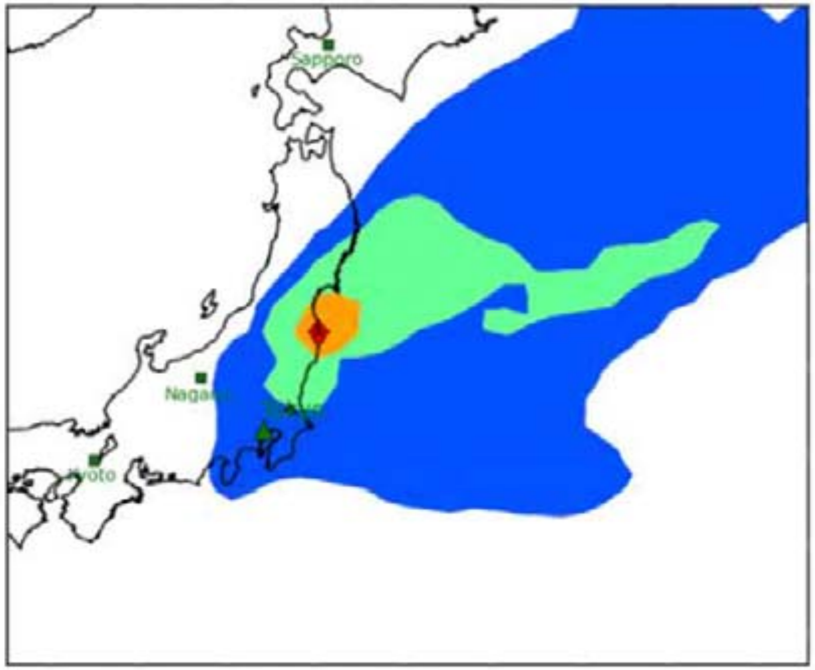
Initial Tepco Limit: 100 mSv

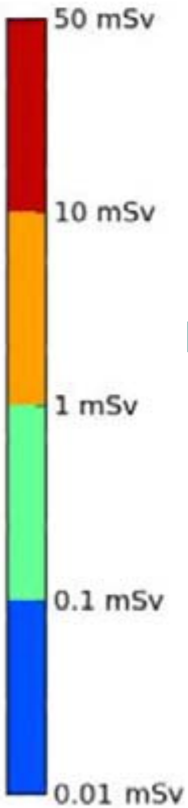
Maximum Allowed [2]): 50 mSv/a

Dose Rates

Natural Background: 2.5 mSv/a

Radioactivity released from March 11 to 20, 2011





Cumulative dose for an unprotected one year old child

Sources: DPA, Nisa, IRSN, March 20, 2011 [1]) in case of short-term exposure [2]) in Japan, 20 mSv/a in Germany

Status of Other Plants as of April 4, 2011

Plant	Status	Diesels, pumps	Venting	Offsite power	Damages
Fukushima Daini Units 1 to 4	cold shutdown	?	prepared	available	tsunami?
Onagawa Units 1 to 3	cold shutdown	at least one, one pump	no	available	fire in unit 1, extinguished, no tsunami damage due to the higher ground level
Tokai Unit 2	cold shutdown	one of three, one emergency pump	no	?	safe status
Rokkasho Reprocessing	none	available	not required	?	not reported

Open Questions

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- ► **Reasons for explosion in reactor building of Fukushima Daiichi unit 4?**
- ► **Status of melted reactor cores?**
- ► **Status of pool inventories?**
- ► **Details of release history?**
- ► **Venting in Fukushima Daini?**
- ► **Draining of trenches?**
- ► **Reasons for obviously having ignored the tsunami data base?**
- ► **Recriticality in Fukushima Daiichi unit 2?**
  (according to soil samples ► might explain radioactivity spike on March 16, 2011)

Casualties

- **Tentative by April 4, 2011**
  - **4 persons dead** (2, earthquake, stack cabin in Fukushima Daiini),
  - **2 persons missing** (found on April 3 as having been drowned),
  - **20+ persons injured** (mostly by Hydrogen exlosions),
  - **less than 20 persons exposed to radiation doses < 250 mSv,** (including 3 workers who tried to lay cables in the flooded unit 2 basement on April 1).
  - **0 persons exposed to radiation doses > 250 mSv** (i.e. one additional late cancer case out of 100 persons).

Preliminary Conclusion

Design basis for nuclear power plants in Japan:

- ► Incident rate of one earthquake within a **50 000 years** period.
- ► Incident rate of one large [1]) tsunami within a **30 years** period.

Design basis for nuclear power plants in Germany:

- ► Incident rate of one earthquake within a **100 000 years** period in combination with relevant flood water heights to be presumed.

[1]) maximum amplitude of at least 10 m

Contact for Questions and Remarks

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Registergericht: Amtsgericht Essen
Registernummer: VR 1788

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