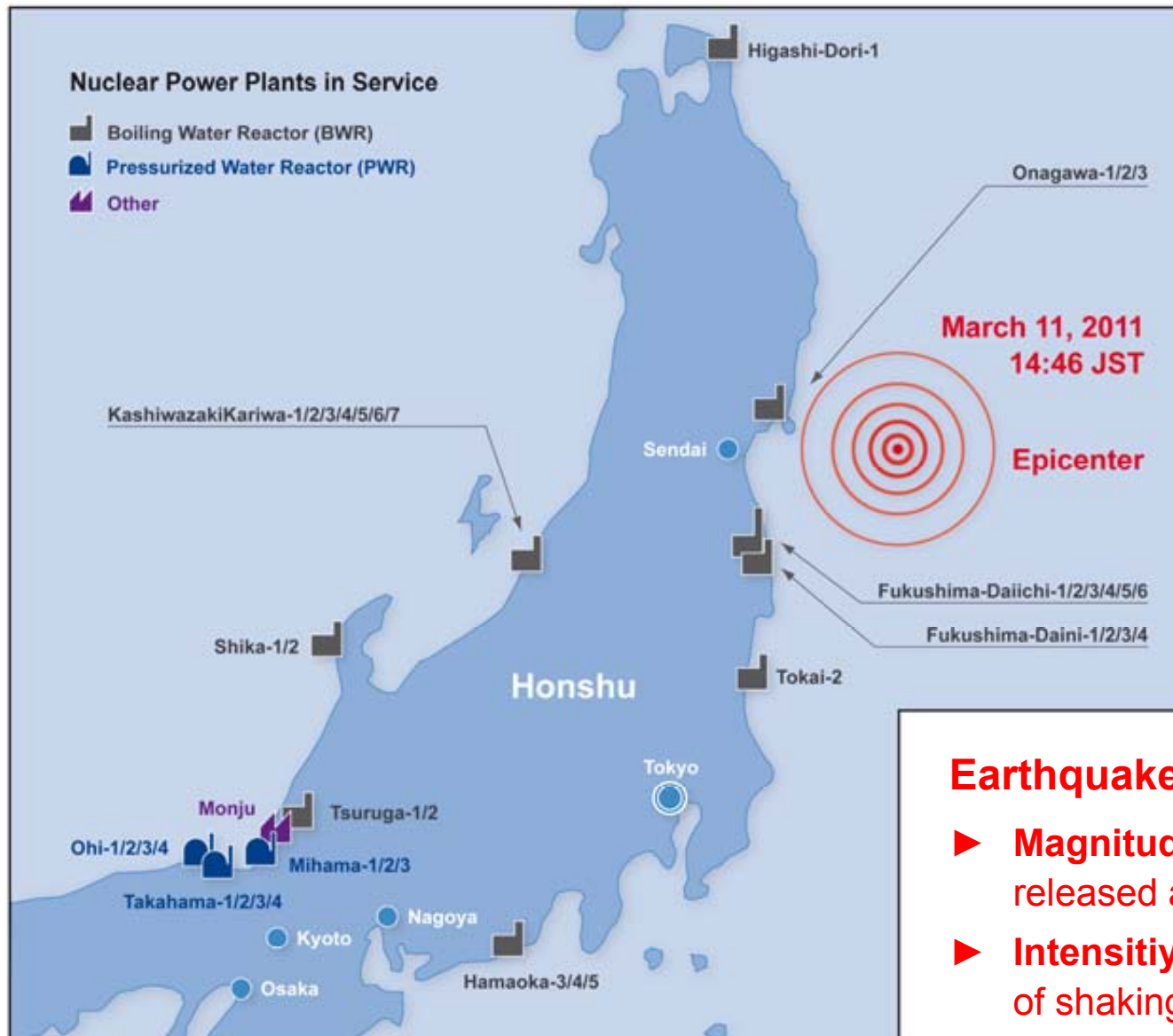


Earthquake and Tsunami in Japan on March 11, 2011 and Consequences for Fukushima and other Nuclear Power Plants

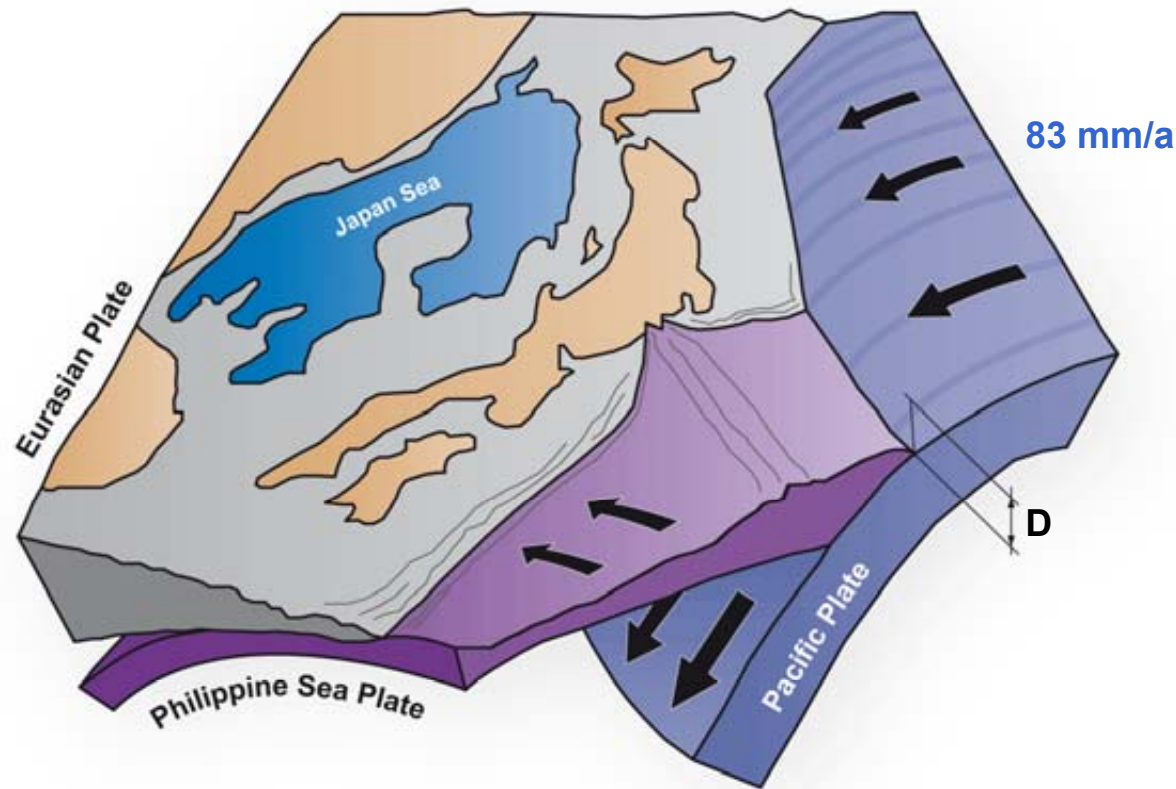
Status: April 15, 2011

**Dr.-Ing. Ludger Mohrbach
Thomas Linnemann, Georg Schäfer, Guido Vallana**

Tohoku-Taiheiyou-Oki Earthquake



Tohoku-Taiheiyou-Oki Earthquake



► **Rough Estimate of Water Volume Involved**

$$V \approx A \cdot \frac{1}{4} D \approx 500 \text{ km} \cdot 100 \text{ km} \cdot 2,5 \text{ m} = 125 \text{ km}^3$$

► **Consequence:** Sudden displacement of a huge water volume ► **Tsunami.**

► **Vertical Displacement**

$$D \approx 7 \text{ to } 10 \text{ m}$$

► **Peak Displacement**

$$D_{\text{max}} \approx 17 \text{ to } 25 \text{ m } ^1)$$

► **Rupture Zone**

$$A \approx 500 \text{ km} \times 100 \text{ km}$$

► **Hypo Center Depth**

$$Z_H \approx 20 \text{ to } 25 \text{ km}$$

► **Crack Velocity**

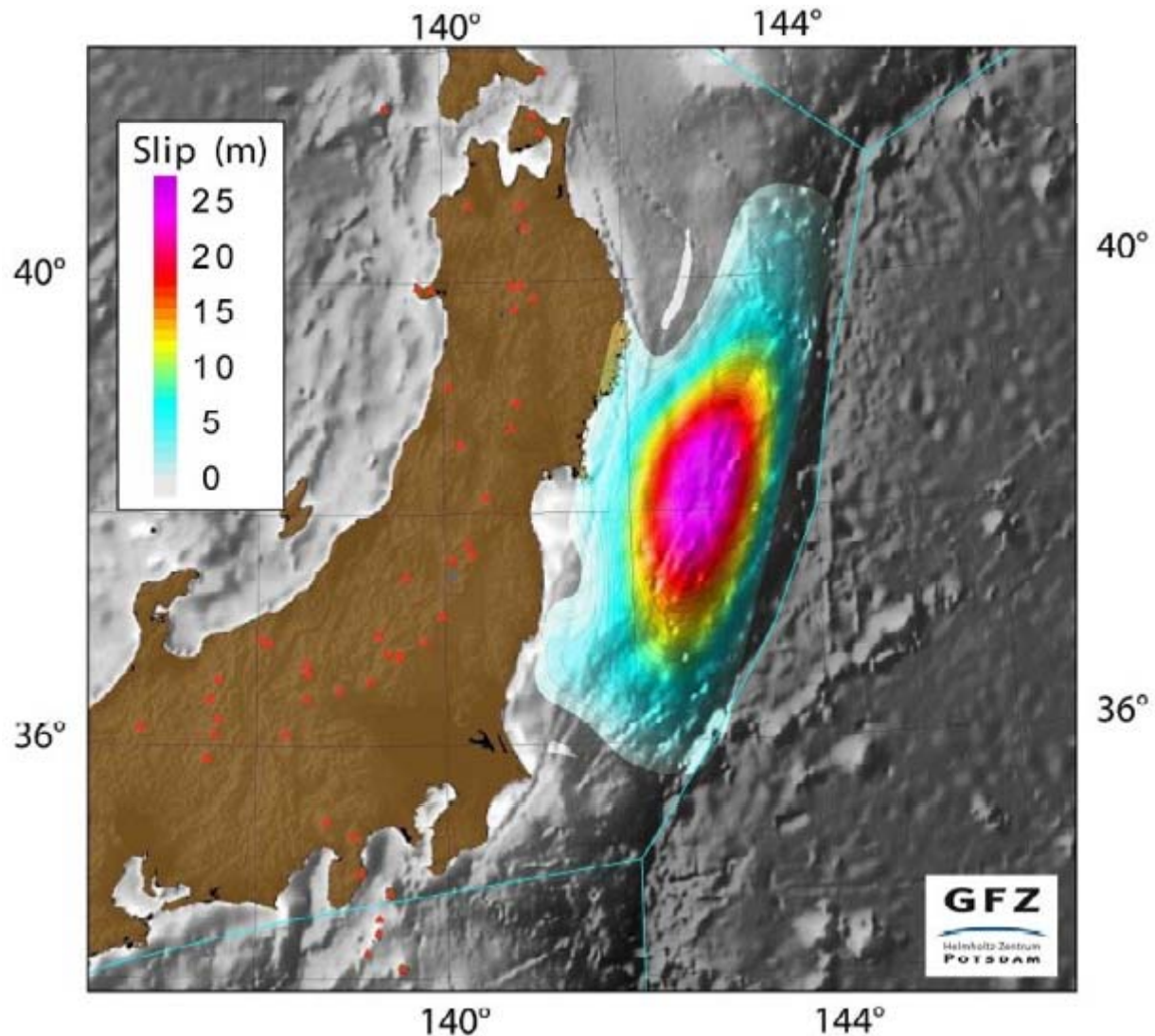
$$v \approx 2 \text{ km/s}$$

► **Water Depth**

$$Z \approx 8 \text{ km}$$

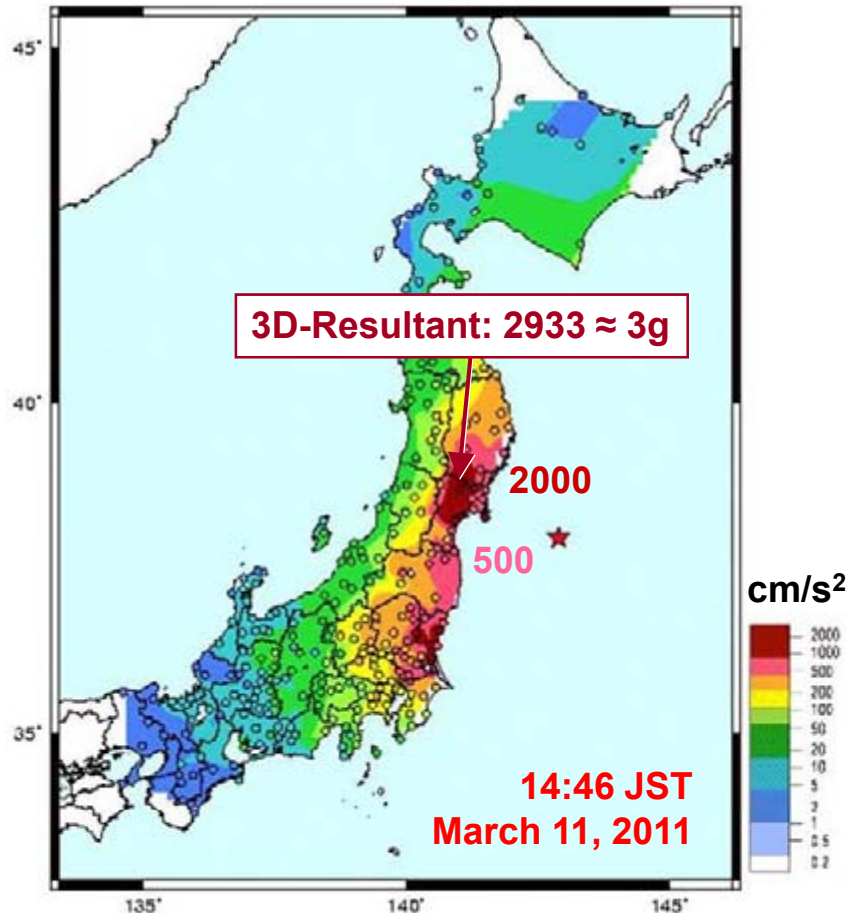
Topographic Effects

- ▶ **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



Tohoku-Taiheiyou-Oki Earthquake

Peak Accelerations Contour Map



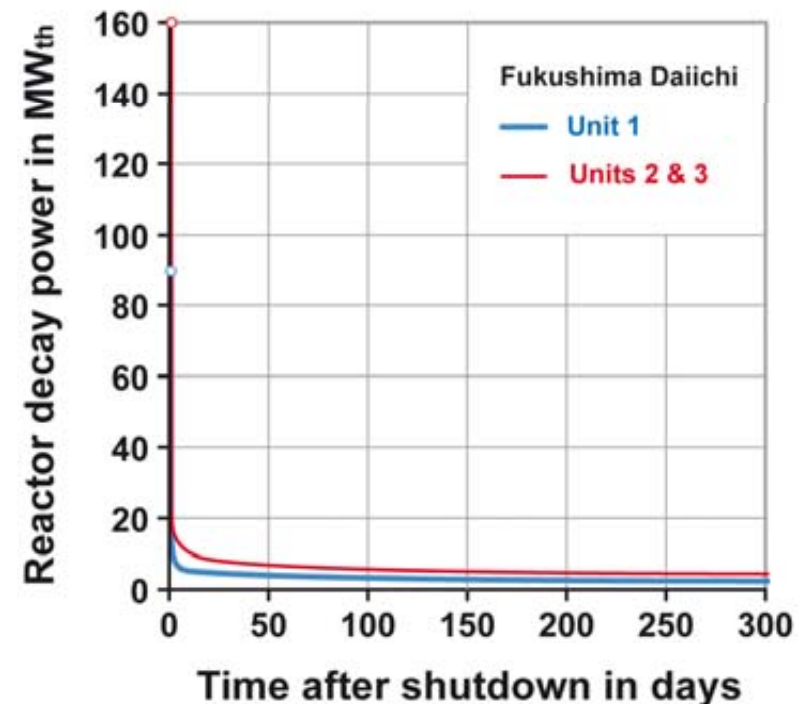
Fukushima	Acceleration ¹⁾ in cm/s ²		
	Horizontal		Vertical
	N-S	E-W	
Daiichi-1	460	447	258
Daiichi-2	348	550	302
Daiichi-3	322	507	231
Daiichi-4	281	319	200
Daiichi-5	311	548	256
Daiichi-6	298	444	244
Design Basis	441	438	412
Daini-1	254	230	305
Daini-2	243	196	232
Daini-3	277	216	208
Daini-4	210	205	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 (\approx 10 % for Onagawa).

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 (extinguished 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.



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).
- ▶ Operators follow:
 - abnormal operating procedures,
 - emergency operating procedures, later
 - severe accident management guidelines (SAMGs).



Tsunami Arrival at Fukushima Daiichi

Tsunami Impact at Fukushima Daiichi



Tsunami Impact at Fukushima Daini

14

VGB
POWERTECH



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

Source: Tepco, 2011

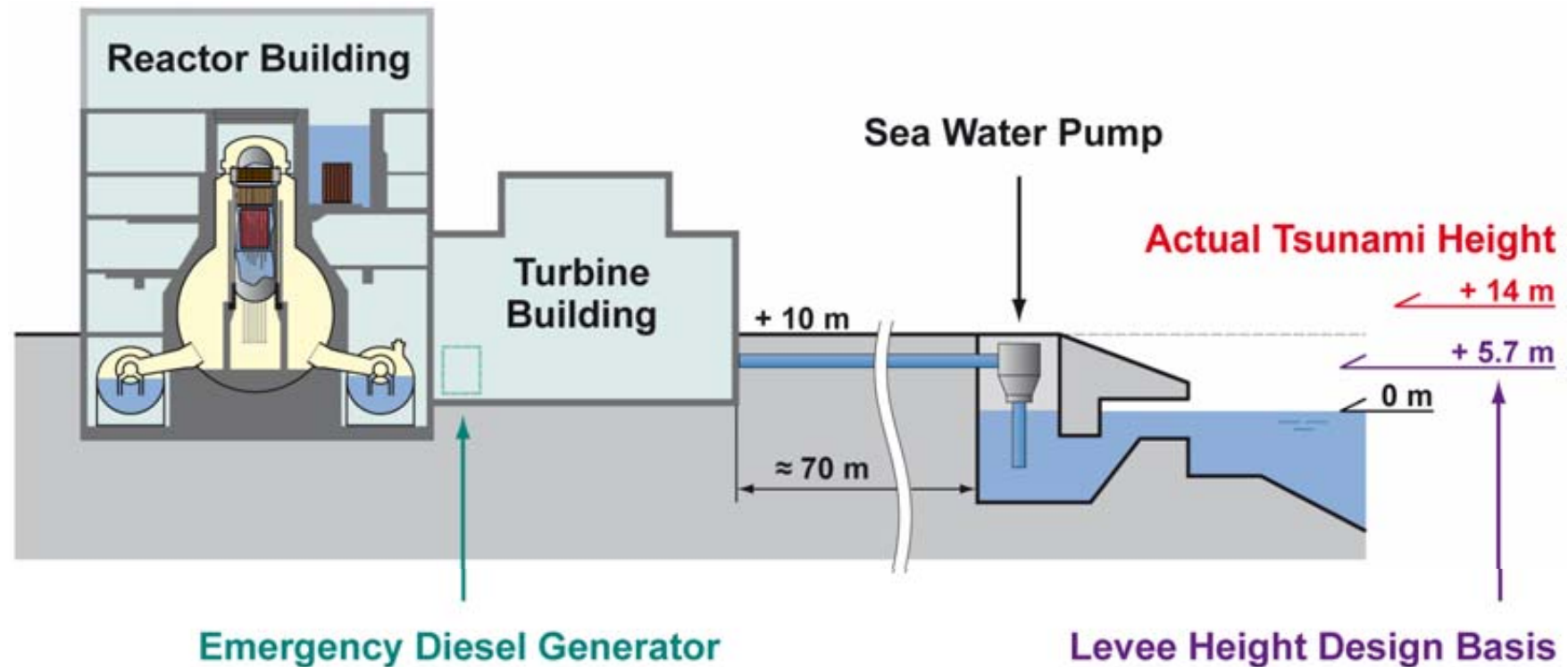
Tsunami

- ▶ **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.**

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.

Design of Fukushima Daiichi Unit 1

Reactor Service Floor
(Steel Construction)

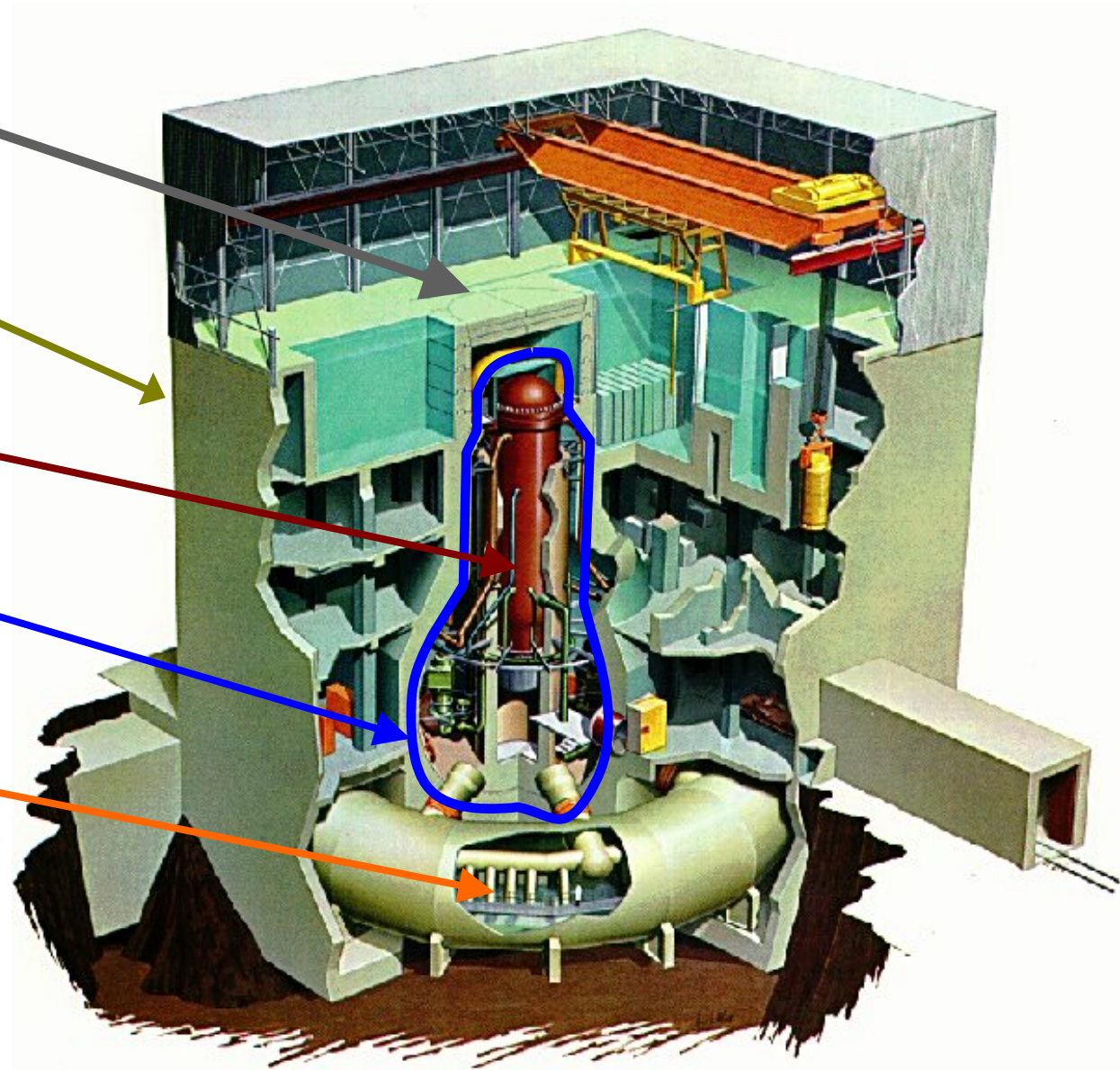
Concrete Reactor Building
(Secondary Containment)

Reactor Pressure Vessel

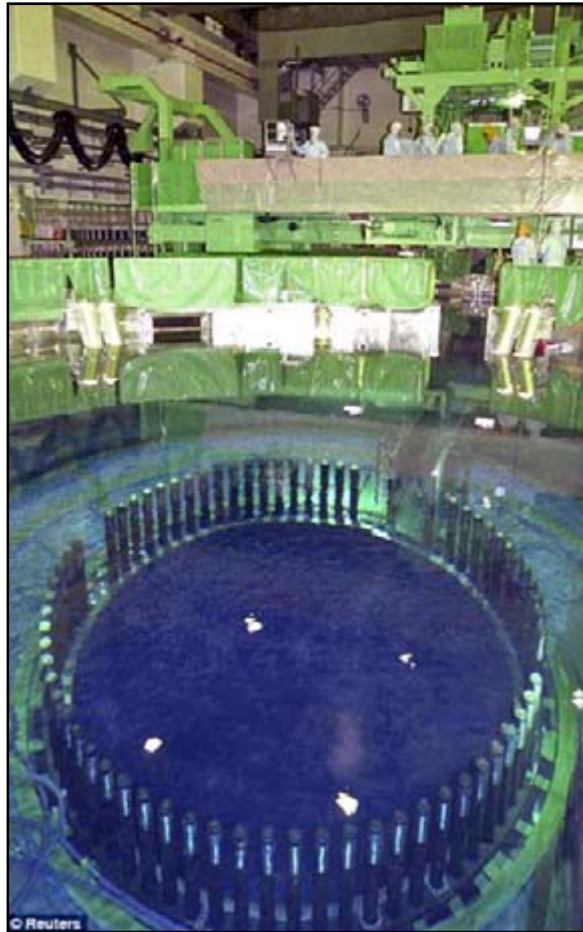
Primary Containment
(Drywell)

Pressure Suppression Pool
(Wetwell)

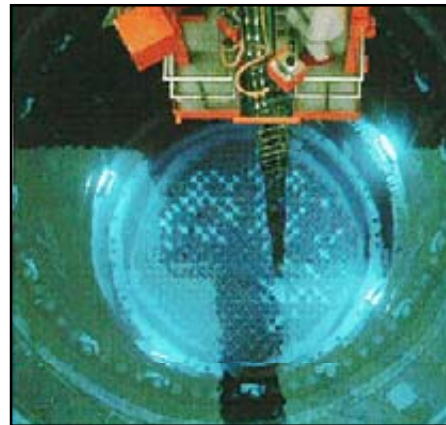
- Reactor: BWR-3
- Containment: Mark-I



Boiling Water Reactor Internals



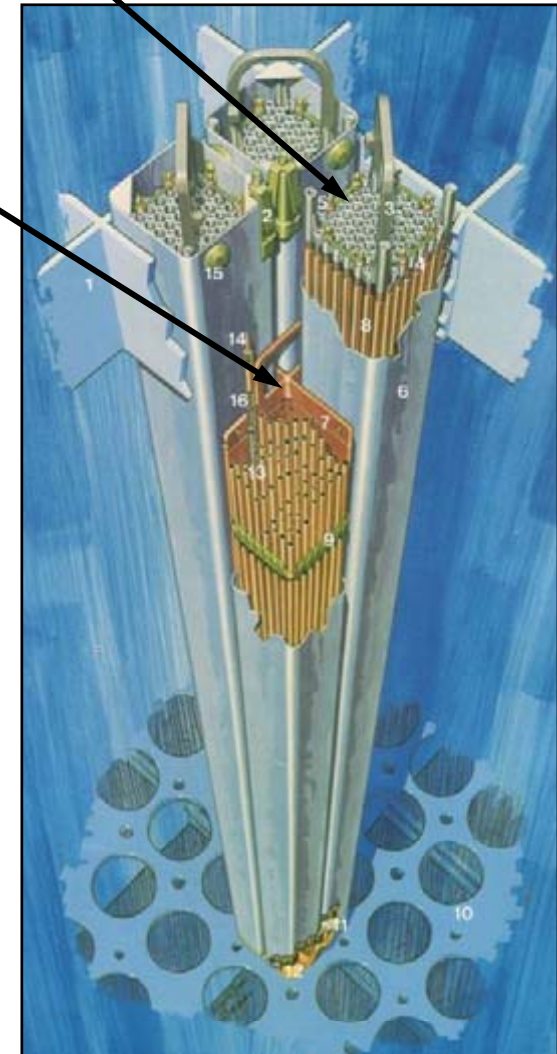
Reactor Building Internal View



Reactor Core

Fuel Assembly

Control Rod



Fuel Assemblies (4)

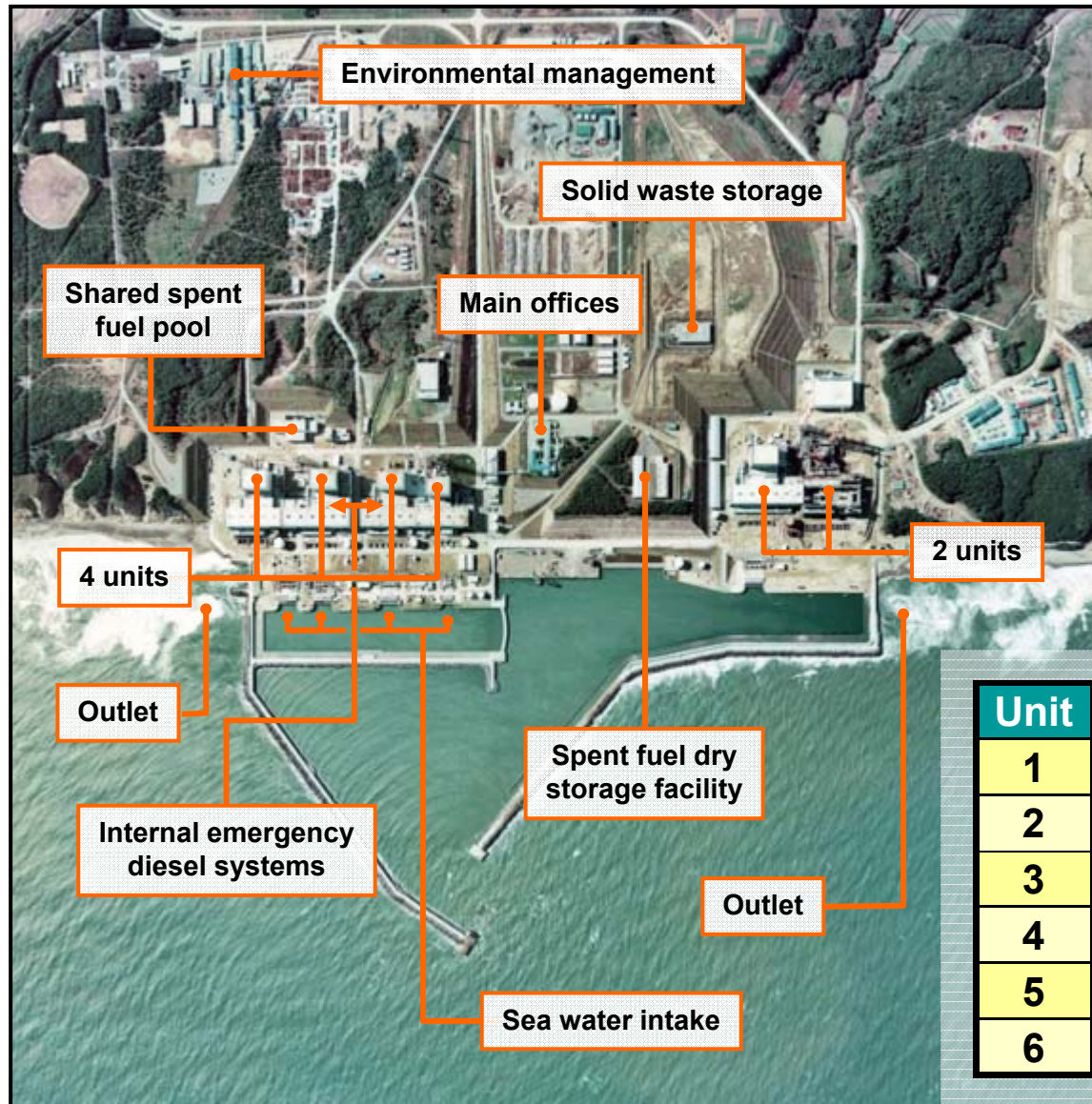
Fukushima Daiichi Aerial View



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

Fukushima Daiichi Site Layout

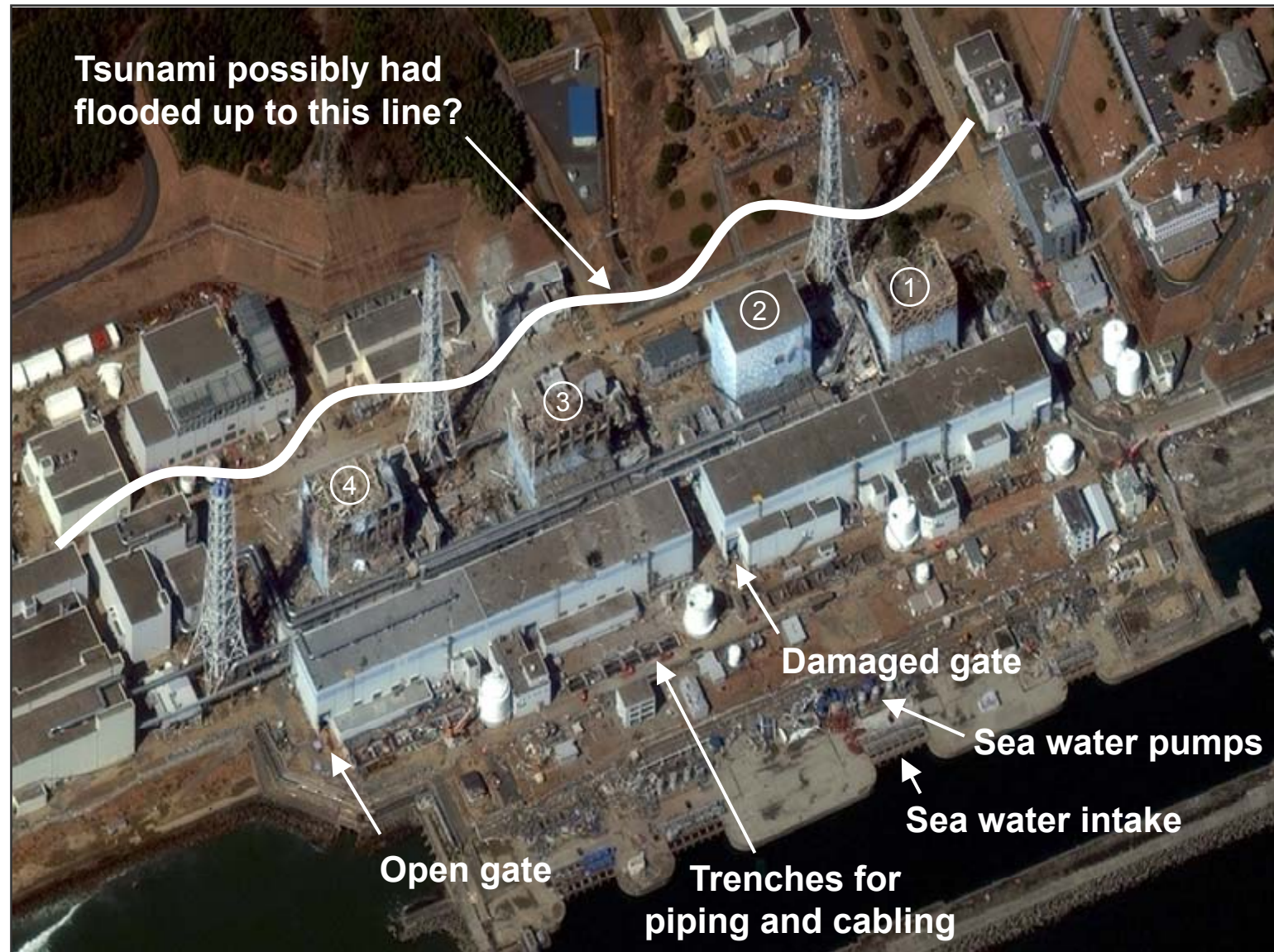


„Bird’s Eye Views“

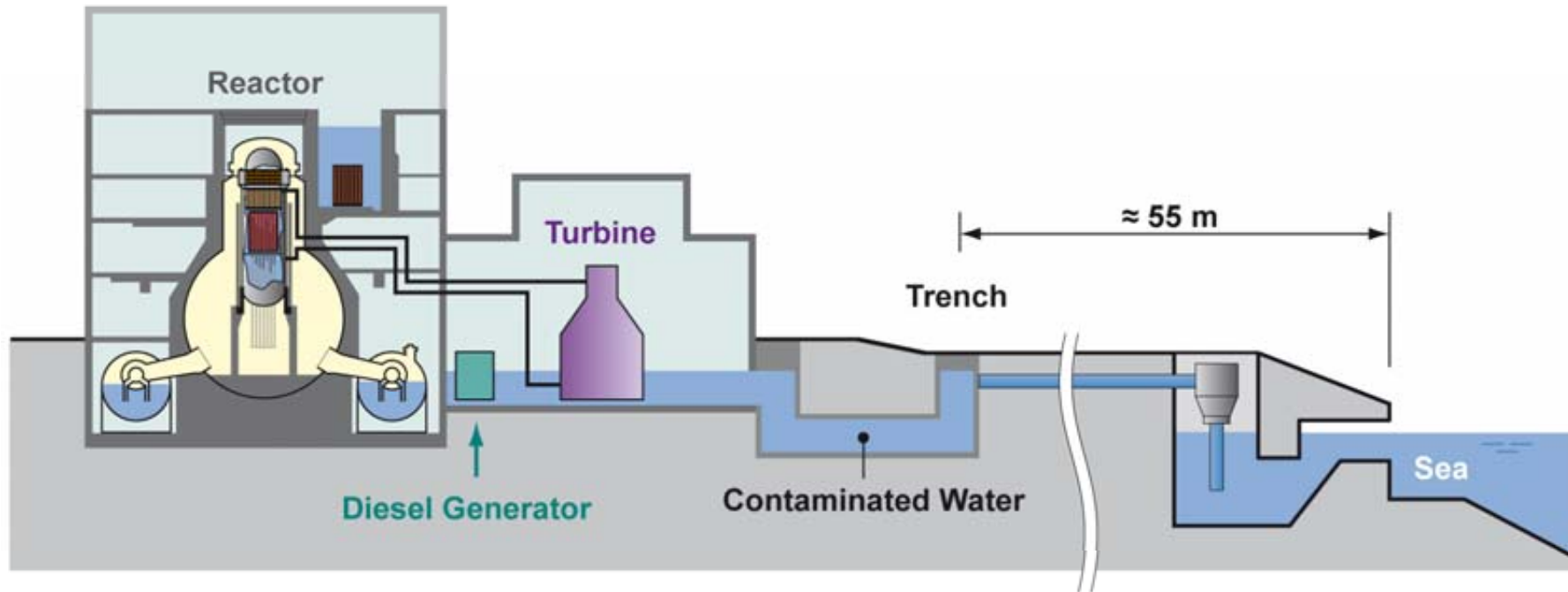


Unit	Year	Reactor	Containment
1	1971	BWR-3	Mark I
2	1974	BWR-4	Mark I
3	1976	BWR-4	Mark I
4	1978	BWR-4	Mark I
5	1978	BWR-4	Mark I
6	1979	BWR-5	Mark II

Fukushima-Daiichi After Tsunami

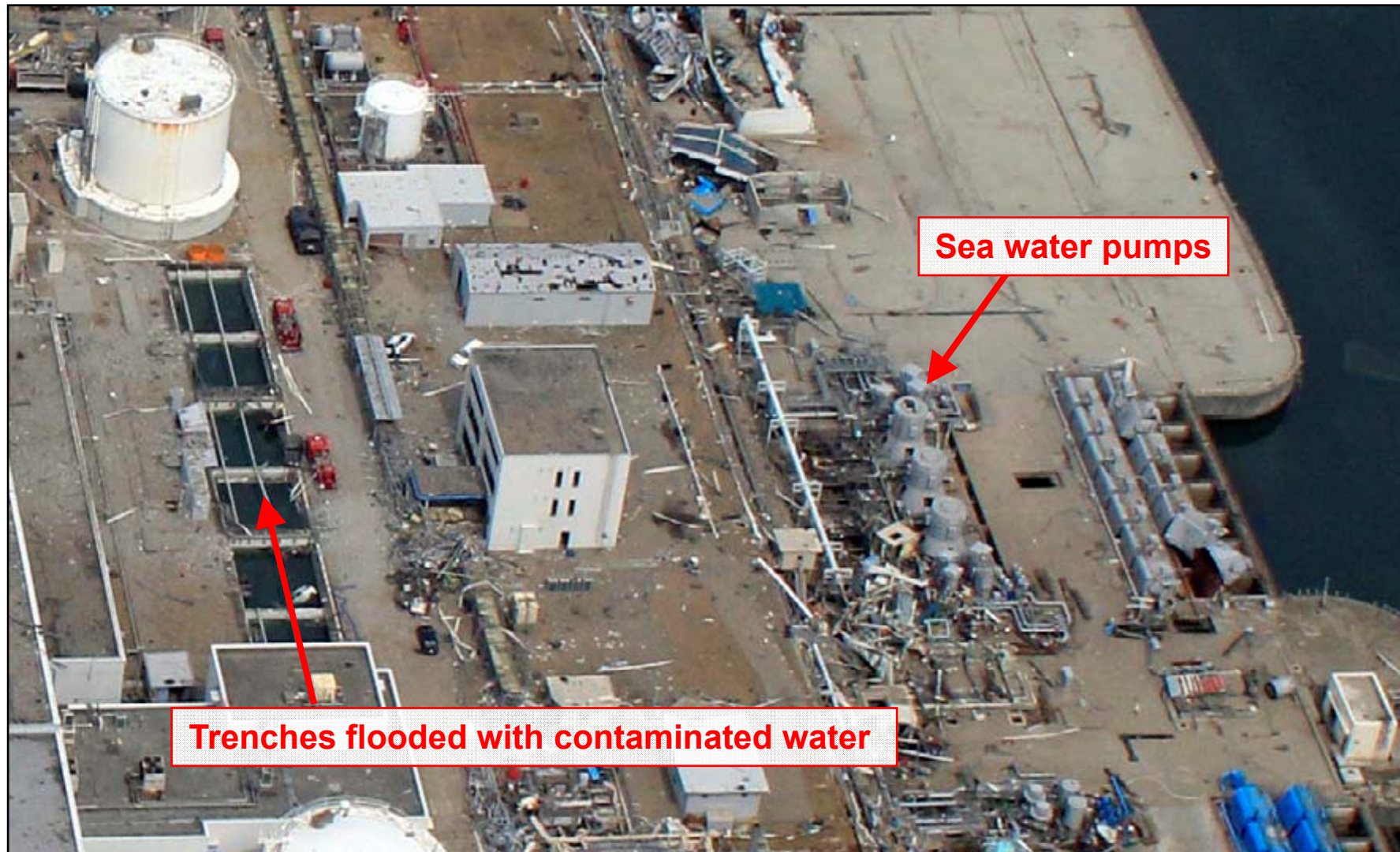


Flooded Trenches for Piping and Cabling



- ▶ 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.

Flooded Trenches for Piping and Cabling



The Fukushima Daiichi Accident

► 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:

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

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!

Severe Accident Management Measures



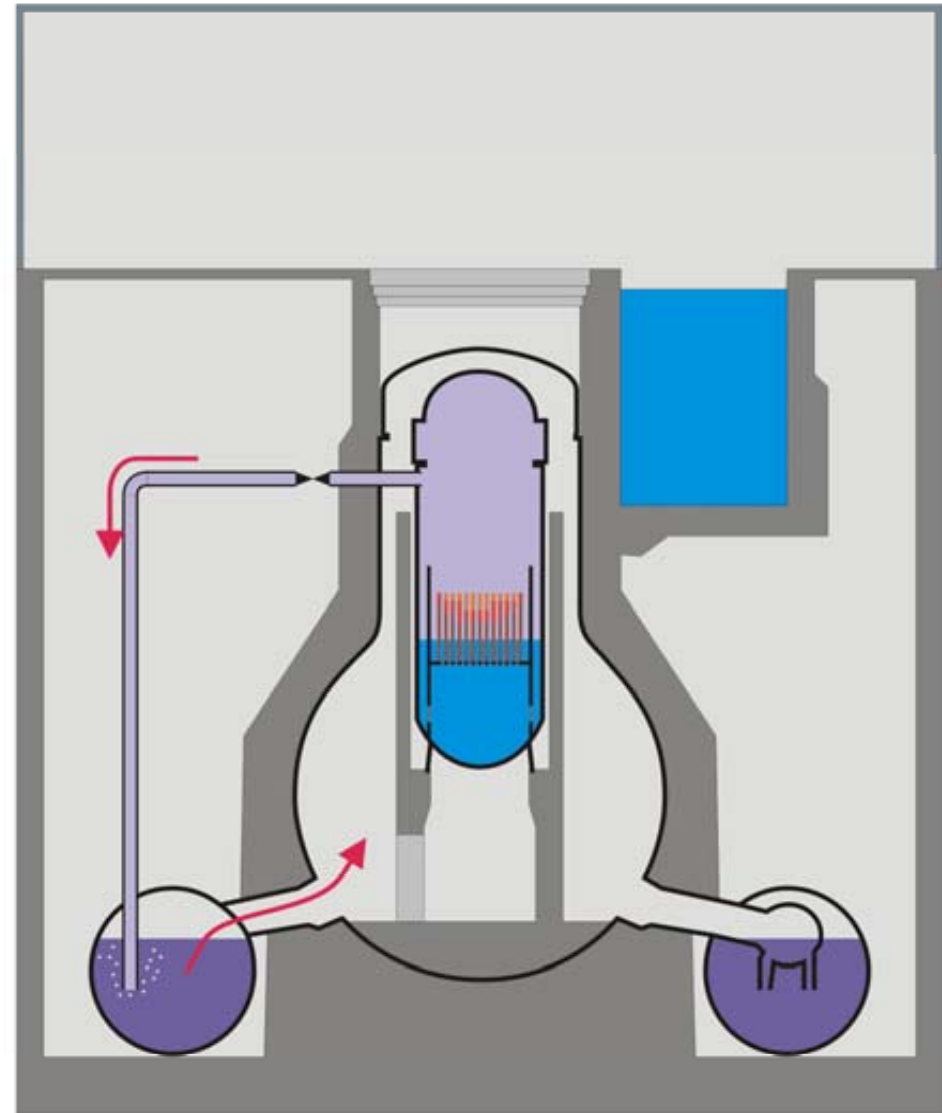
March 11, 2011, 14:46 JST ► Some hours later at Fukushima-Daiichi

- 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).

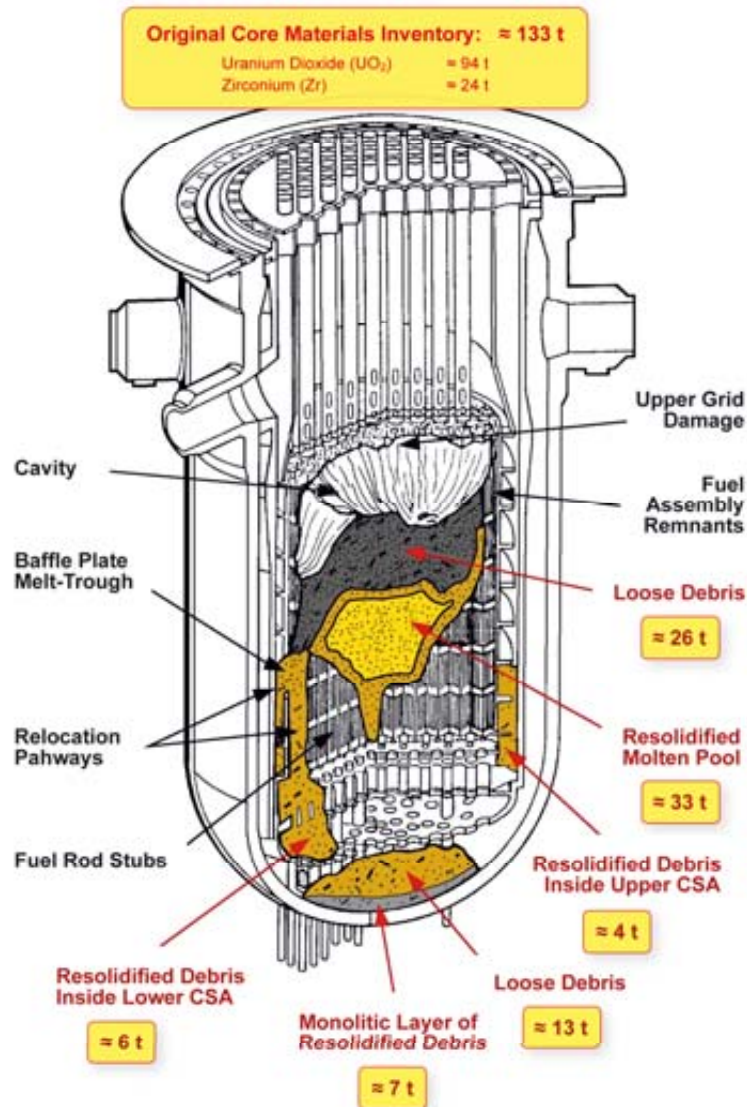
Event Sequence – Accident Progression

Temperature Escalation Phase

- ▶ About 75 % of the core cooled by steam only.
 - Cladding temperatures exceed $\approx 1200\text{ }^{\circ}\text{C}$.
 - Start of significant zirconium oxidation in steam atmosphere.
 $\text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2 + \text{Heat}$
 - Exothermal reaction leads to an additional core heatup.
 - Oxidation of 1 kg of zirconium generates $\approx 44.2\text{ g}$ 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.



TMI-2 Reactor Core Endstate Configuration



- **Post-accident analyses** indicated that ≈ 70 % of core materials had been displaced or damaged.

- **Total hydrogen mass** produced:

$$m \approx 459 \text{ kg}$$

This corresponds to a hydrogen volume of about 5500 to 6000 m³ 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	absolute temperature in K
V	volume

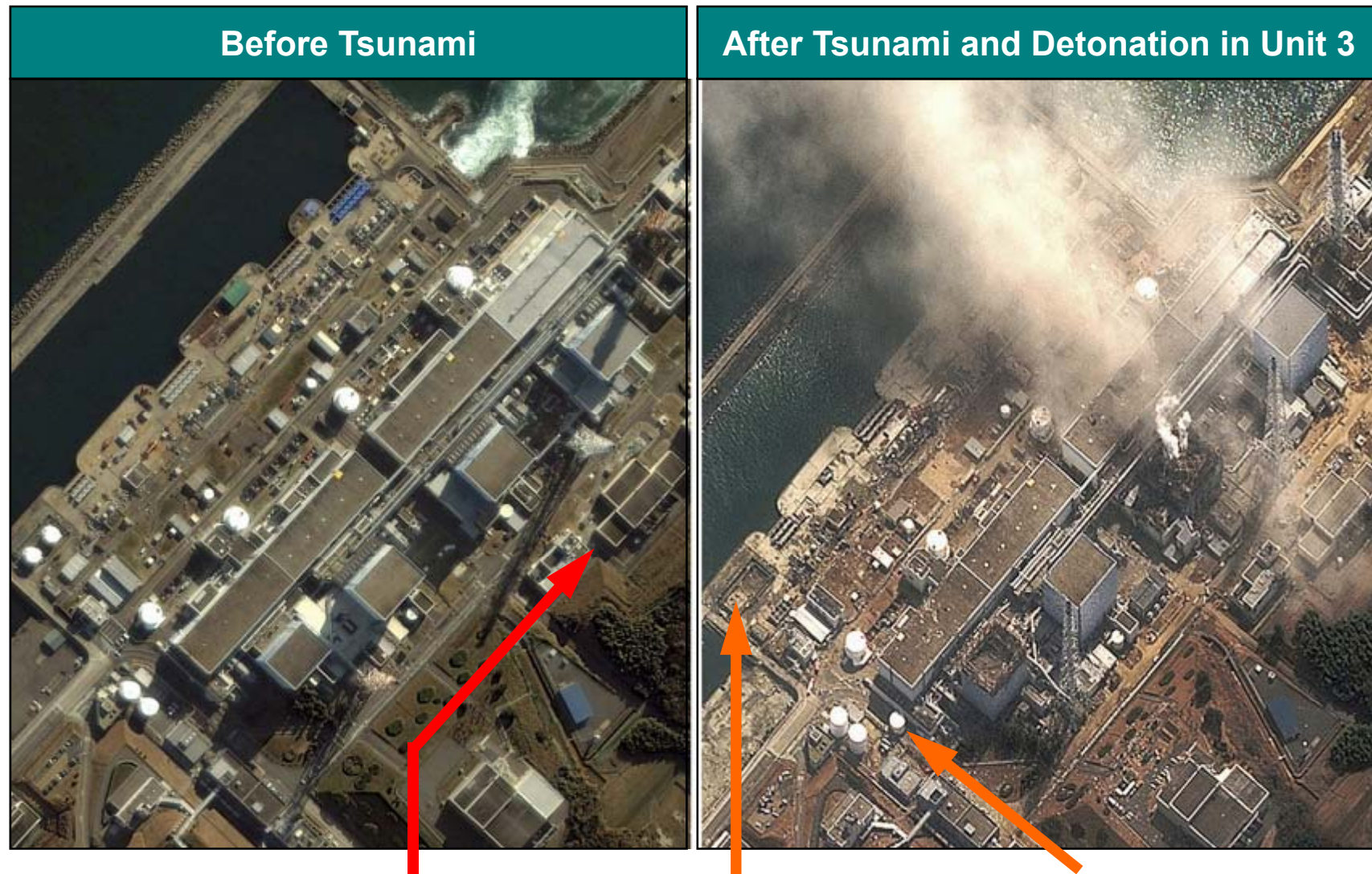
- **Complete oxidation** of the zirconium inventory would have led to a hydrogen mass of ≈ 1061 kg.

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).



Aerial Views at Fukushima Daiichi



Shared spent fuel pool building

Missing heavy oil tanks

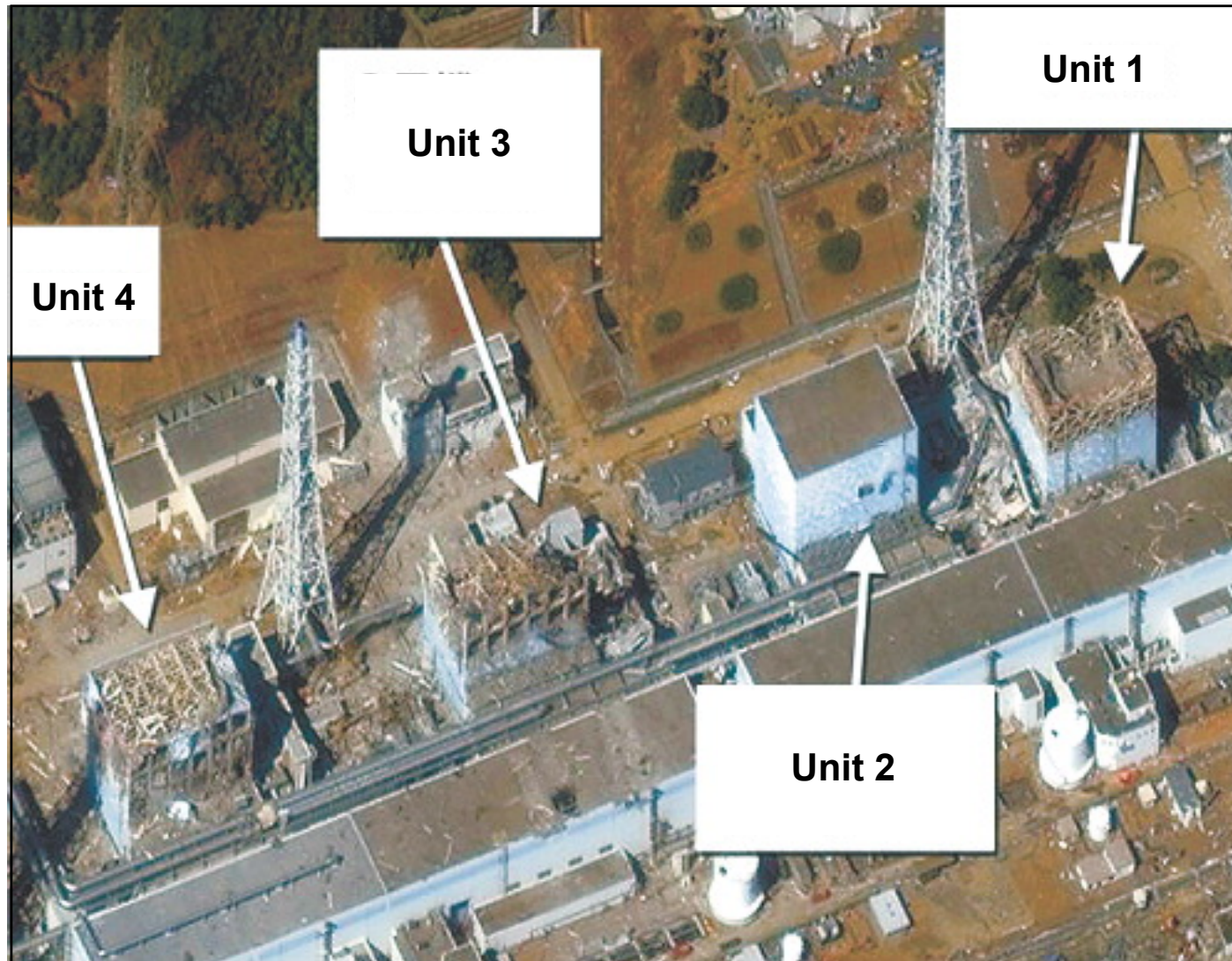
Displaced oil tank?

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!**

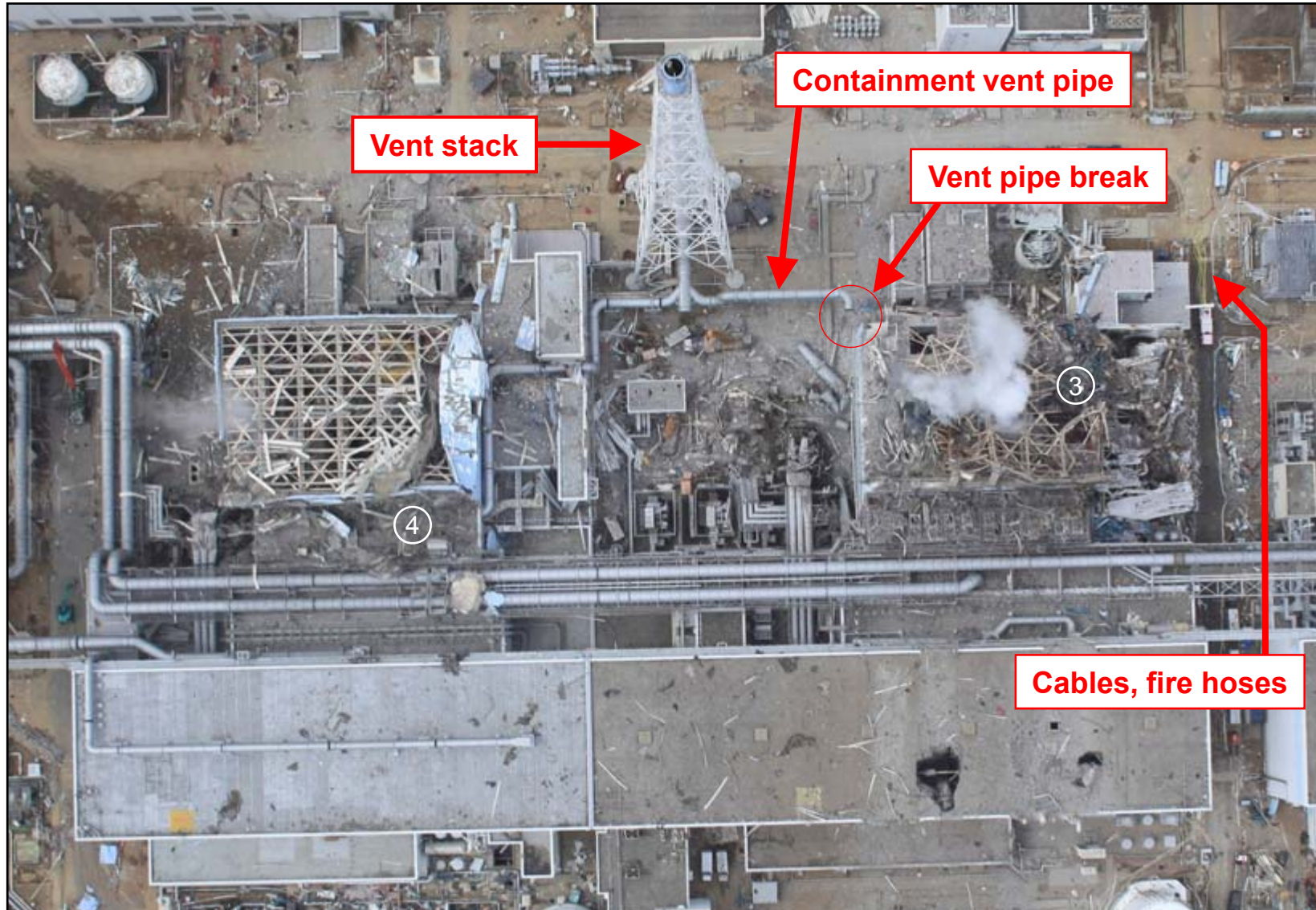
Units 1 to 4 after Hydrogen Explosions



Aerial View after Hydrogen Explosions



Aerial View after Hydrogen Explosions



TODAY IN ENERGY

[HOME](#)

[BROWSE BY TAG ▾](#)

[PRICES](#)

[ARCHIVE](#)

[ABOUT](#)

[GLOSSARY ›](#)

[FAQS ›](#)

 [Email Updates](#)

 [RSS Feeds](#)

 [Facebook](#)

 [Twitter](#)

 [YouTube](#)

 [Add us to your site](#)

Have a question, comment, or
suggestion for a future article?
Send your feedback to
todayinenergy@eia.gov

Archive

▾ 2017

- [February](#)
- [January](#)

▸ 2016

▸ 2015

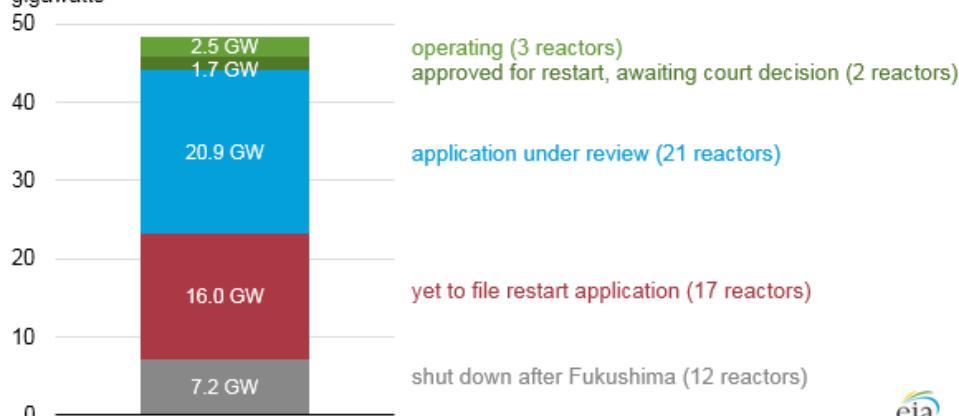
▸ 2014

SEPTEMBER 13, 2016

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

Current status of nuclear capacity in Japan (as of August 2016)

gigawatts



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

Nuclear Power in Japan

(Updated August 2023)

- 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 plan is now for at least 20% by 2030, from a depleted fleet.
- The first two reactors restarted in August and October 2015, with a further nine having restarted since. 16 reactors are currently in the process of restart approval.

Operable Reactors



31,679 MWe

Reactors Under Construction



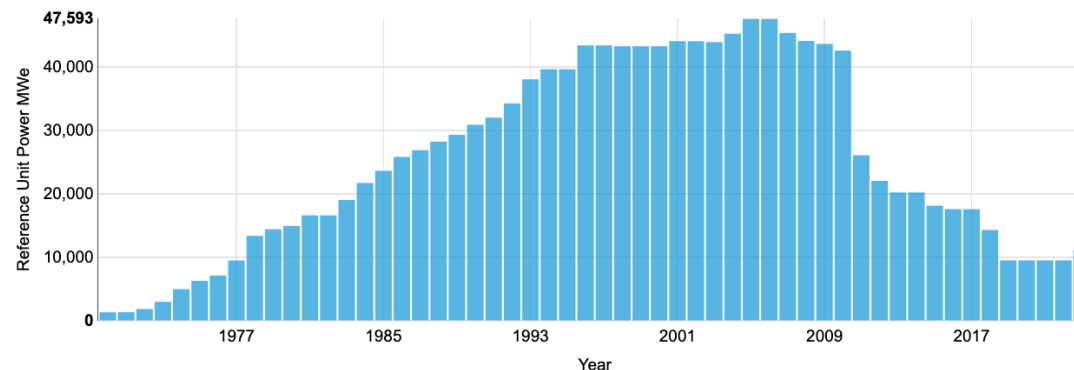
2,653 MWe

Reactors Shutdown



17,128 MWe

Operable nuclear power capacity



Contents

[Electricity sector](#)

[Nuclear power industry](#)

[Energy policy](#)

[Reactor development, 1970 onwards](#)

[Licence extension and 30-year reviews](#)

[Particular plants: under construction and planned](#)

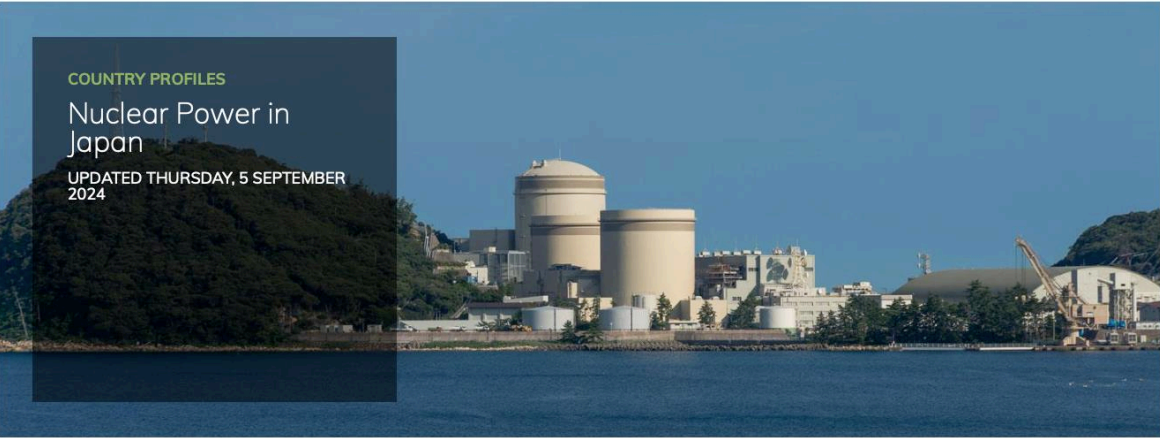
[Fast neutron reactors](#)

[Public opinion](#)

[Notes & references](#)

[Related Information](#)

<https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx>



COUNTRY PROFILES

Nuclear Power in Japan

UPDATED THURSDAY, 5 SEPTEMBER 2024

- 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 plan is now for at least 20% by 2030, from a depleted fleet.
- The first two reactors restarted in August and October 2015, with a further 10 having restarted since. 13 reactors are currently in the process of restart approval.

Contents

Electricity sector

Nuclear power industry

Energy policy

Reactor development, 1970 onwards

Licence extension and 30-year reviews

Particular plants: under construction and planned

Fast neutron reactors

Public opinion

Notes & references

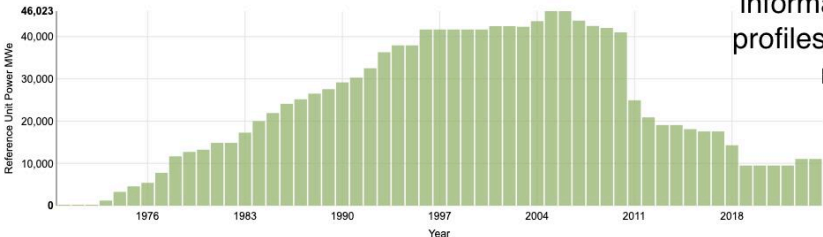
Related Information

33
OPERABLE REACTORS
31,679 MWe

2
REACTORS UNDER CONSTRUCTION
2,653 MWe

27
REACTORS SHUTDOWN
17,155 MWe

Operable nuclear power capacity



<https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power>

Operable reactors in Japan

Name	Model	Reactor Type	Reference Unit Power (MWe)	Grid Connection
Genkai 3	M (4-loop)	PWR	1,127	1993-06
Genkai 4	M (4-loop)	PWR	1,127	1996-11
Hamaoka 3	BWR-5	BWR	1,056	1987-01
Hamaoka 4	BWR-5	BWR	1,092	1993-01
Hamaoka 5	ABWR	BWR	1,325	2004-04
Higashi Dori 1 (Tohoku)	BWR-5	BWR	1,067	2005-03
Ikata 3	M (3-loop)	PWR	846	1994-03
Kashiwazaki Kariwa 1	BWR-5	BWR	1,067	1985-02
Kashiwazaki Kariwa 2	BWR-5	BWR	1,067	1990-02
Kashiwazaki Kariwa 3	BWR-5	BWR	1,067	1992-12
Kashiwazaki Kariwa 4	BWR-5	BWR	1,067	1993-12
Kashiwazaki Kariwa 5	BWR-5	BWR	1,067	1989-09
Kashiwazaki Kariwa 6	ABWR	BWR	1,315	1996-01
Kashiwazaki Kariwa 7	ABWR	BWR	1,315	1996-12
Mihama 3	M (3-loop)	PWR	780	1976-02
Ohi 3	M (4-loop)	PWR	1,127	1991-06
Ohi 4	M (4-loop)	PWR	1,127	1992-06
Onagawa 2	BWR-5	BWR	796	1994-12
Onagawa 3	BWR-5	BWR	796	2001-05
Sendai 1	M (3-loop)	PWR	846	1983-09
Sendai 2	M (3-loop)	PWR	846	1985-04
Shika 1	BWR-5	BWR	505	1993-01
Shika 2	ABWR	BWR	1,108	2005-07
Shimane 2	BWR-5	BWR	789	1988-07
Takahama 1	M (3-loop)	PWR	780	1974-03
Takahama 2	M (3-loop)	PWR	780	1975-01
Takahama 3	M (3-loop)	PWR	830	1984-05
Takahama 4	M (3-loop)	PWR	830	1984-11
Tokai 2	BWR-5	BWR	1,060	1978-03
Tomari 1	M (2-loop)	PWR	550	1988-12
Tomari 2	M (2-loop)	PWR	550	1990-08
Tomari 3	M (3-loop)	PWR	866	2009-03
Tsuruga 2	M (4-loop)	PWR	1,108	1986-06

Status of nuclear power plants in Japan

Reactor	Status	Type	Applied	Basic design	Detailed design	Safety programme	Pre-service inspection	Restart date (commercial operation)
Genkai 3	OP	PWR	July 2013	Jan 2017	Aug 2017	Sept 2017	CO	May 2018
	After installation of the specialized safety facility (SSF), Genkai 3 started supplying power to the grid again in December 2022 and returned to commercial operation in January 2023.							
Genkai 4	OP	PWR	July 2013	Jan 2017	Sept 2017	Sept 2017	CO	June 2018
	Periodic inspection from Sept 2022 to Feb 2023, the deadline for the installation of the SSF. Successful installation of SSF announced in Feb 2023. Power generation resumed in Feb 2023, return to commercial operation expected in March 2023.							
Hamaoka 3	OP	BWR	June 2015	UR	NA	NA		
Hamaoka 4	OP	BWR	Feb 2014	UR	UR	UR		
Higashidori 1 Tohoku	OP	BWR	June 2014	UR	UR	UR		
Ikata 3	OP	PWR	July 2013	July 2015	Mar 2016	Apr 2016	CO	Sept 2016
Kashiwazaki-Kariwa 6	OP	ABWR	Sept 2013	Dec 2017	UR	UR		
Kashiwazaki-Kariwa 7	OP	ABWR	Sept 2013	Dec 2017	Oct 2020	Oct 2020	UR	
	End date of work on safety measures is undecided.							
Mihama 3	OP	PWR	Mar 2015	Oct 2016	Oct 2016	Nov 2016	CO	June 2021
	The NRA approved a 20-year licence extension (beyond the 40-year initial licence period) in Nov 2016. Work on safety measures completed Sept 2020. Final approval for restart granted Apr 2021. Restarted June 2021. Shutdown Oct 2021 due to missing the deadline for the installation of the SSF, which was later completed on 28 July 2022.. Restart delayed due to water leak in auxiliary reactor building. Restarted in September 2022.							

Ohi 3	OP	PWR	July 2013	May 2017	Aug 2017	Sept 2017	CO	Apr 2018
	Shut down in Aug 2022 due to the deadline of the installation of SSF on 24 August 2022. Power generation resumed in January 2023.							
Ohi 4	OP	PWR	July 2013	May 2017	Aug 2017	Sept 2017	CO	June 2018
Onagawa 2	OP	BWR	Dec 2013	Feb 2020	Dec 2021	Dec 2021	CO	
	Work on safety measures is ongoing. Power generation scheduled to resume in September 2024.							
Sendai 1	OP	PWR	July 2013	Sept 2014	Mar 2015	May 2015	CO	Aug 2015
Sendai 2	OP	PWR	July 2013	Sept 2014	May 2015	May 2015	CO	Nov 2015
Shika 2	OP	ABWR	Aug 2014	UR	UR	UR		Expected January-March 2026
Shimane 2	OP	BWR	Dec 2013	Sept 2021	UR	UR	UR	
	Work on safety measures is ongoing. Power generation scheduled to resume in August 2024.							
Takahama 1	OP	PWR	Mar 2015	Apr 2016	June 2016	Feb 2021	CO	August 2023
Takahama 2	OP	PWR	Mar 2015	Apr 2016	June 2016	CO	CO	September 2023
Takahama 3	OP	PWR	July 2013	Feb 2015	Aug 2015	Oct 2015	CO	Feb 2016
Takahama 4	OP	PWR	July 2013	Feb 2015	Oct 2015	Oct 2015	CO	June 2017
Tokai 2	OP	BWR	May 2014	Sept 2018	Oct 2018	UR	UR	
	The NRA approved a 20-year licence extension (beyond the 40-year initial licence period) in November 2018. Work on safety measures including the installation of specialized safety facility (SSF) was to be completed in September 2024. In October 2023 JAPC suspended construction works for the unit when multiple gaps near the seawall's steel reinforcement pillars were discovered. JAPC had originally planned to restart Tokai 2 by 2025.							
Tomari 1	OP	PWR	July 2013	UR	UR	UR		
Tomari 2	OP	PWR	July 2013	UR	UR	UR		
Tomari 3	OP	PWR	July 2013	UR	UR	UR		
Tsuruga 2	OP	PWR	Nov 2015	UR	NA	UR		
Japan's Nuclear Regulation Authority concluded in July 2024 that unit does not comply with regulatory safety standards due to active fault running under facility.								
Total applied restart			25					12
Ohma	UC	ABWR	Dec 2014	UR	UR	NA		
Shimane 3	UC	ABWR	Aug 2018	UR	NA	NA		

JAPAN / FOCUS

Japan shifting back to nuclear to ditch coal and power AI



A Tokyo Electric Power Co. employee opens a watertight door inside the Unit 7 reactor building at the Kashiwazaki-Kariwa nuclear power station in Kashiwazaki, Niigata Prefecture, on Aug. 6. | AFP-JIJI

BY SIMON STURDEE
AFP-JIJI

🔗 SHARE/SAVE Oct 19, 2024

WHAT'S TRENDING

EDITORS' PICKS

Tokyo court upholds dual nationality ban, rejecting teen's citizenship case



Wise becomes first foreign firm to gain direct access to Japan's payment clearing network



Mid- to long-term foreign residents in Japan hit record high



Australian man claiming language mix-up jailed over Tokyo break-in

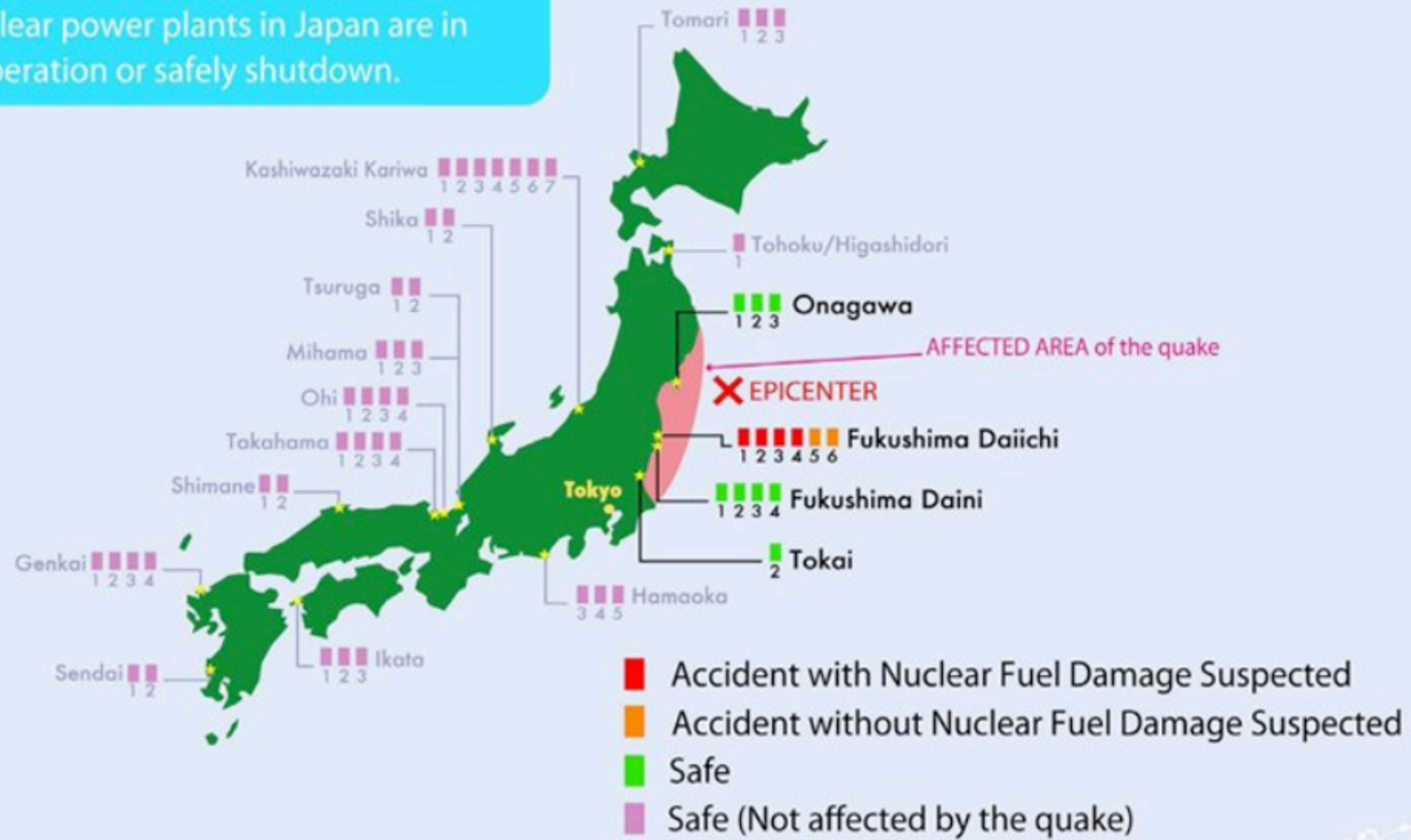


Shohei Ohtani making major impact on viewership numbers during MLB playoffs



Map reveals status of Japan's 54 nuclear reactors

Every efforts and measures have been taken at Fukushima Daiichi nuclear power plants. Other nuclear power plants in Japan are in normal operation or safely shutdown.





Hamaoka Nuclear Power Plant



Hamaoka Nuclear Power Plant

浜岡原子力発電所

2.9 ★★★★★ 77 reviews

Nuclear power plant



Directions



Save



Nearby



Send to your
phone



Share



5561 Sakura, Omaezaki, Shizuoka 437-1604,
Japan



〒437-1604 静岡県御前崎市佐倉 5 5 6 1



Open now: 9AM–5PM



chuden.co.jp



+81 537-86-3481



Claim this business



Add a label



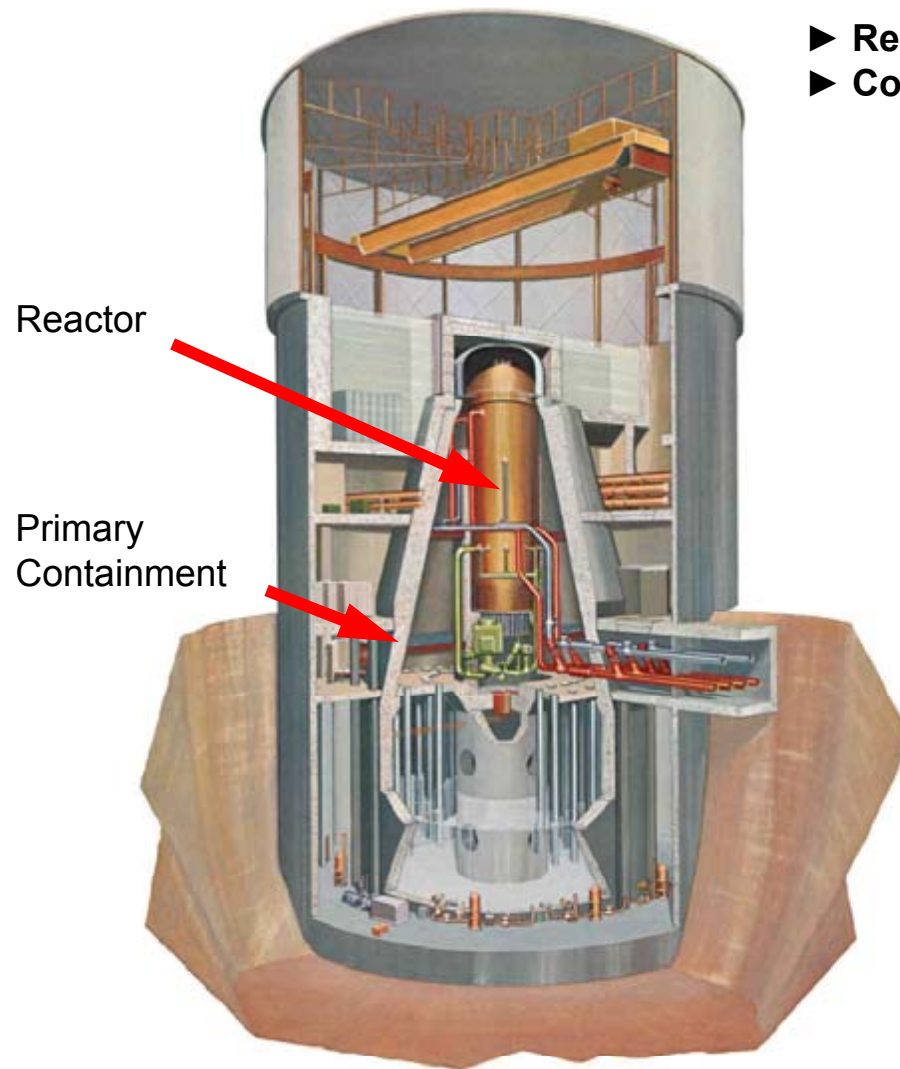
Suggest an edit



Google

Design of Fukushima Daiichi Unit 6

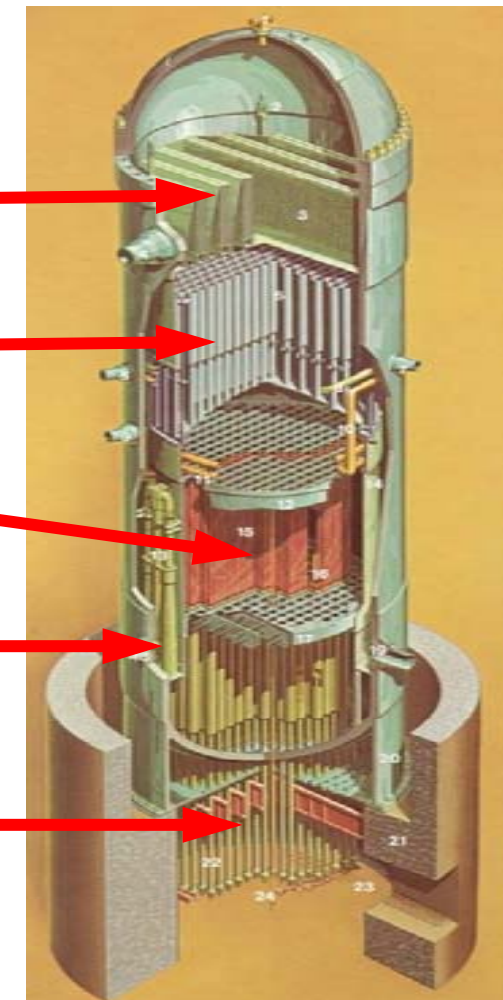
- **Reactor:** BWR-5
- **Containment:** Mark-II



GENERAL ELECTRIC

- Steam Dryer
- Water/Steam-Separator
- Reactor Core Fuel Assemblies
- Internal Jet Pumps
- Control Rods

Reactor Pressure Vessel



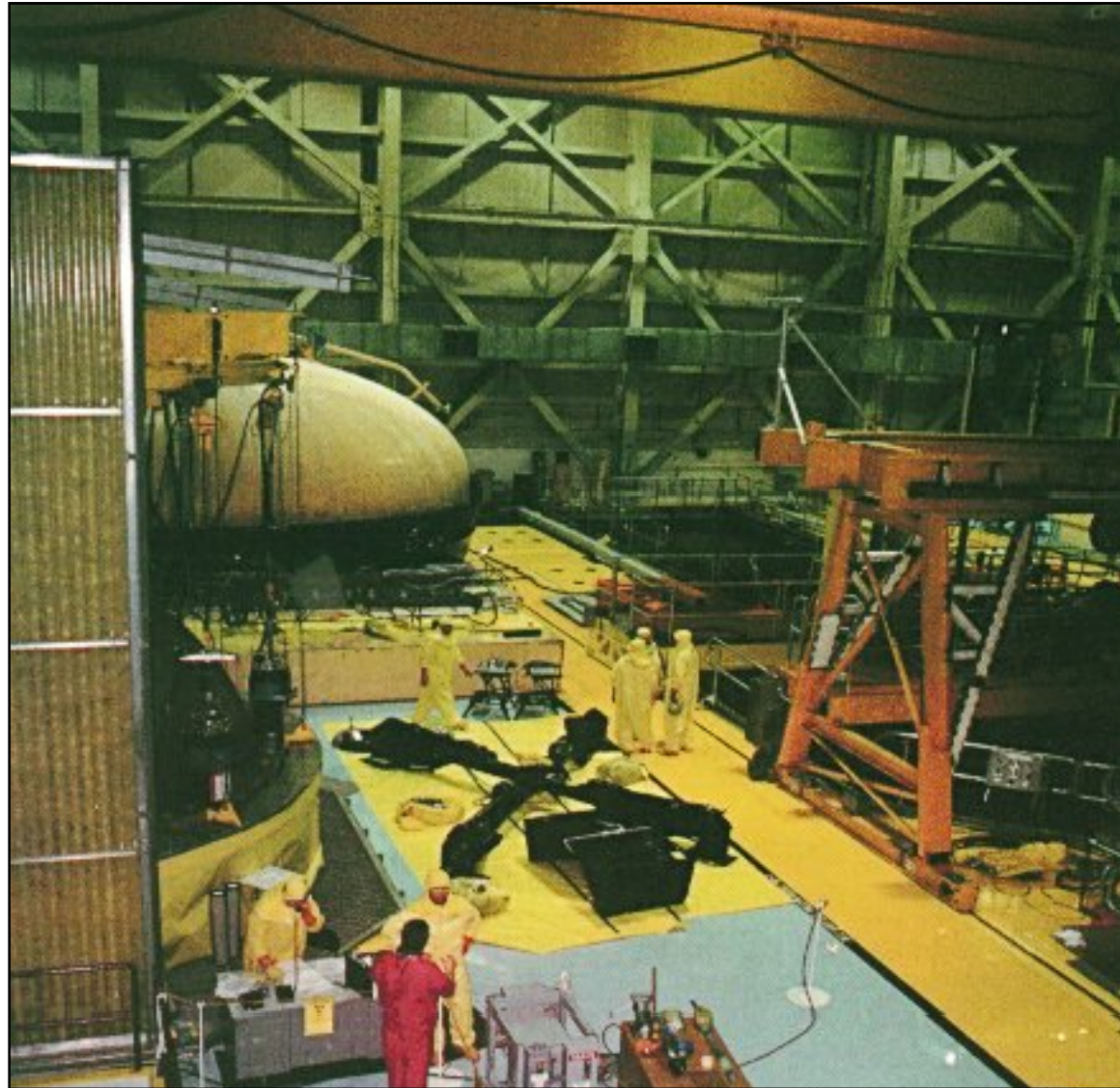
Service Floor of Fukushima Daiichi Unit 1



Service Floor with Primary Containment Head

35

VGB
POWERTECH



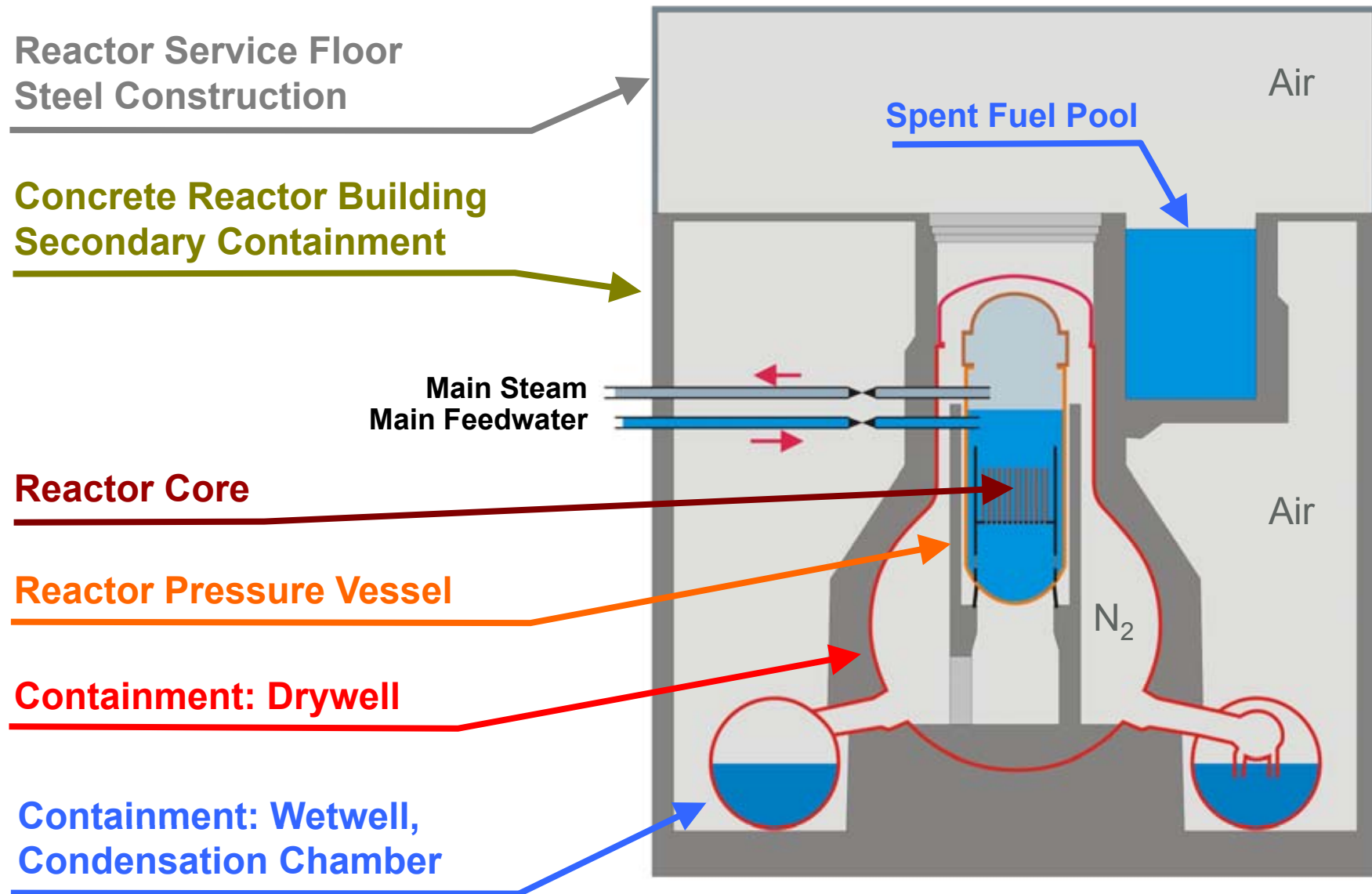
Source: www.nucleartourist.com

Reactor Pressure Vessel Head



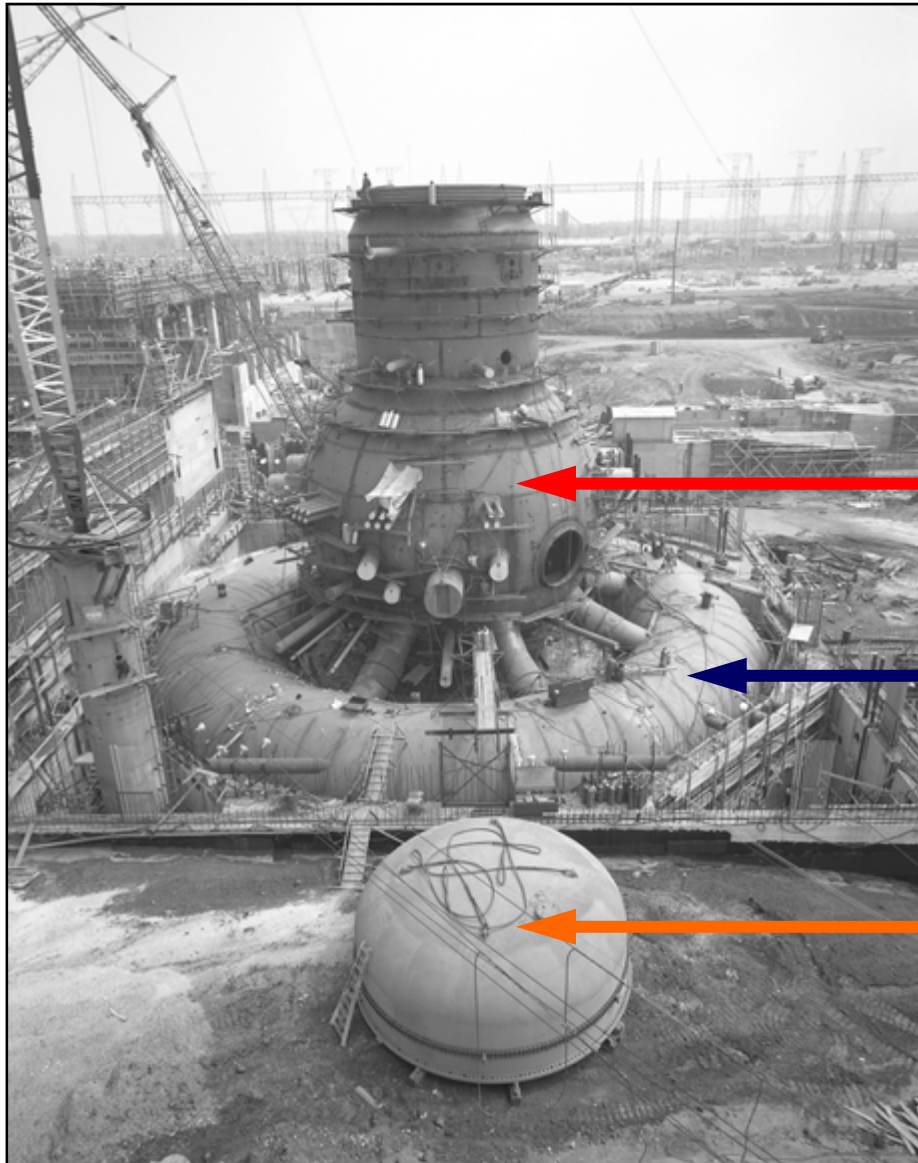
Plant Design

VGB
POWERTECH



Primary Containment Construction Phase

Design: Mark-I



Primary containment

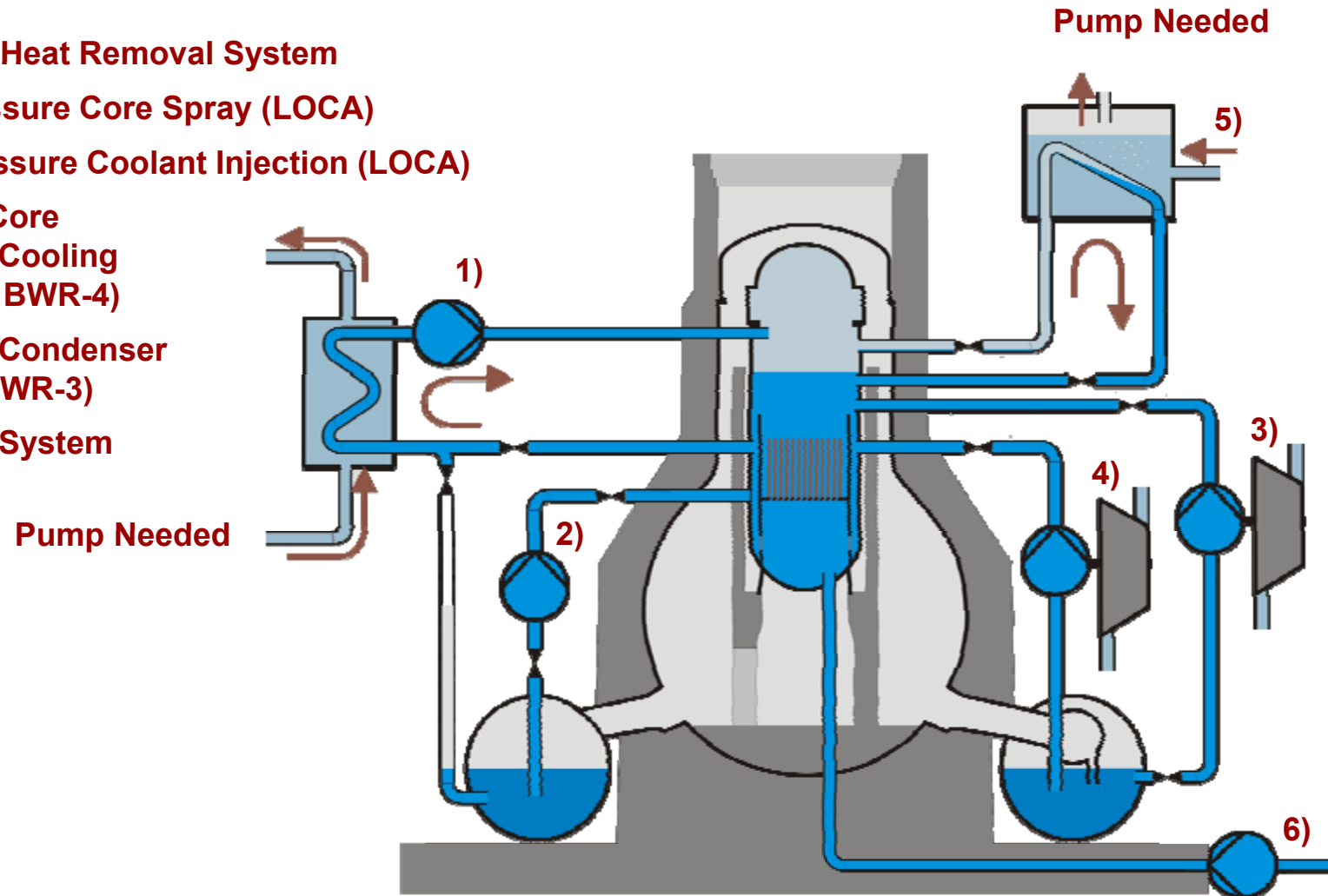
Pressure suppression pool

Containment closure head

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



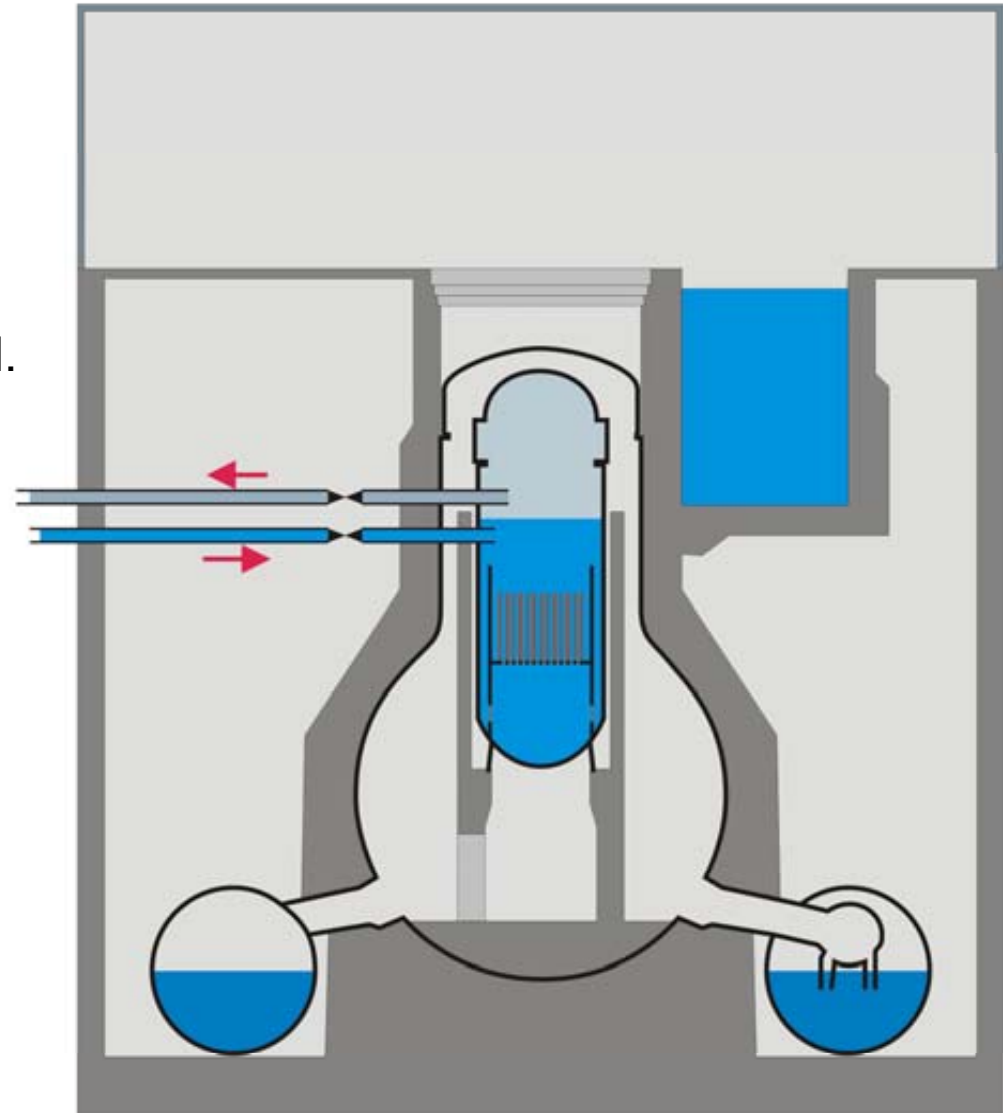
Event Sequence – Accident Progression

► 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 $\approx 6\%$
 - after 1 day $\approx 1\%$
 - after 5 days $\approx 0.5\%$



Event Sequence – Accident Progression

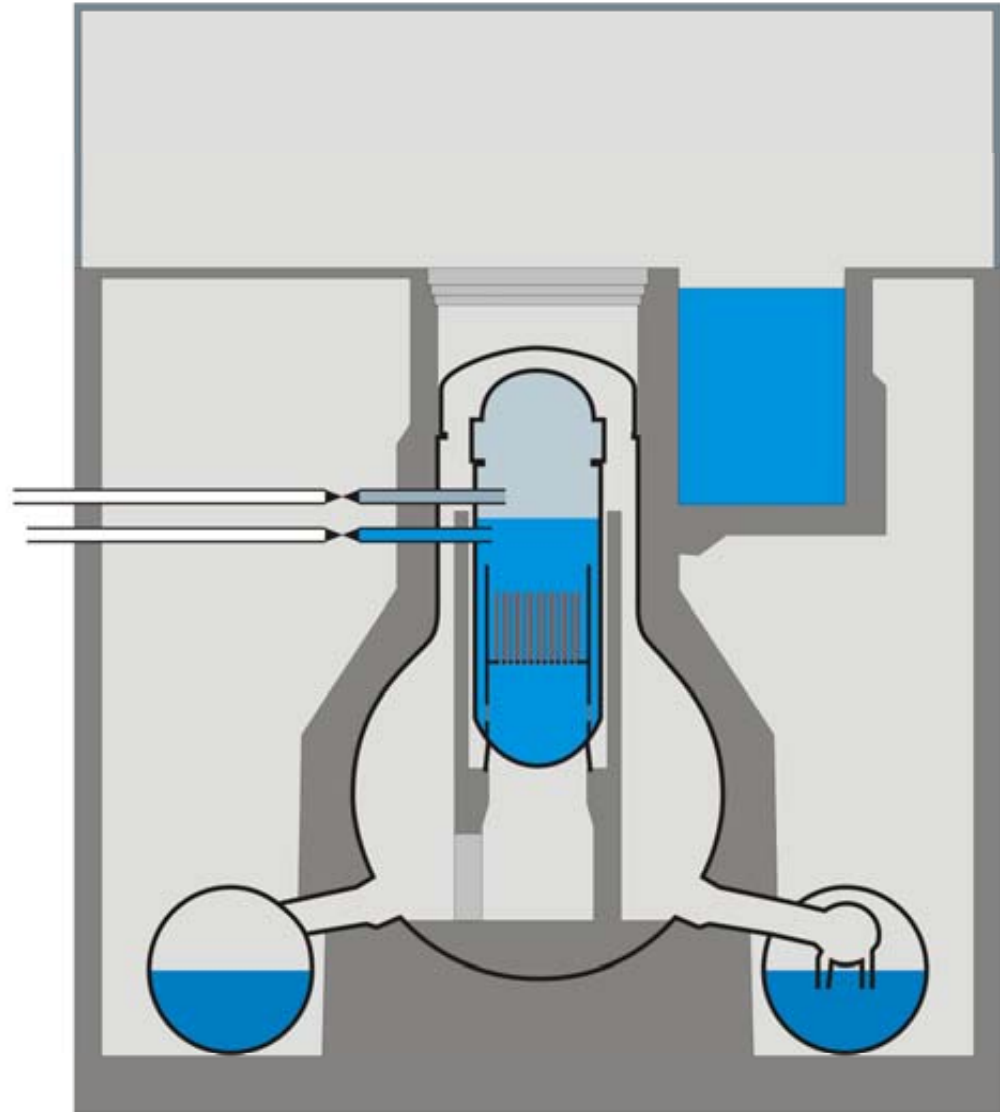
► Containment Isolation

- 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



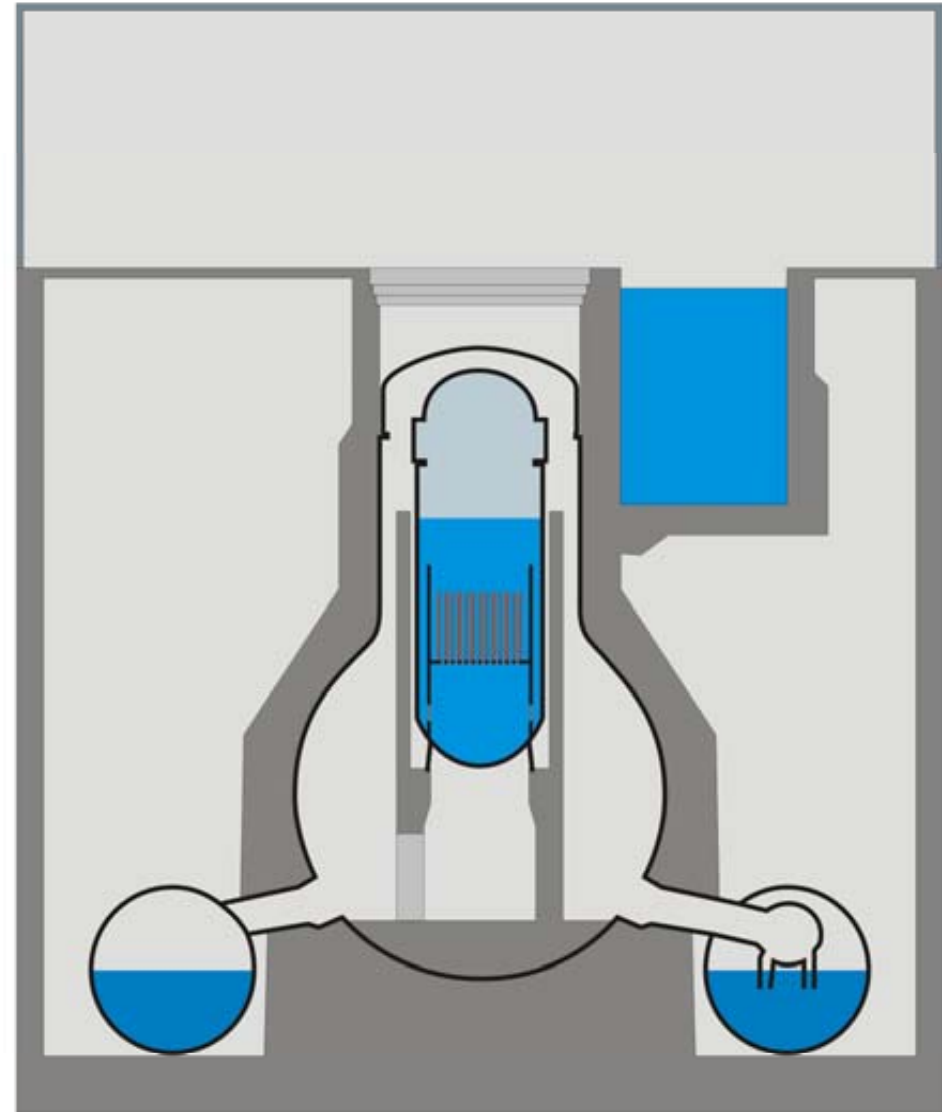
Event Sequence – Accident Progression

► 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.

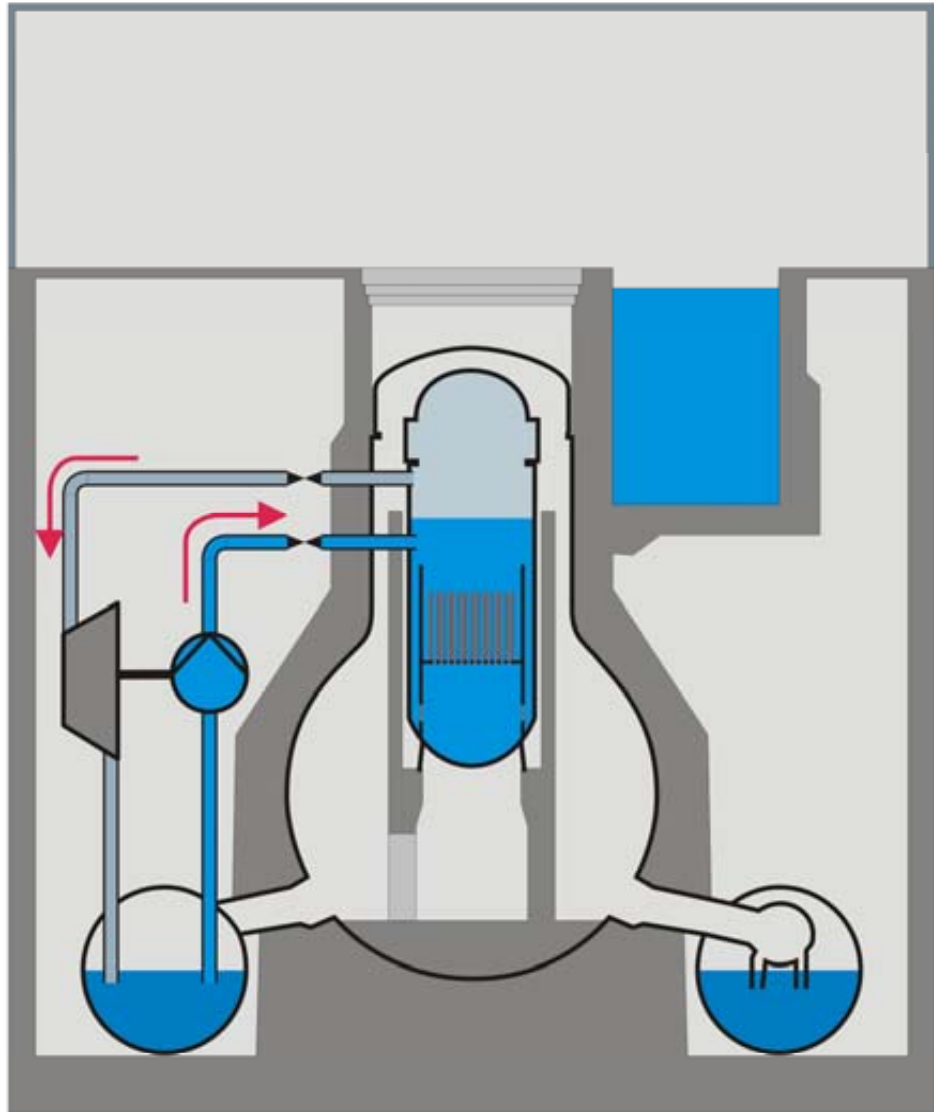


Event Sequence – Accident Progression

► 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.



Event Sequence – Accident Progression

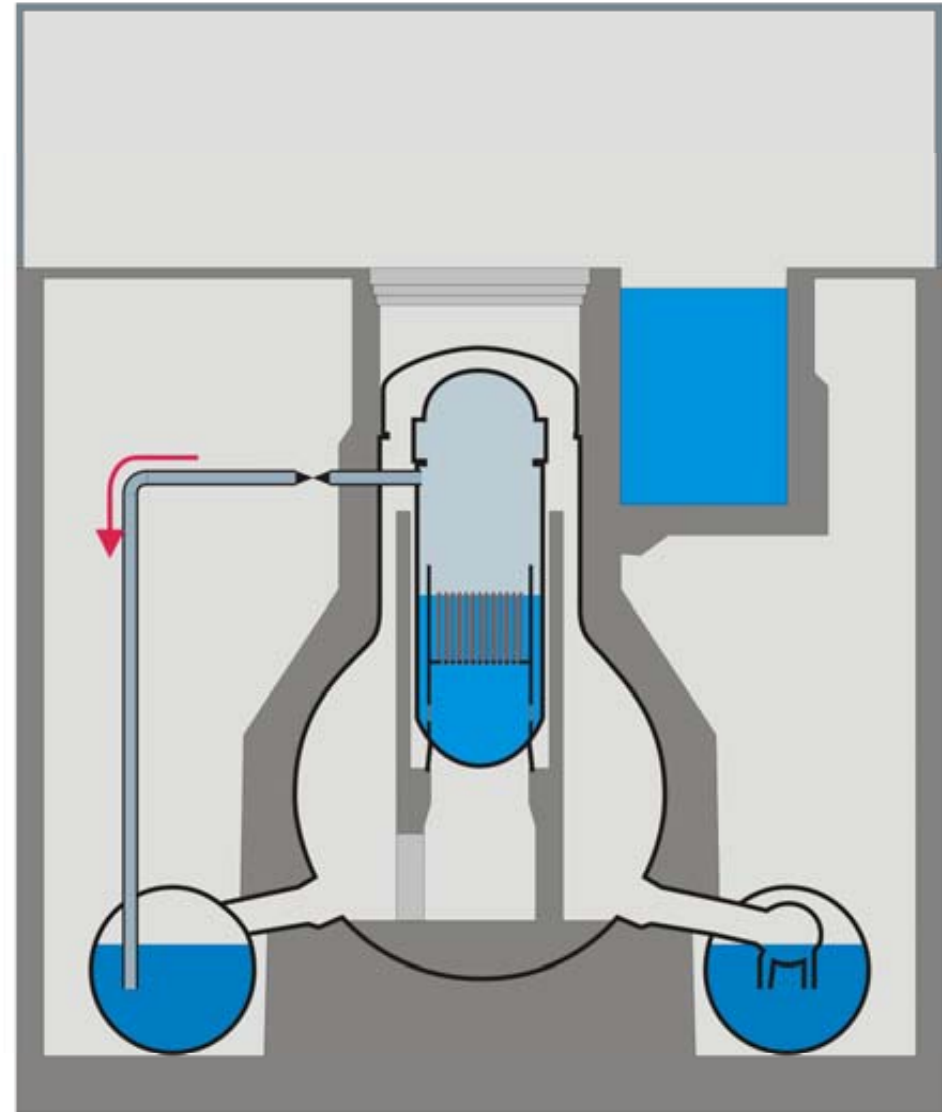
► Reactor Core Isolation Pump Stop

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

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

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

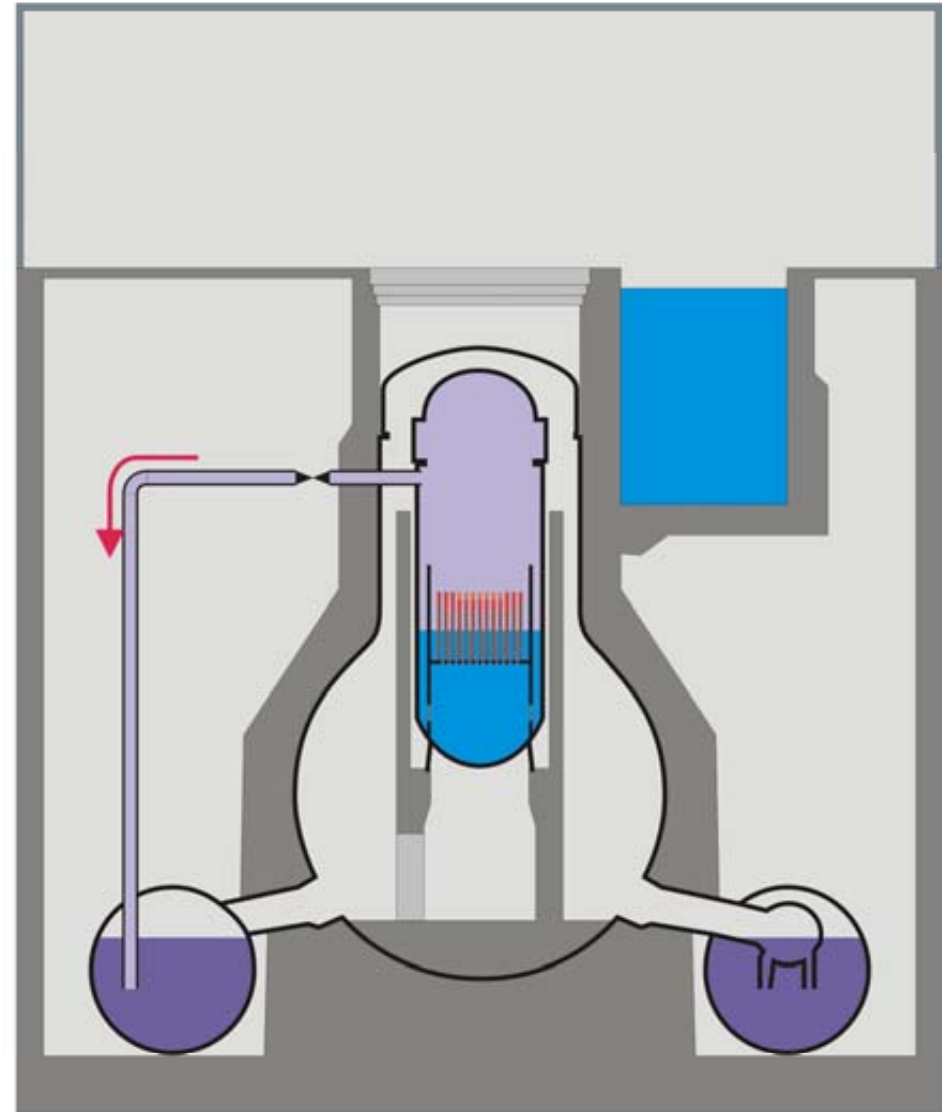
- **Decay heat** still produces steam in the reactor pressure vessel, leading to a pressure rise.
- **Steam discharge** into the wetwell due to steam relieve valve opening.
- **Decreasing liquid level** within the reactor pressure vessel.
- The measured liquid level is the „static” level. The actual swell level is higher due to steam bubbles in the liquid phase.



Event Sequence – Accident Progression

Core Heatup Phase

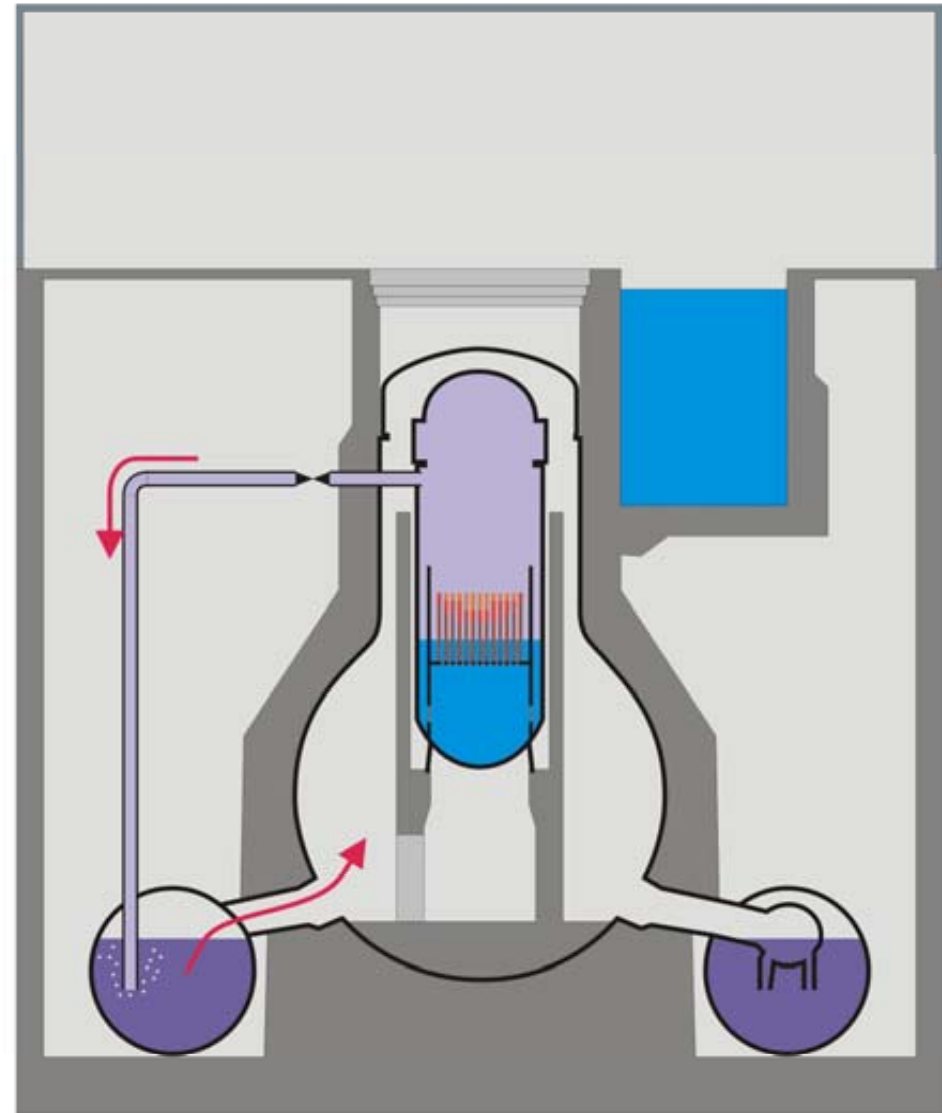
- ▶ About 50 % of the core cooled by steam only.
- ▶ Cladding temperatures rise, but still no significant core damage.
- ▶ About 67 % of the core cooled by steam only.
 - Cladding temperatures exceed $\approx 900\text{ }^{\circ}\text{C}$.
 - Ballooning and/or bursting of claddings (local damages).
 -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



Event Sequence – Accident Progression

Temperature Escalation Phase

- ▶ About 75 % of the core cooled by steam only.
 - Cladding temperatures exceed $\approx 1200\text{ }^{\circ}\text{C}$.
 - Start of significant zirconium oxidation in steam atmosphere.
 $\text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2 + \text{Heat}$
 - Exothermal reaction leads to an additional core heatup.
 - Oxidation of 1 kg of zirconium generates $\approx 44.2\text{ g}$ 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.



Core Materials Liquefaction Regimes

Melting Temperatures

UO₂
2850 °C

ZrO₂
2690 °C

B₄C
2450 °C

Zircaloy 4
1760 °C

Stainless Steel
1450 °C

2000 °C

1000 °C



3000 °C

Liquefaction Regimes

Melting of the ceramic materials UO₂ and ZrO₂ as well as formation of ceramic (U, Zr, O) melts

Melting of metallic Zircaloy and α-Zry(O) results in fast dissolution of UO₂

Start of rapid oxidation of Zircaloy by steam and macroscopic liquefaction by eutectic interaction of B₄C with stainless steel or stainless steel with Zircaloy

Ballooning and bursting of fuel rod claddings, release of volatile fission products

Core Damage

► Complete

► Extended

► Localized

► Initiation

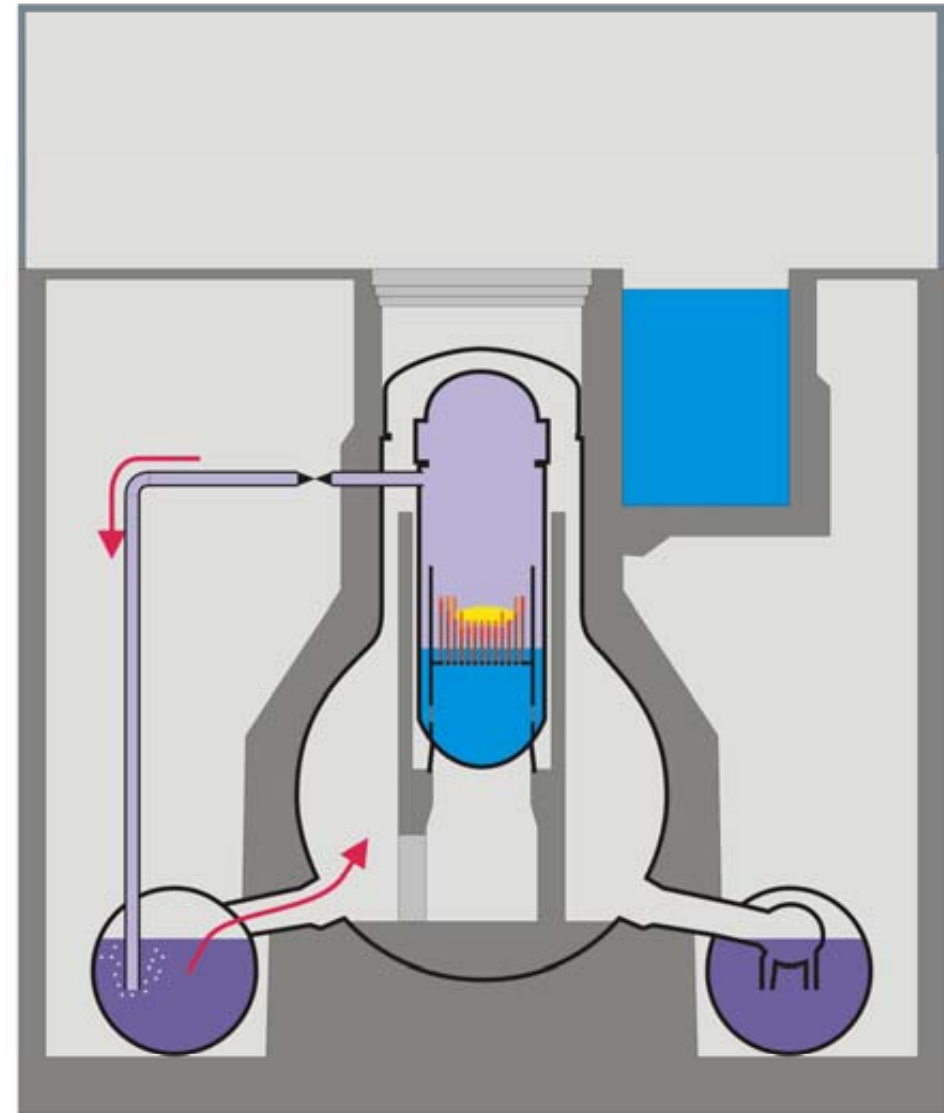
Event Sequence – Accident Progression

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)O₂ eutectics.

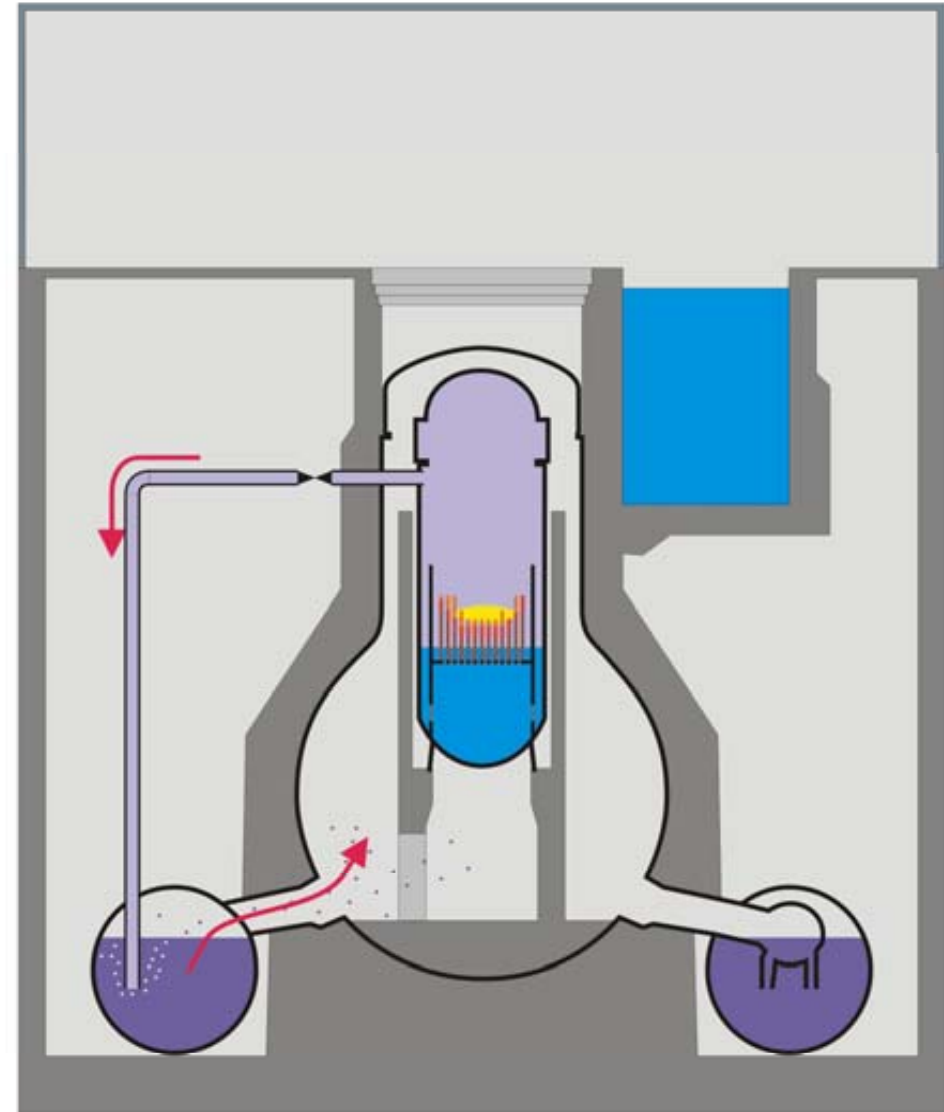
Reflood Phase

- ▶ **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.



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.



Event Sequence – Accident Progression

► Containment Safety Function

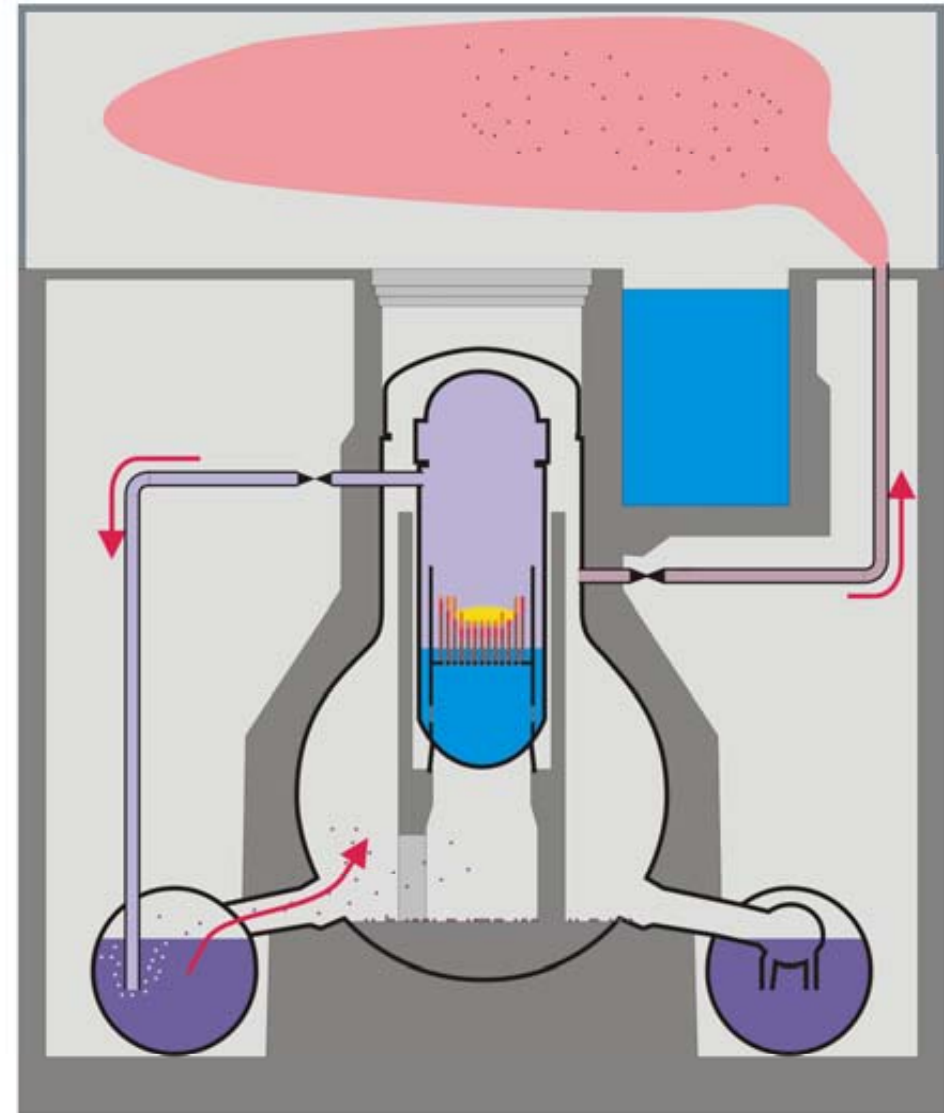
- Last barrier between fission products and environment.
- Wall thickness: ≈ 3 cm.
- Design pressure: 4 to 5 bar.

► Actual Pressures up to 8 bar

- Inert gas filling (nitrogen),
- hydrogen from core oxidation,
- boiling condensation chamber (like a pressure cooker).

► Containment Depressurization

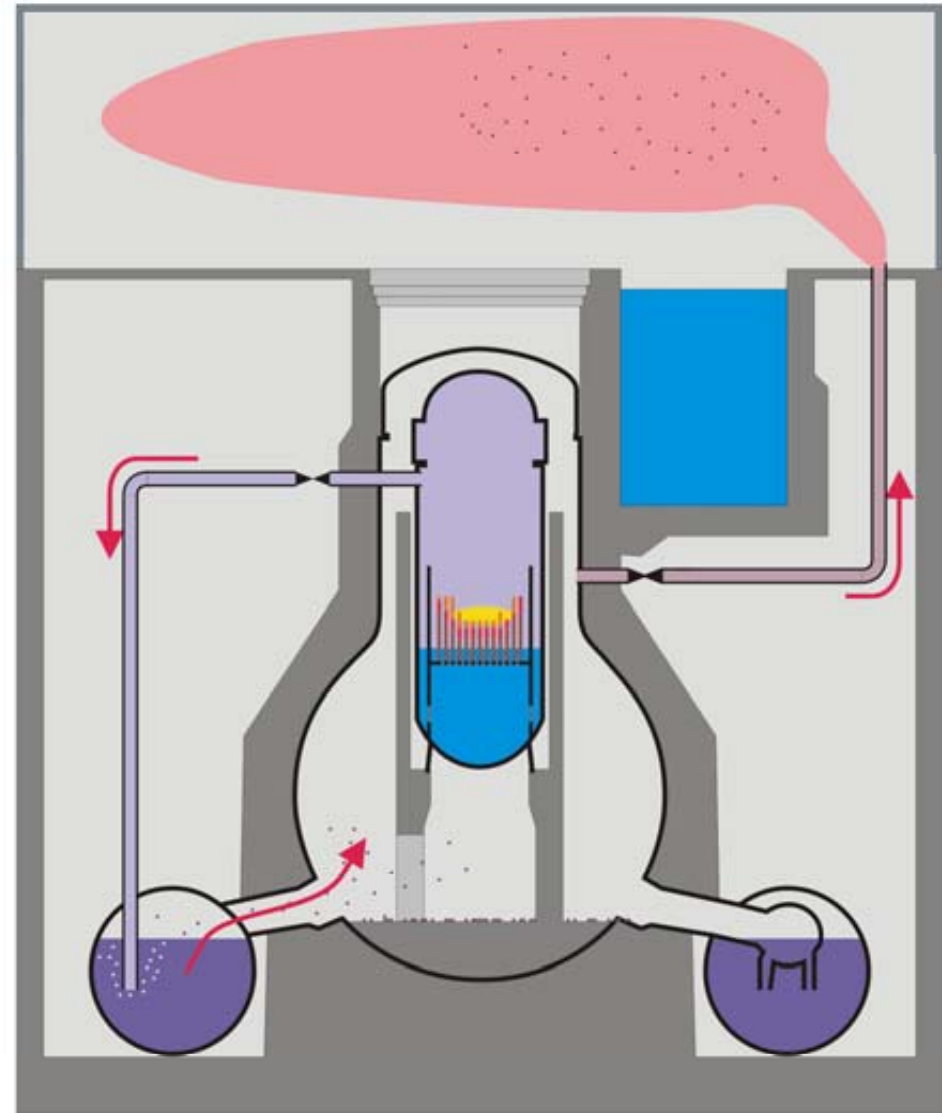
- **Unit 1:** March 12, 04:00,
- **Unit 2:** March 13, 00:00,
- **Unit 3:** March 13, 08:41.



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.

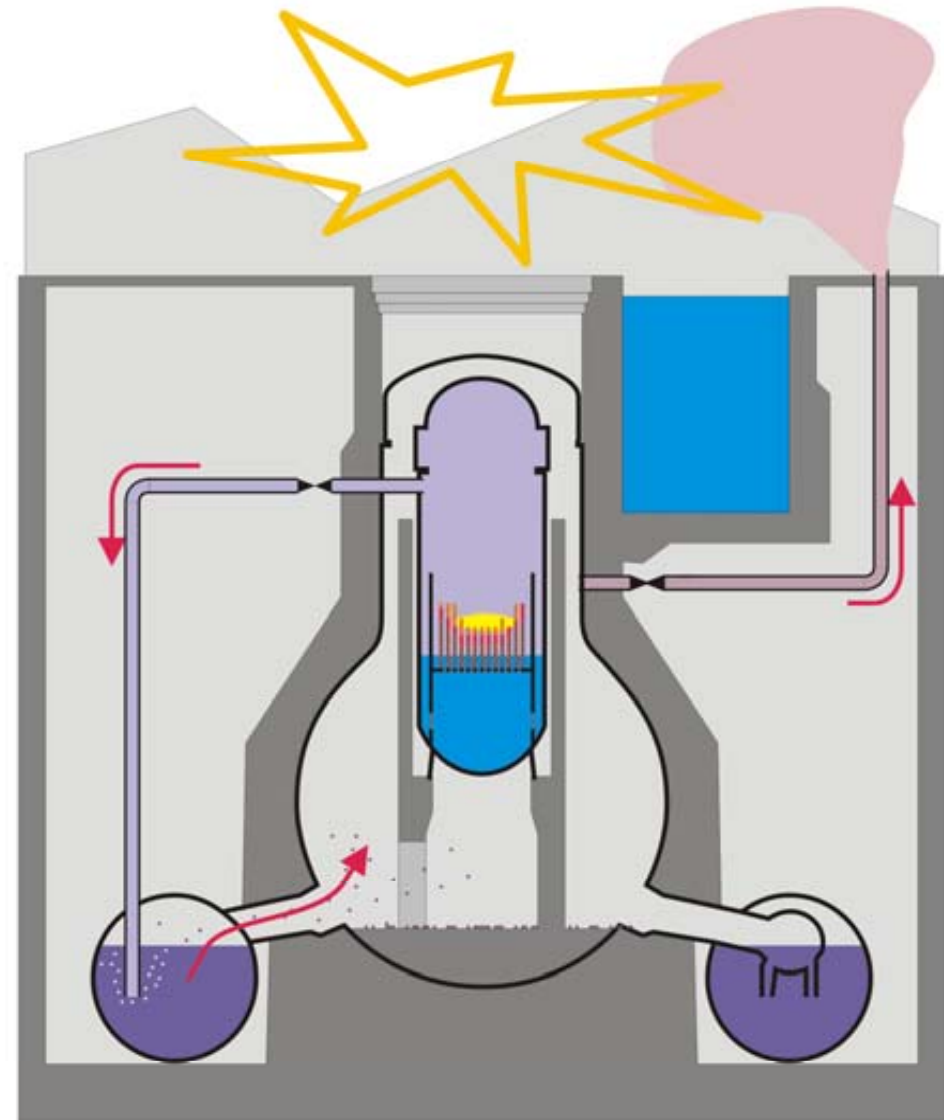
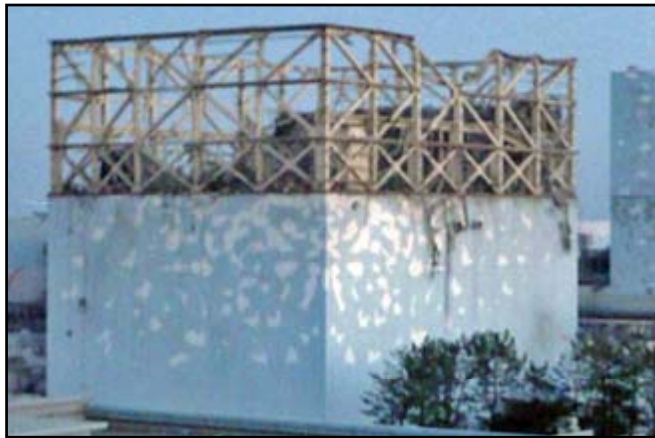


Event Sequence – Accident Progression

VGB
POWERTECH

► **Units 1 and 3:**

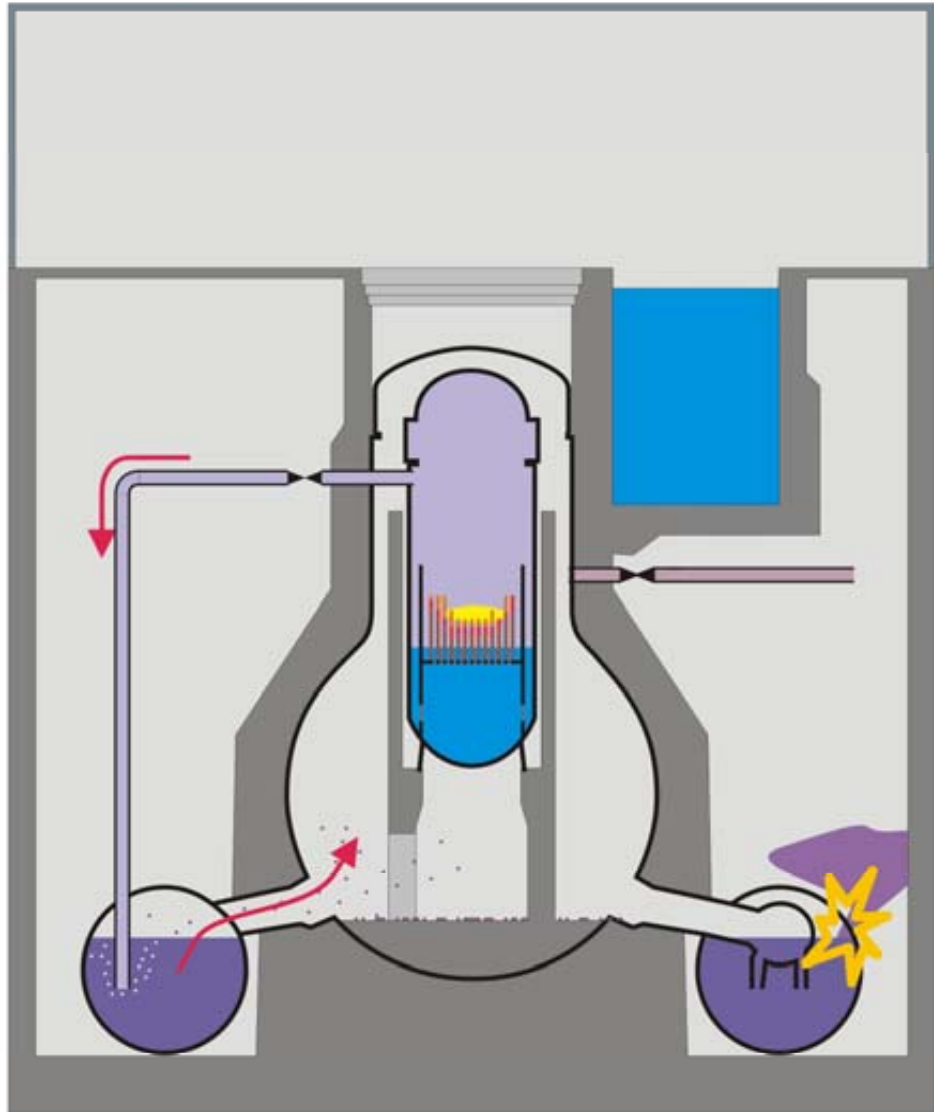
- No recombiners (?).
- Hydrogen explosion inside the reactor service floor.
- This leads to destruction of the steel-frame construction.
- Reinforced concrete reactor building remains undamaged.



Event Sequence – Accident Progression

► Unit 2:

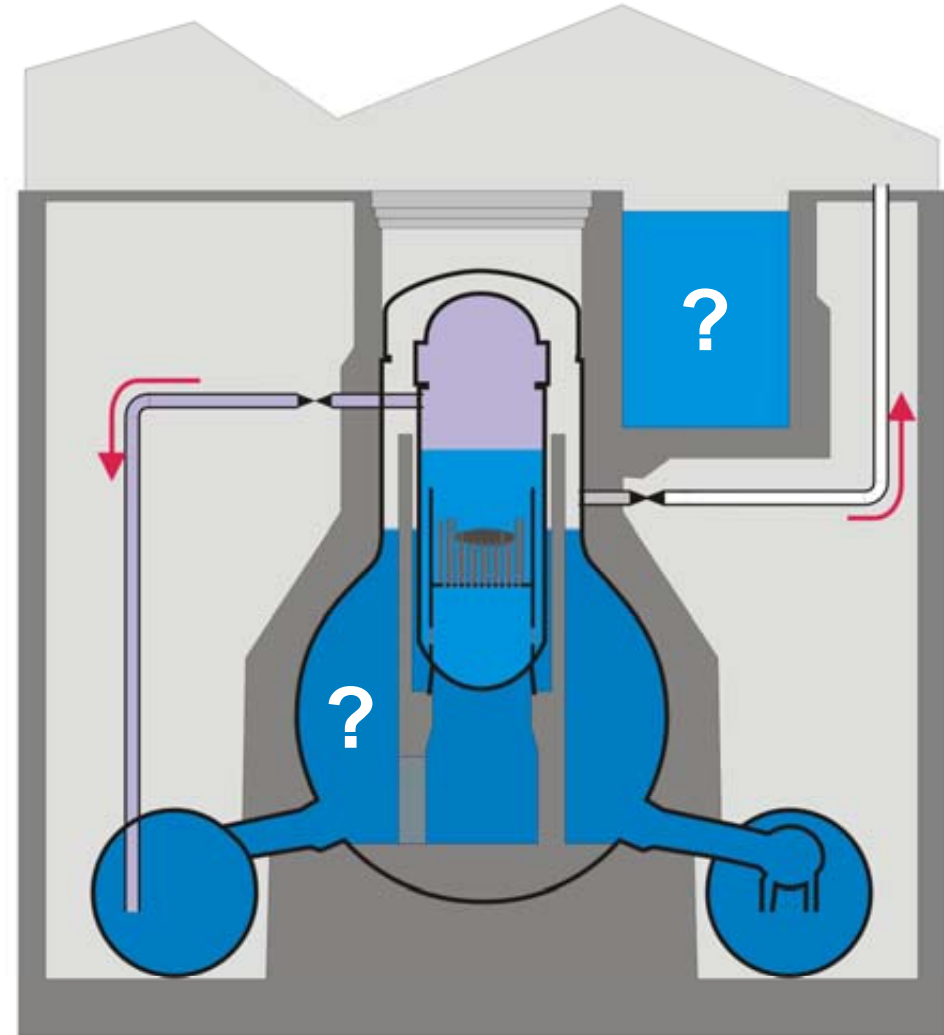
- Probable damage of drywell following a pressure increase within the reactor pressure vessel and containment.
- Highly contaminated water.
- Uncontrolled release of gas from the containment.
- **Release of fission products.**
- Temporary plant evacuation due to high local dose rates on the plant site.



Event Sequence – Accident Progression

► Reactor Status as of March 24:

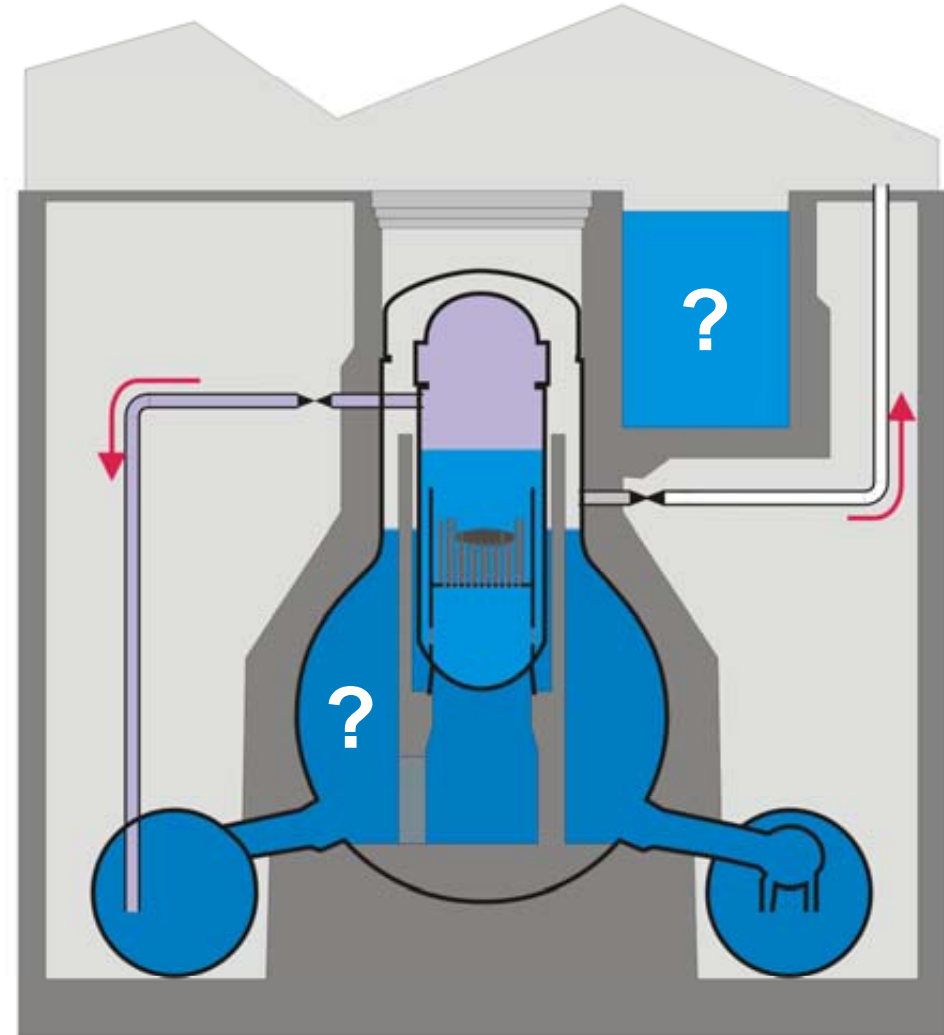
- Core damage in units 1, 2, 3.
- Damaged reactor buildings of units 1 to 4.
- Reactor pressure vessels of all units are fed with seawater or sweet water by mobile pumps.
- Estimates of General Electric indicate that about 45 tonnes of salt could have been injected into the reactor cores so far, with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



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.



Fukushima-Daiichi-1

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



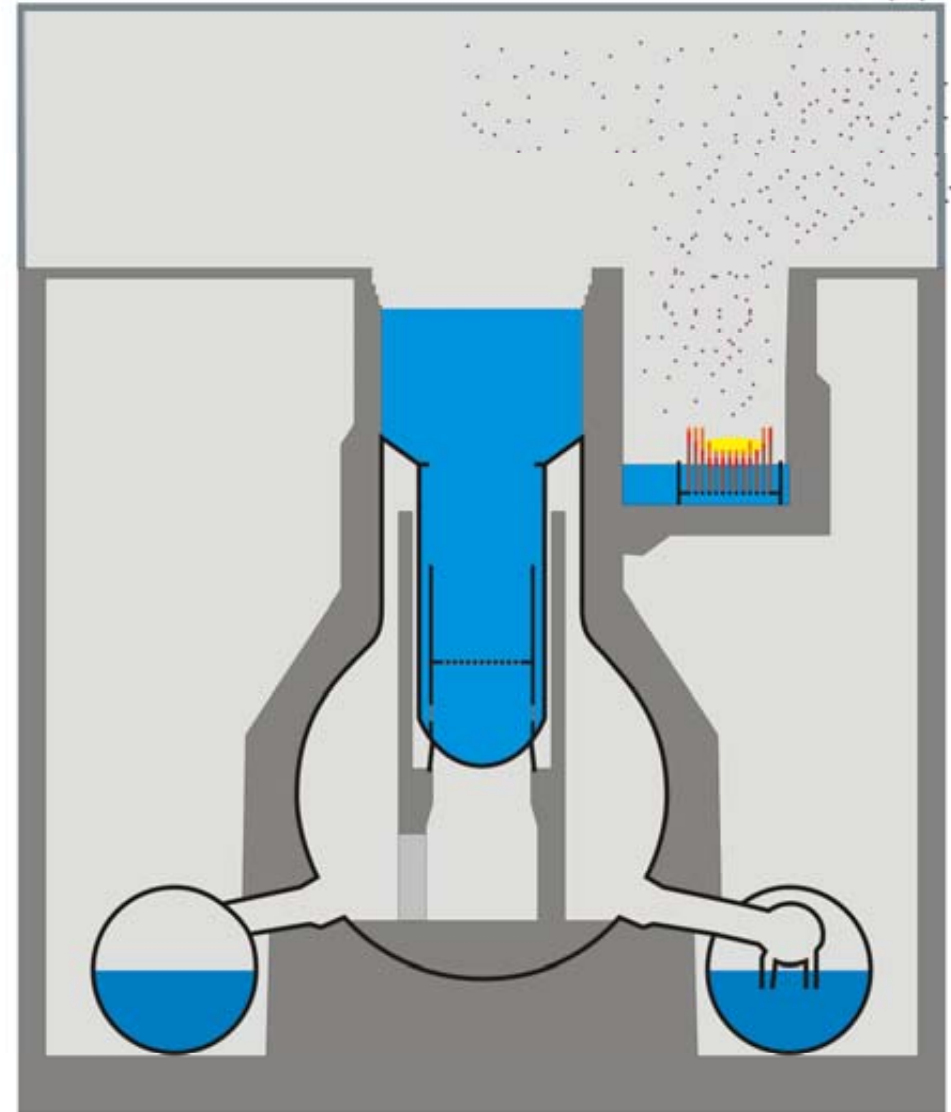
Spent Fuel Transfer Pools

► 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.



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).

Unit 4 Spent Fuel Transfer Pool Cooling

- ▶ **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).

Unit 4 Spent Fuel Transfer Pool Cooling

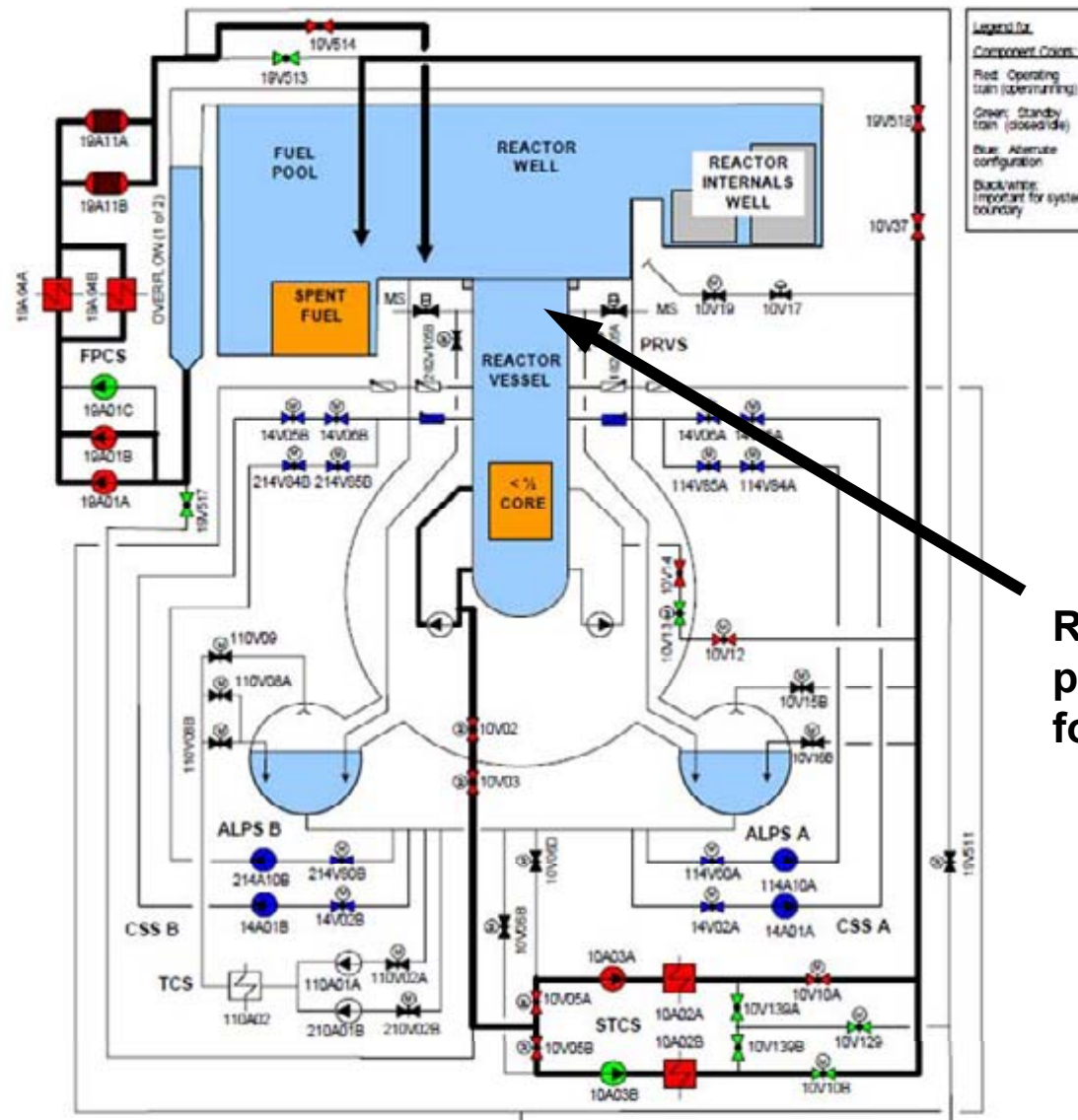


Unit 4 Spent Fuel Transfer Pool Cooling



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

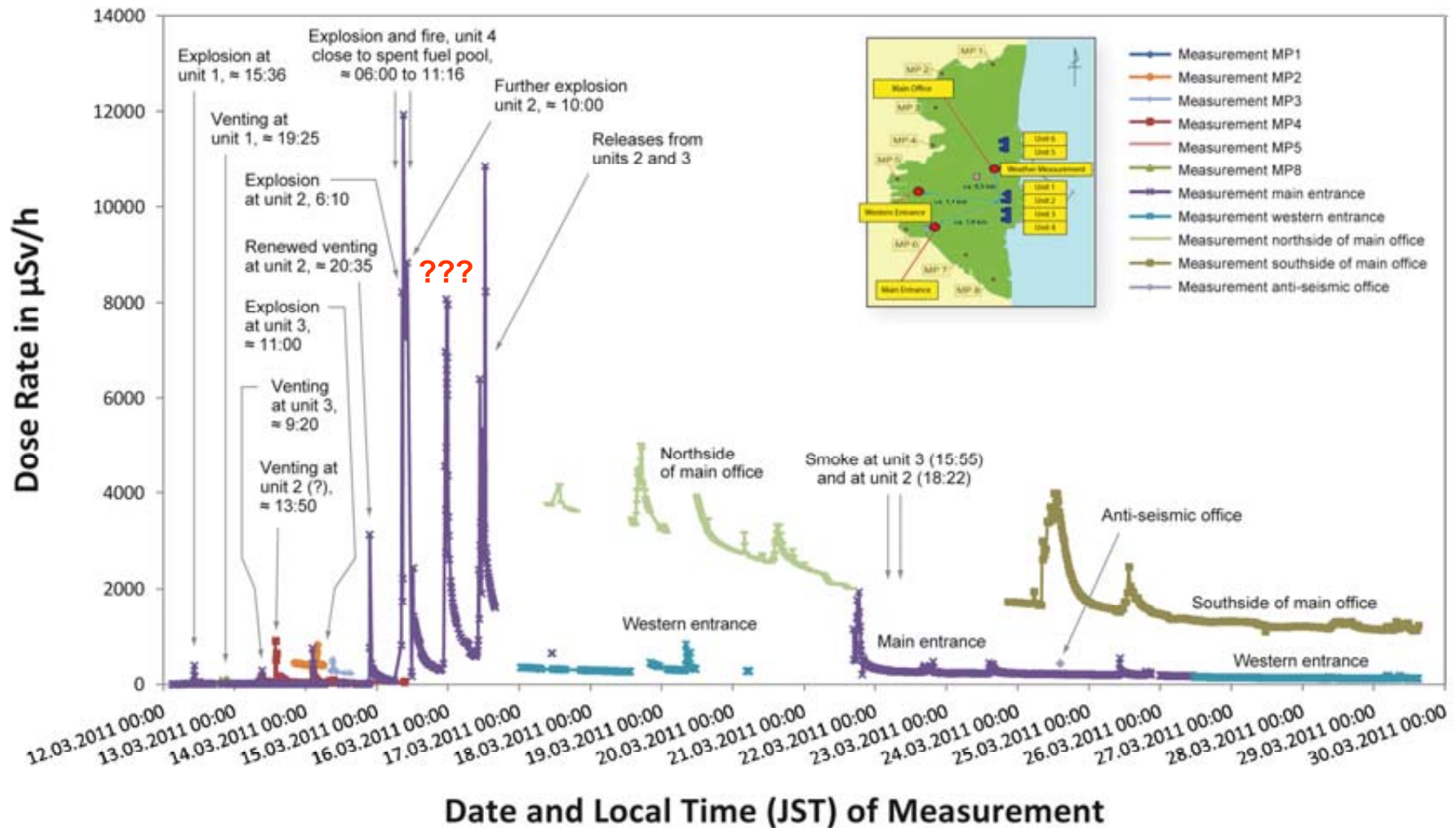
Fukushima Daiichi Refueling Cooling System



Reactor pressure vessel and primary containment are open for refueling.

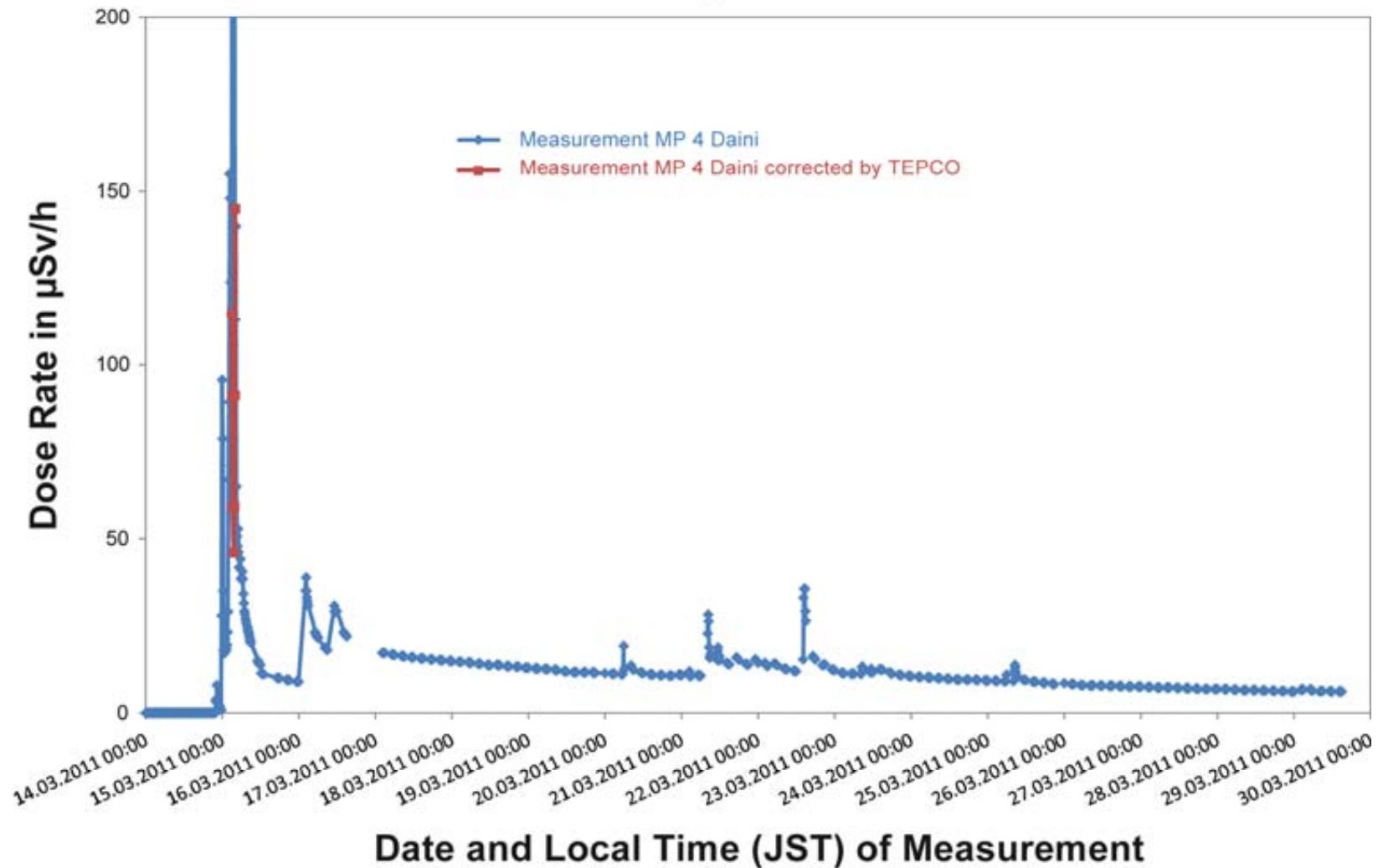
Dose Rates at Fukushima Daiichi

Measured Dose Rates at Different Fukushima-Daiichi Locations
Data of Plant Operator TEPCO



Dose Rates at Fukushima Daini

Measured Dose Rates at Different Fukushima-Daini Locations
Data of Plant Operator TEPCO




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.

Fukushima Daiichi, Status as of March 19, 2011

U 	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

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

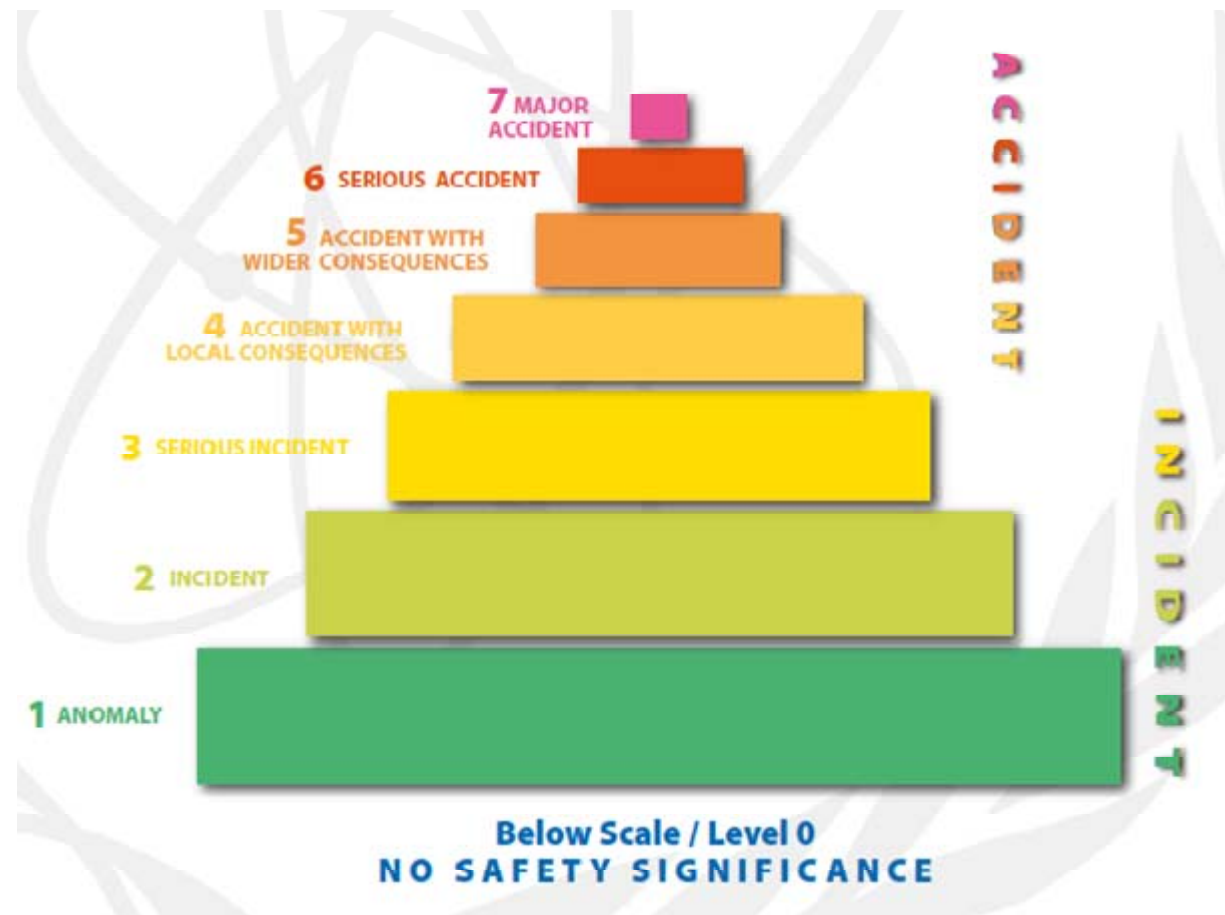
INES-Classification as of April 12, 2011

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



Radiology

Lethal Dose ¹⁾: 5000 mSv

Extended Tepco Limit: 250 mSv

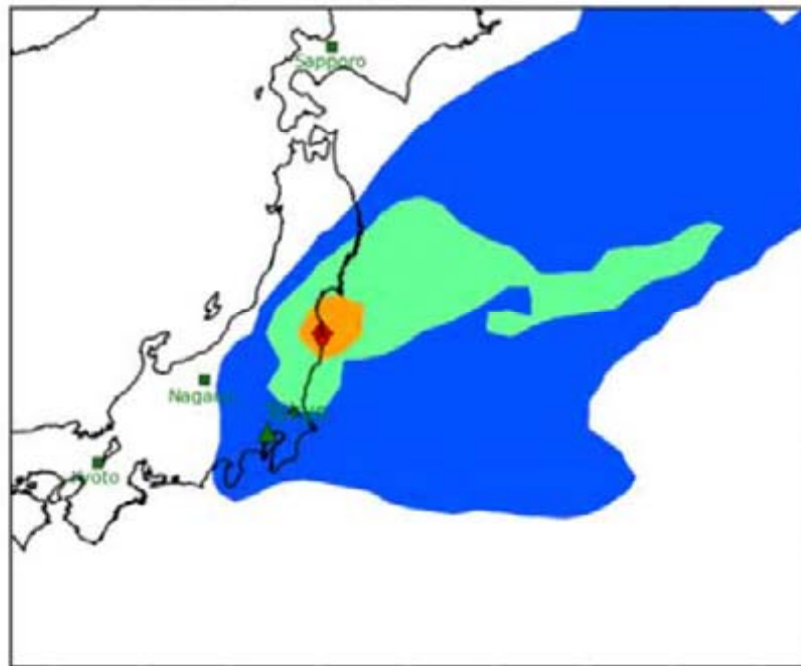
Initial Tepco Limit: 100 mSv

Maximum Allowed ²⁾: 50 mSv/a

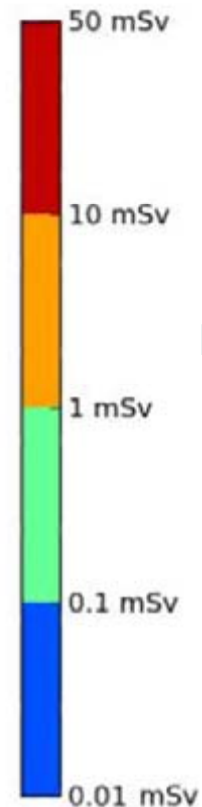
Dose Rates

Natural Background: 2.5 mSv/a

Radioactivity released from March 11 to 20, 2011



Cumulative dose for an unprotected one year old child



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

- ▶ 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 Daiichi?
- ▶ 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)

► **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 explosions),
- **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



Dr.-Ing. Ludger Mohrbach
ludger.mohrbach@vgb.org

VGB PowerTech e.V.
Klinkestraße 27 - 31, 45136 Essen, Germany
Telefon: +49-(0)2 01-81 28-0 (Zentrale)
Telefax: +49-(0)2 01-81 28-3 50

Vertretungsberechtigter Vorstand: Prof. Dr. Gerd Jäger
Registergericht: Amtsgericht Essen
Registernummer: VR 1788

www.vgb.org