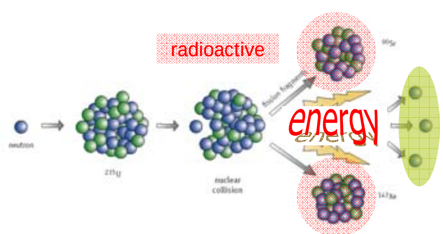
Fukushima Daiichi accident

- Safety of Nuclear Power Plants
- Earthquake and Tsunami
- Accident initiators and progression

Nuclear fission

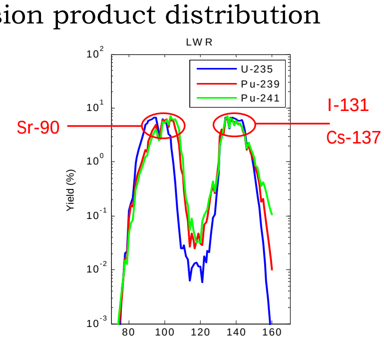


Fissioning of 1 gram uranium yields as much energy as burning 2500 liters petrol or 3000 kilograms coal

Distribution of energy

Energy Distribution (MeV)	
Kinetic energy of fission fragments	~ 165*
Energy of prompt gamma-rays	7*
KE of prompt neutrons	5
KE of beta-rays from fragments	7
E of gamma-rays from fragments	6
E of neutrinos from fragments	10
Total	~ 200

Fission product distribution



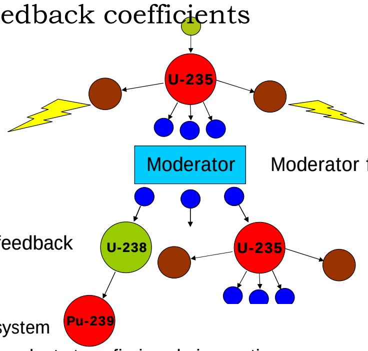
Nuclear fuel

Fuel assembly

Reactor safety

- Reactivity control
- Fuel cooling (in and outside reactor pressure vessel)
- Safe confinement of radioactivity

Feedback coefficients

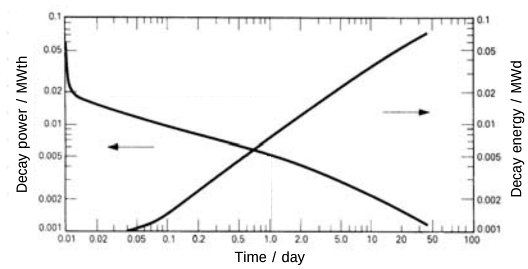


Moderator feedback

Doppler feedback

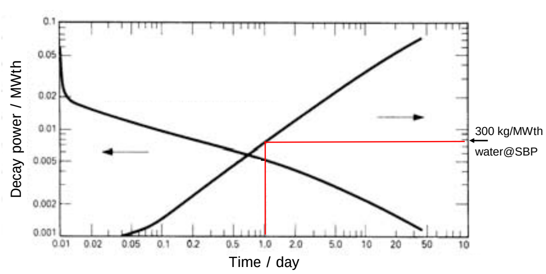
1) Stable system
2) Loss of coolant stops fission chain reaction
3) Loss of moderation stops fission chain reaction

Decay heat production

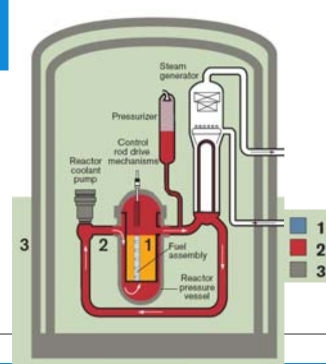


Also after shut down of the reactor, the fuel needs to be cooled for a long time!

Decay heat production



Containments nuclear power plant

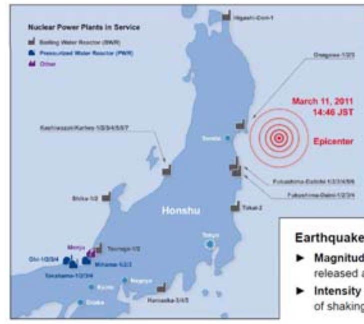


1 Fuel rod
2 Primary system (steel)
3 Containments (2x concrete+steel)

Fukushima-Daiichi Nuclear Power Plants

Unit	Type	Containment	Power (MWe)	Core #	Fuel type
1	BWR3	Mark I	460	400	UO2
2	BWR4	Mark I	784	548	UO2
3				548	516 LEU 32 MOX
4				-	UO2
5				548	UO2
6	BWR5	Mark II	1100	764	UO2

Source: NRG

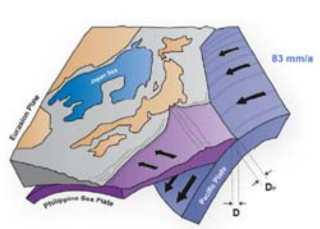


Epicenter Location
38.3°N, 142.4°E

Epicenter Distance
- Onagawa ≈ 90 km
  - Sendai ≈ 150 km
- F- Daiichi ≈ 160 km
- F-Daini ≈ 170 km
- Tokai ≈ 260 km

Earthquake Parameters
- **Magnitude** measures the energy released at the epicenter.
- **Intensity** measures the strength of shaking at a certain location.

Source: GRS, 2011 JST: Japan Standard Time



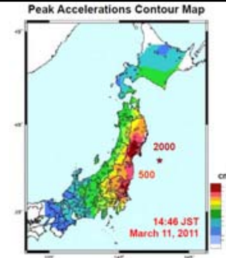
- **Vertical displacement** D ≈ 10 m
- **Plate displacement** D_P ≈ 17 m [1]
- **Rupture length** L ≈ 500 km
- **Hypocenter depth** Z_H ≈ 20 to 25 km
- **Water depth** Z ≈ 8 km

- **Estimated water volume**
  $V ≈ ½ (L \cdot W_A \cdot Z) ≈ ½ (500\ km \cdot 10\ m \cdot 8\ km) =$ **20 km³ (20 x 10^9 t Water)**
- **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

Ground Acceleration Values

Peak Accelerations Contour Map



Measured accelerations did not exceed design base values significantly

Unit	Observed max gal -Tentative			Design base earthquake		
	South-north	East-west	Up-down	South-north	East-west	Up-down
1	460	447	258	487	489	412
2	348	550	302	441	438	420
3	322	507	231	449	441	429
4	281	319	200	447	445	422
5	311	548	256	452	452	427
6	298	444	244	445	448	415

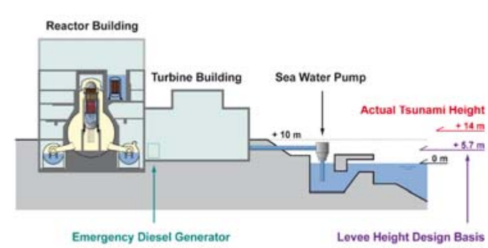
Source: JAIF

- Travel time from
  - Epicenter to shore 15 min
  - Epicenter to Fukushima 55 min
- Arrival at Fukushima-Daiichi 15:41 JST
- Maximum wave height [1]) ≈ 23 m
- Wave height at Fukushima [2]) ≈ 14 m
- Level of reactor building 10 to 13 m
- Levee height at
  - Fukushima- Daiichi 5.7 m
  - Fukushima- Daini 5.2 m
- Level of reactor buildings at
  - Onagawa ≈ 20 m

March 11, 2011

- **Tentative: If seismic data can be confirmed, practically all damages at Fukushima-Daiichi would have to be contributed to the tsunami.**

Sources: GRS, AFP, 2011 [1]) based on calculations and GPS-data [2]) according to TEPCO [3]) compared to normal sea water level



- 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 **10 m**.

Source: JANTI, 2011 All levels are related to the lowest Osaka Bay water level, referred to as Osaka Peil (OP)

Fukushima Daiichi nuclear site

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

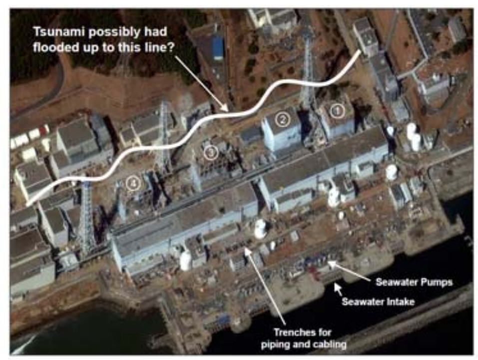
Source: Nuclear Engineering Handbook, 2010

Fukushima Daiichi nuclear site

Aerial view Fukushima Daiichi

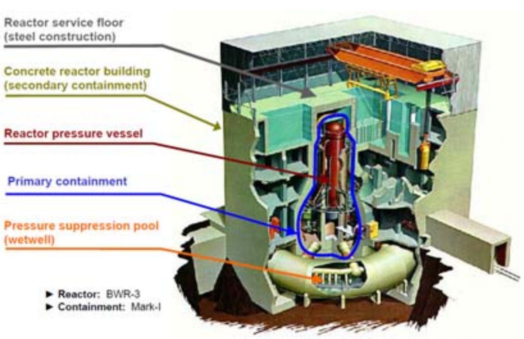
Source: WANO PC, Barnwood, 2011

Fukushima Daiichi after Tsunami



Sources: JANTI, Digital Globe, 2011

Plant design

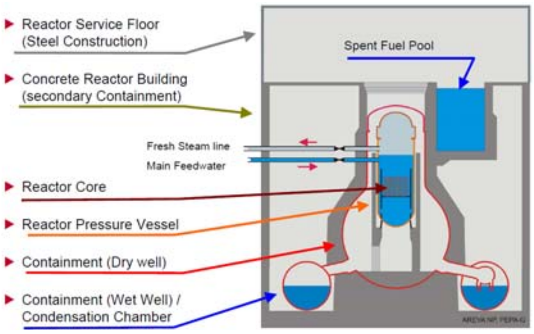


- Reactor: BWR-3
- Containment: Mark-I

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

Plant design

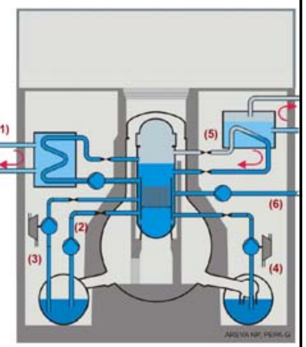
Plant design

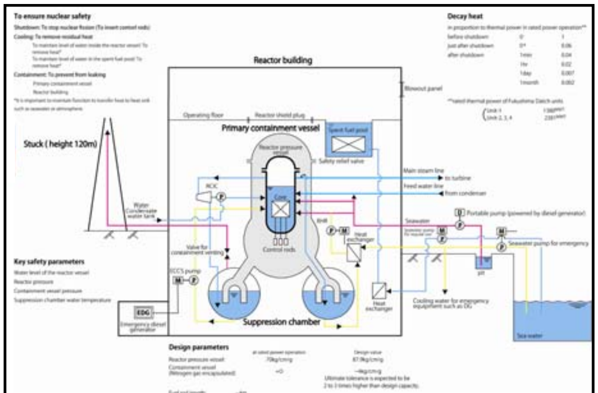


Plant design

- Emergency Core Cooling Systems

1) Residual Heat Removal System
2) Low-Pressure Core Spray (for LOCA only)
3) High-Pressure Core Injection (for LOCA only)
4) Reactor Core isolation cooling (in Unit 2,3 [BWR4])
5) Isolation Condenser (in Unit 1 [BWR3])
6) Borating System





Plant design – service floor

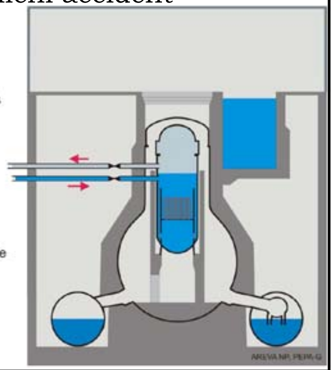
Plant design – service floor

Lifting the containment closure head

Plant design – reactor vessel head

Fukushima Daiichi accident

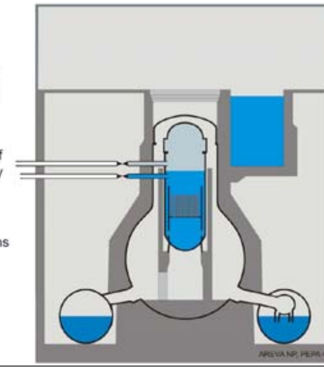
- 11.3.2011 14:46 - Earthquake
  - Magnitude 9
  - Power grid in northern Japan fails
  - Reactors itself are mainly undamaged
- SCRAM
  - Power generation due to Fission of Uranium stops
  - Heat generation due to radioactive Decay of Fission Products
    - After Scram ~6%
    - After 1 Day ~1%
    - After 5 Days ~0.5%



TU Delft — Source: Matthias Braun, Areva —

Fukushima Daiichi accident

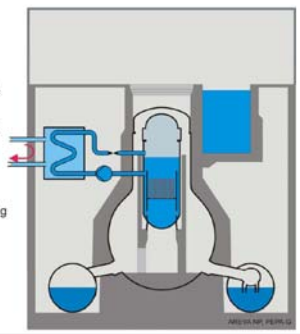
- Containment Isolation
  - Closing of all non-safety related Penetrations of the containment
  - Cuts off Machine hall
  - Due to successful containment isolation, a large early release of fission products is highly unlikely
- Diesel generators start
  - Emergency Core cooling systems are supplied
- Plant is in a stable save state



TU Delft — Source: Matthias Braun, Areva —

Fukushima Daiichi accident

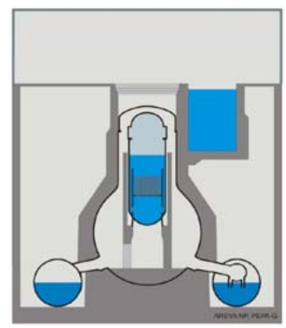
- Usual course of action:
  - Cooling reactor by Residual Heat Removal Systems
  - Active spend fuel pool cooling
  - Active containment heat removal
- Necessary
  - Electricity for pumps
  - Heat sink outside Reactor building (Service Water)



TU Delft — Source: Matthias Braun, Areva —

Fukushima Daiichi accident

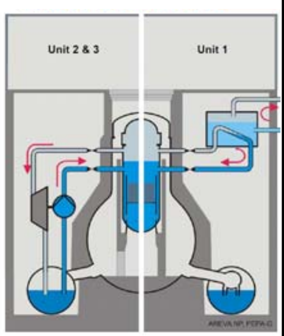
- 11.3. 15:41 Tsunami hits plant
  - Plant Design for Tsunami height of up to 5.7-6.5m
  - Actual Tsunami height 14 m
  - Flooding of
    - Diesel and/or
    - Switchgear building and/or
    - Fuel Tanks and/or
    - Essential service water buildings
- 11.3. 15:41 Station Blackout
  - Common cause failure of the power supply
  - Only Batteries are still available
  - Failure of all but one Emergency core cooling system



TU Delft — Source: Matthias Braun, Areva —

Fukushima Daiichi accident

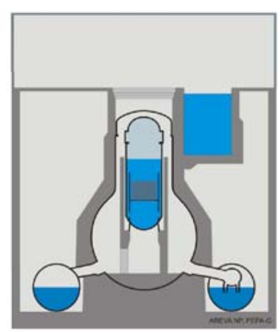
- Fukushima I -Unit 1
  - Isolation Condenser
    - Steam enters heat exchanger
    - Condensate drains back to RPV
    - Secondary steam released from plant
  - Need Pumps for Water supply
  - Can't replace water in Reactor
- Fukushima I Unit 2 & 3
  - Reactor Core Isolation Pump
    - Steam from Reactor drives Turbine
    - Steam gets condensed in Wet-Well
    - Turbine drives a Pump, pumping Water from the Wet-Well in reactor
  - Necessary:
    - Battery power for control
    - Wet-Well Temperature < 100°C
  - No heat removal out of containment



TU Delft — Source: Matthias Braun, Areva —

Fukushima Daiichi accident

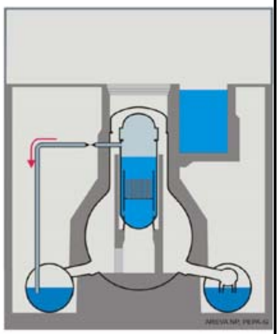
- 11.3. 16:36 in Unit 1
  - Isolation condenser stops
  - Tank empty(?)
- 13.3. 2:44 in Unit 3
  - Reactor Isolation pump stops
  - Batteries empty
- 14.3. 13:25 in Unit 2
  - Reactor Isolation pump stops
  - Pump failure
- Consecutively, all reactors are cut of from any kind of heat removal



TU Delft — Source: Matthias Braun, Areva —

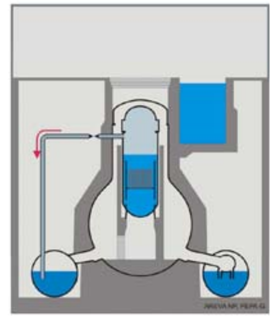
Fukushima Daiichi accident

- Decay Heat produces still steam in Reactor pressure Vessel
  - Pressure rising
- Opening the steam relieve valves
  - Discharge Steam into the Wet-Well
- Descending of the Liquid Level in the Reactor pressure vessel



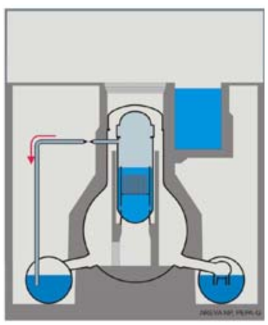
Fukushima Daiichi accident

- Decay Heat produces still steam in Reactor pressure Vessel
  - Pressure rising
- Opening the steam relieve valves
  - Discharge Steam into the Wet-Well
- Descending of the Liquid Level in the Reactor pressure vessel



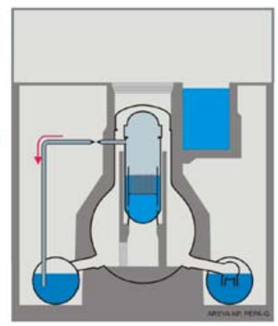
Fukushima Daiichi accident

- Decay Heat produces still steam in Reactor pressure Vessel
  - Pressure rising
- Opening the steam relieve valves
  - Discharge Steam into the Wet-Well
- Descending of the Liquid Level in the Reactor pressure vessel



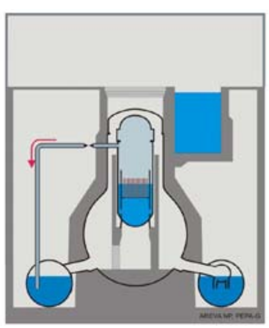
Fukushima Daiichi accident

- Decay Heat produces still steam in Reactor pressure Vessel
  - Pressure rising
- Opening the steam relieve valves
  - Discharge Steam into the Wet-Well
- Descending of the Liquid Level in the Reactor pressure vessel



Fukushima Daiichi accident

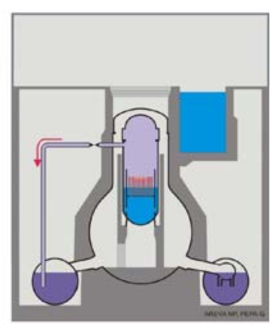
- Decay Heat produces still steam in Reactor pressure Vessel
  - Pressure rising
- Opening the steam relieve valves
  - Discharge Steam into the Wet-Well
- Descending of the Liquid Level in the Reactor pressure vessel



Fukushima Daiichi accident

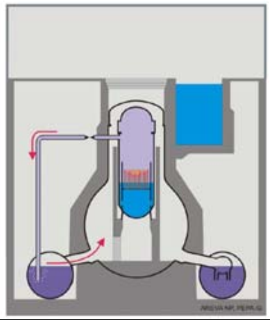
- ~50% of the core exposed
  - Cladding temperatures rise, but still no significant core damage
- ~2/3 of the core exposed
  - Cladding temperature exceeds ~900°C
  - Balooning / Breaking of the cladding
  - Release of fission products from the fuel rod gaps

(Measured levels are collapsed level. The actual liquid level lies higher due to the steam bubbles in the liquid)



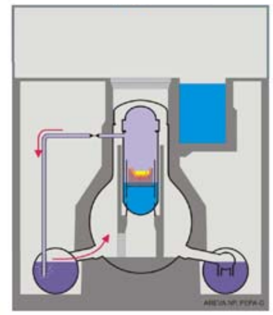
Fukushima Daiichi accident

- ~3/4 of the core exposed
  - Cladding exceeds ~1200°C
  - Zirconium in the cladding starts to burn under steam atmosphere
  - **$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$**
  - Exothermal reaction further heats the core
  - Estimated masses hydrogen
    - Unit 1: 300 600kg(max)
    - Unit 2/3: 300-1000kg(max)
  - Hydrogen gets pushed via the wet-well and the wet-well vacuum breakers into the dry-well



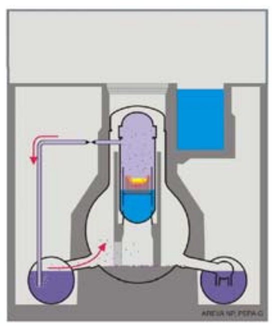
Fukushima Daiichi accident

- at ~1800°C [expected in Unit 1,2,3]
  - Melting of the Cladding
  - Melting of the steel structures
- at ~2500°C [expected in Unit 1,2]
  - Formation of a Debris bed inside the core region
- at ~2700°C [maybe in Unit 1]
  - Significant melting of Uranium-Zirconium-oxides
- Restoration of the water supply stops accident in all 3 Units
  - Unit 1: 12.3. 20:20
  - Unit 2: 14.3. 20:33
  - Unit 3: 13.3. 9:38
    (27 / 7 / 7h without water injection)



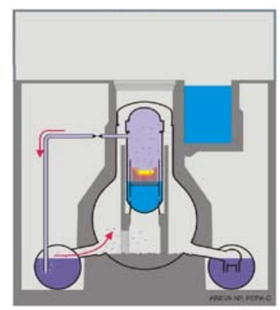
Fukushima Daiichi accident

- Release of fission products during melt down
  - Xenon, Cesium, Iodine,...
  - Uranium/Plutonium remain in core
  - Fission products condensate to airborne Aerosols
- Discharge through valves into water of the condensation chamber
  - Pool scrubbing binds a fraction of Aerosols in the water
- Xenon and remaining aerosols enter the Dry-Well
  - Aerosols partly deposition on surfaces in containment



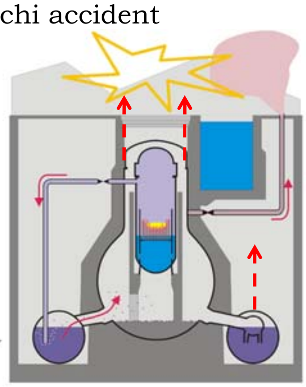
Fukushima Daiichi accident

- Containment
  - Last barrier between Fission Products and Environment
  - Wall thickness ~3cm
  - Design Pressure 4-5bar
- Actual pressure up to 8 bars
  - Normal inert gas filling (Nitrogen)
  - Hydrogen from core oxidation
  - Boiling condensation chamber (like a pressure cooker)
- First depressurization of the containment
  - Unit 1: 12.3. 4:00
  - Unit 2: 13.3 00:00
  - Unit 3: 13.3. 8.41



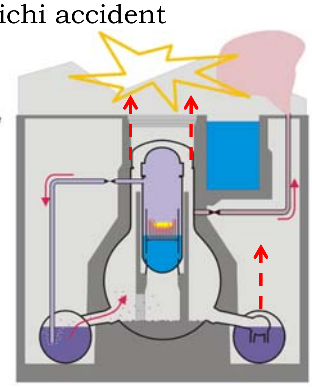
Fukushima Daiichi accident

- Positive und negative Aspects of depressurizing the containment
  - Removes energy out of containment (only way left)
  - Reducing the pressure to ~4 bar
  - Release of small amounts of Aerosols (Iodine, Cesium...)
  - Release of all noble gases
  - Release of Hydrogen
- Release of unfiltered venting?
- Gas is released into the reactor building
  - Gas accumulates on service floor
  - Hydrogen is flammable



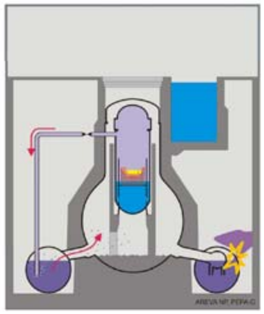
Fukushima Daiichi accident

- Unit 1 und 3
  - Hydrogen explosion inside the reactor service floor
  - Destruction of the steel-frame roof
  - Reinforced concrete reactor building seems undamaged
  - Spectacular but minor safety relevant



Fukushima Daiichi accident

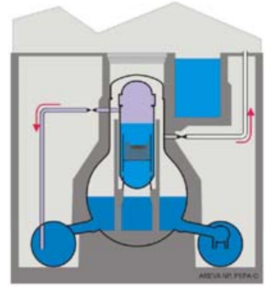
- Unit 2
  - Probably Hydrogen leakage of the condensation chamber (actual pressure exceeds design pressure)
  - Explosion inside the reactor building in proximity to the wet-well
  - Damage to the condensation chamber
  - Uncontrolled release of
    - Gas
    - highly contaminated water
    - Aerosols of fission products
  - Temporal evacuation of the plant
  - High local dose rates on the plant site due to wreckage hinder further recovery work



TUDelft Source: Matthias Braun, Areva

Fukushima Daiichi accident

- Current status of the Reactors
  - Core Damage in Unit 1,2, 3
  - Building damage due to various burns Unit 1-4
  - Reactor pressure vessels flooded in all Units with mobile pumps
  - At least containment in Unit 1 flooded
- Further cooling of the Reactors
  - Unit 1: by Isolation Condensers
  - Unit 2&3: by releasing steam
- Only small further releases of fission products can be expected from Unit 2 and 3



TUDelft Source: Matthias Braun, Areva

Fukushima Daiichi
Spent fuel pools

Unit	Assemblies	MW	Fresh Core	Cooling	Fuel Damage
1	292	0.3	No	?	?
2	587	1.0	No	Steam Plume	?
3	514	0.7	No	Boiling	?
4	1331	3.0	Yes	Water Cannon	Major
5	946	4.5	Probably	Diesel ²)	No
6	876	1.5	Probably	Diesel	No
Shared	6291 ¹)	?	No	Working	No

¹) Total number on site in November 2010, overall capacity: 6840 assemblies ²) Temporarily from unit 6

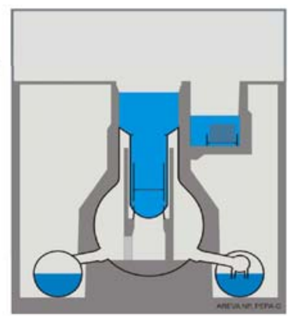
Fukushima-Daiichi
- **Unit 1:** 400 fuel rod assemblies,
- **Units 2 to 5:** 548 fuel rod assemblies,
- **Unit 6:** 764 fuel rod assemblies.

- **Unit 3:** Small number (32) of old (10 years) mixed oxide (MOX) fuel assemblies in fuel pool. No significant difference of plutonium inventory compared to other pools, since uranium fuel does also breed plutonium, but old MOX fuel contains higher amounts of Americium (more volatile than plutonium).

TUDelft Source: VGB Powertech

Spent fuel pools

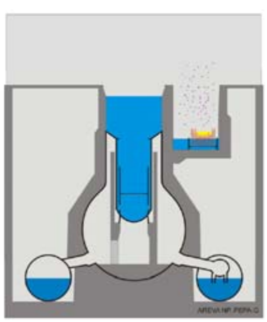
- Spent fuel stored in Pool on Reactor service floor
  - Due to maintenance in Unit 4 entire core stored in Fuel pool
  - Dry-out of the pools
    - Unit 4: in 10 days
    - Unit 1-3,5,6 in few weeks
  - **Leakage of the pools due to Earthquake?**
- Consequences
  - Core melt „open air "
  - Nearly no retention of fission products
  - Large release possible



TUDelft Source: Matthias Braun, Areva

Spent fuel pools

- Spent fuel stored in Pool on Reactor service floor
  - Due to maintenance in Unit 4 entire core stored in Fuel pool
  - Dry-out of the pools
    - Unit 4: in 10 days
    - Unit 1-3,5,6 in few weeks
  - **Leakage of the pools due to Earthquake?**
- Consequences
  - Core melt „open air "
  - Nearly no retention of fission products
  - Large release possible



TUDelft Source: Matthias Braun, Areva

Spent fuel pools

- **150 tonnes of seawater** 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)**.

TUDelft Source: Tepco, March 22, 2011

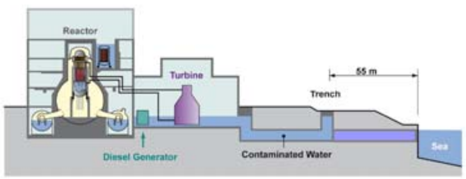
Spent fuel pools

Source: www.cryptome.org, 2011

Fukushima Daiichi Unit 4

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

Fukushima Daiichi accident
Flooded trenches



- 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, leading to speculation about possible pipe breaks in the reactor circuits.
- It now appears likely that the turbine floodings were caused through trench tunnels (NISA has now ordered watertight doors).

Sources: IAEA, WNN, 2011

Fukushima Daiichi accident
Flooded trenches

INES scale