EPFL

Severe Accidents: Fukushima

What is a severe accident ?

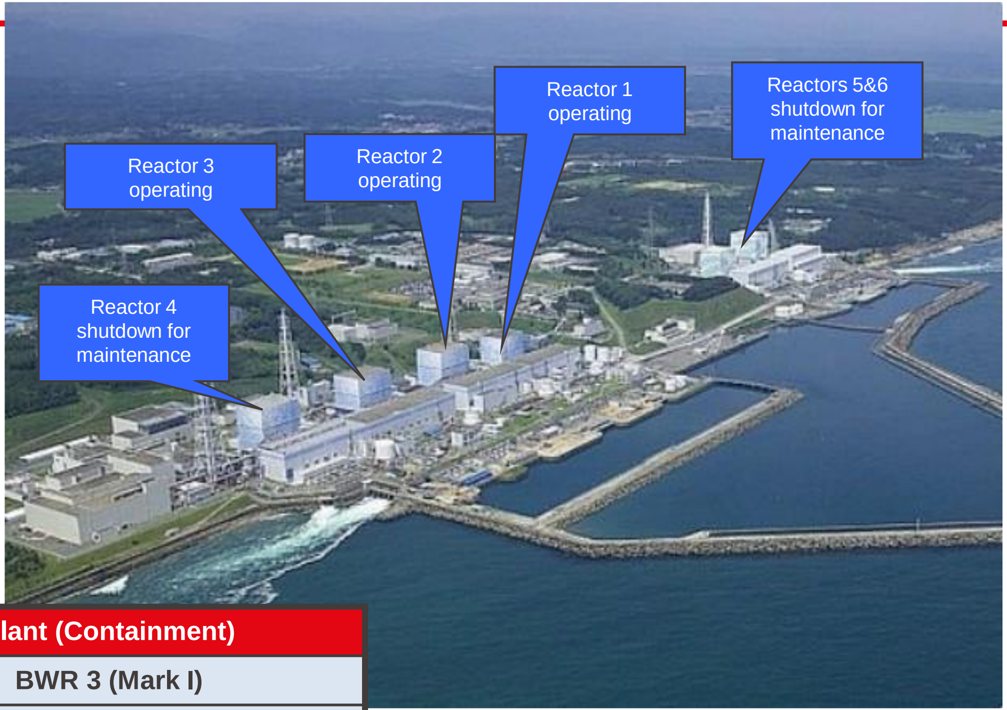
- A scenario with a very low probability (~10^{-5}/reactor-year for internally initiated events) in the domain of Beyond Design Basis Accidents (BDBA)

- Can lead to significant damage to fuel and core materials (partial or complete core melting).

- It may then have serious consequences such as:
  - Loss of containment integrity.
  - Release of radioactive elements into the environment.

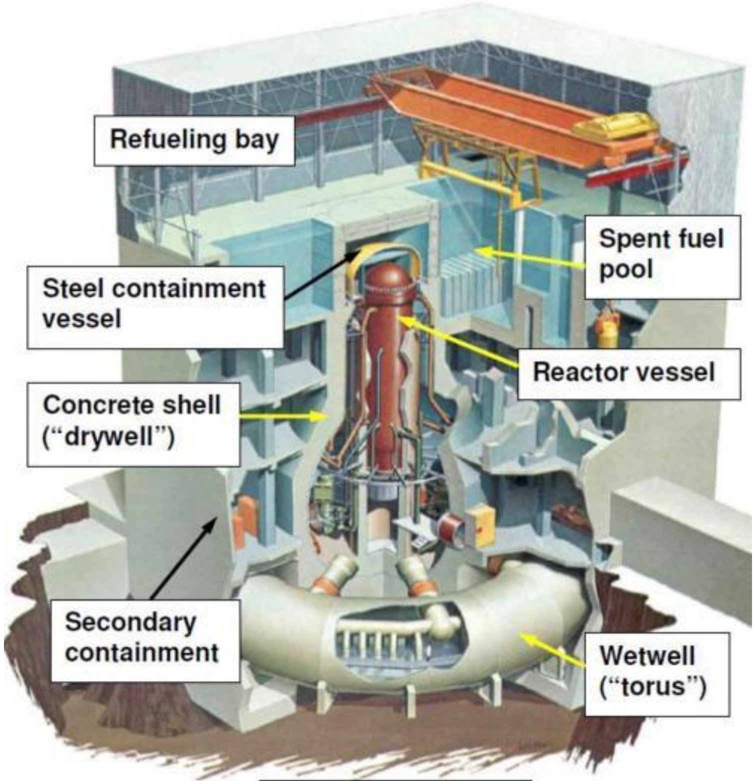
- Three major severe accidents:
  1. Three Mile Island (1979)
  2. Chernobyl (1986)
  3. **Fukushima Daiichi (2011)**

The Fukushima Daiichi Power Plants



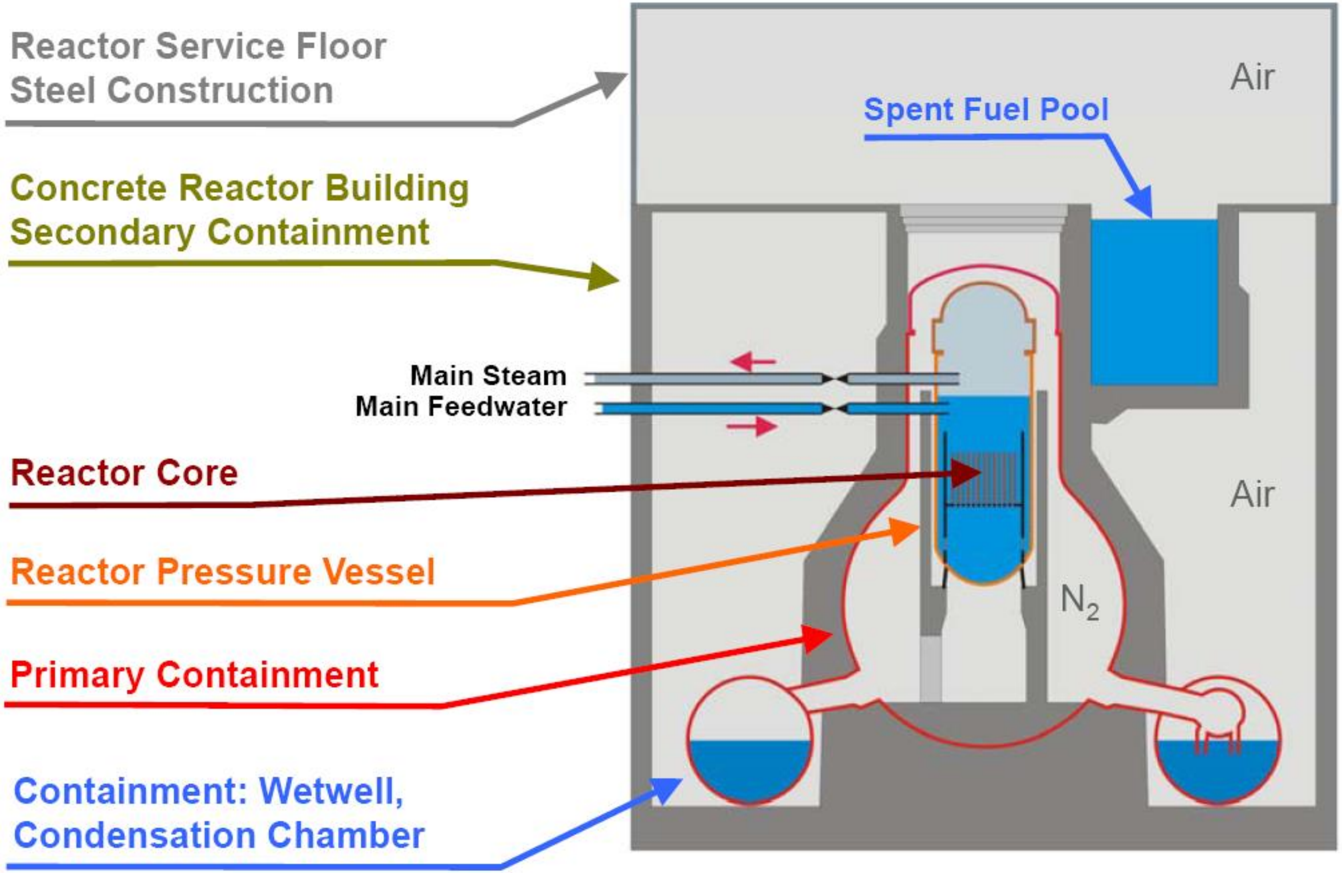
Bloc	Commissioned	Power MWe	Hersteller	Plant (Containment)
1	1971	460	GE	**BWR 3 (Mark I)**
2	1974	784	Toshiba/GE	**BWR 4 (improved Mark I)**
3	1976	784	Toshiba	**BWR 4 (improved Mark I)**
4	1978	784	Hitachi	**BWR 4 (improved Mark I)**
5	1978	784	Toshiba	**BWR 4 (improved Mark I)**
6	1979	1100	Toshiba/GE	**BWR 5 (Mark II)**

The Mark I Containment



Mark I Containment

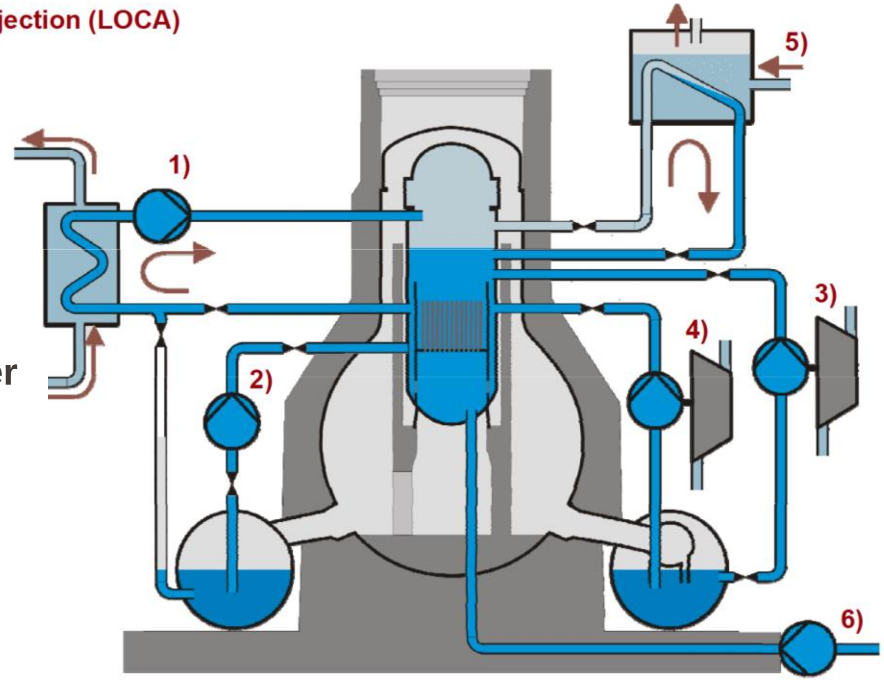
Fukushima Daichi General Scheme



Mark-I Emergency Cooling and Heat Removal Systems

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

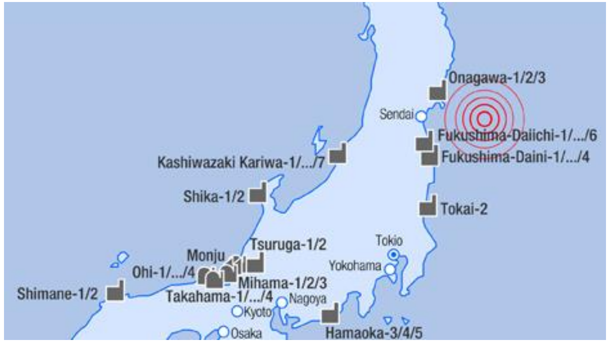
Electrical power necessary



Electrical power necessary

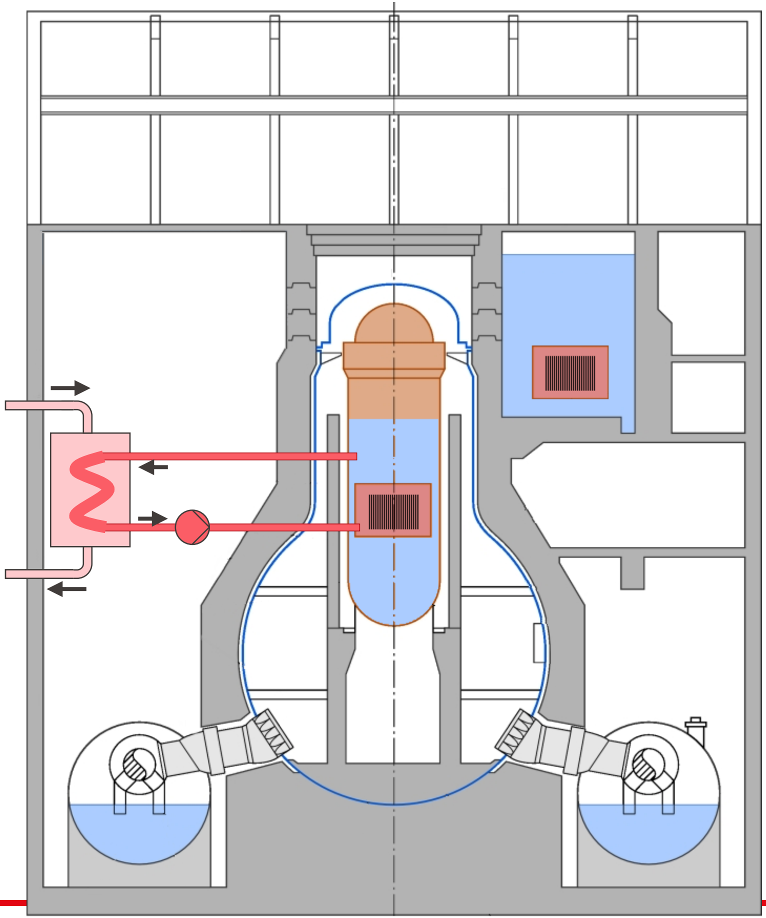
The Tohoku Earthquake on March 11, 2011, 14:46

- Epicenter 163 km North-East of Fukushima Daiichi NPP.
- Magnitude 9 (Richter Scale) – Severe destructions in the country but all reactor units are mainly undamaged.
- Power grid fails and reactors are safely scrammed (Daiichi Blocks 4-6 were already in shutdown).

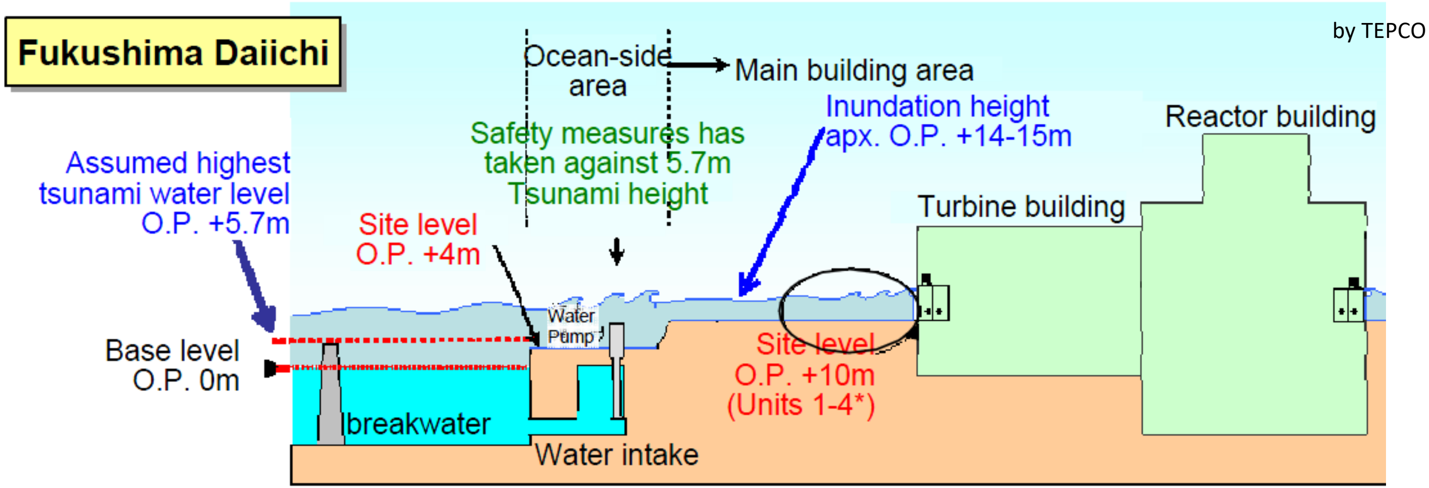


Accident Progression

- Reactors are shutdown but decay heat continues to generate power (~1% after 1 day)
- Blackout – loss of external power supply
  - Containment is isolated.
  - Diesel generators are started and drive the ECCS.
- **<u>At this point in time, no severe loss of safety functions and plant is in a stable state</u>**



The Tsunami on March 11, 2011, 15:41

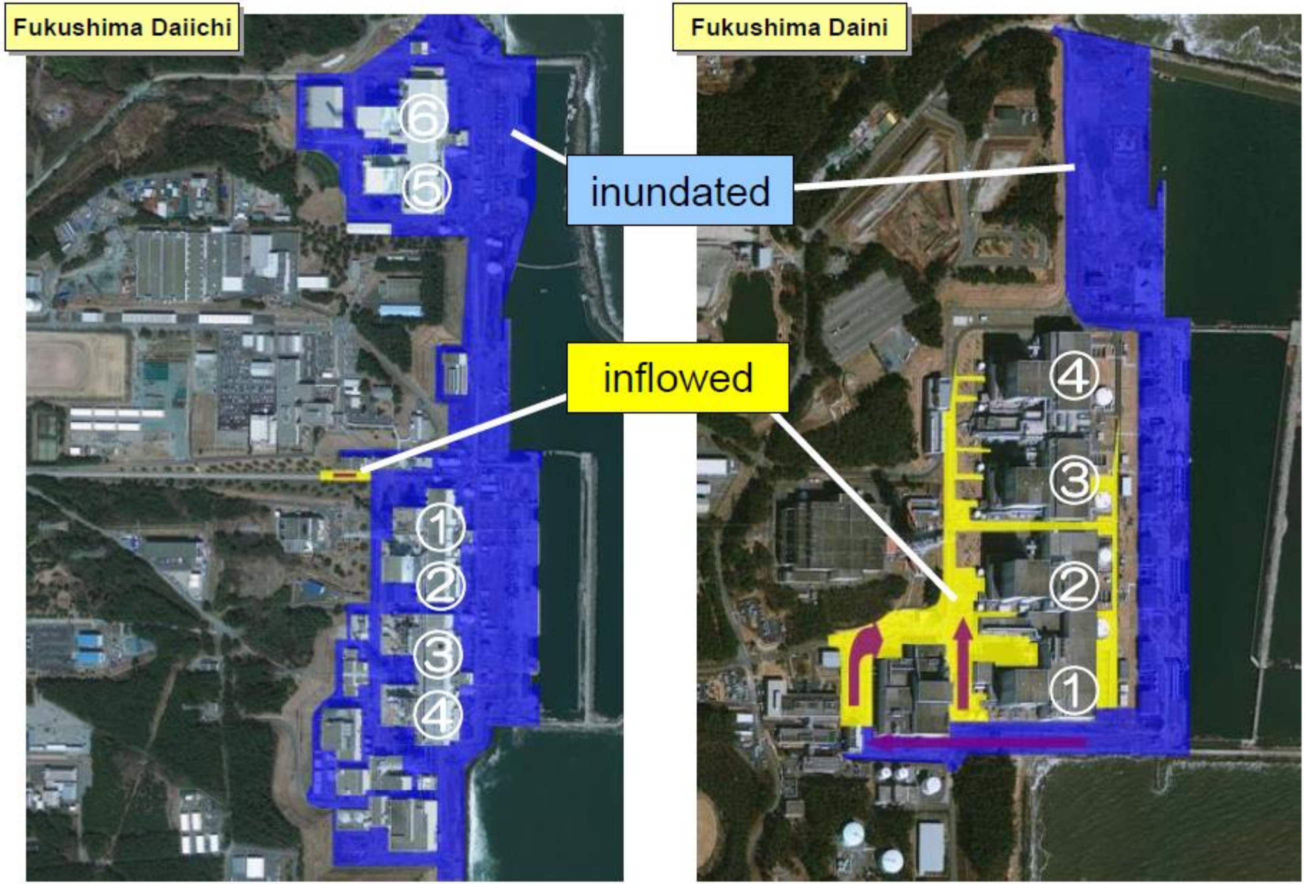


- Height of flood wave 14 m against a site level of 10m…
- Loss of all emergency diesel generators (inundated) → loss of all cooling functions.
- Area non-accessible due to debris everywhere and no access from the outside.

Tsunami hitting the Fukushima Daiichi site

The Tsunami on March 11, 2011, 15:41

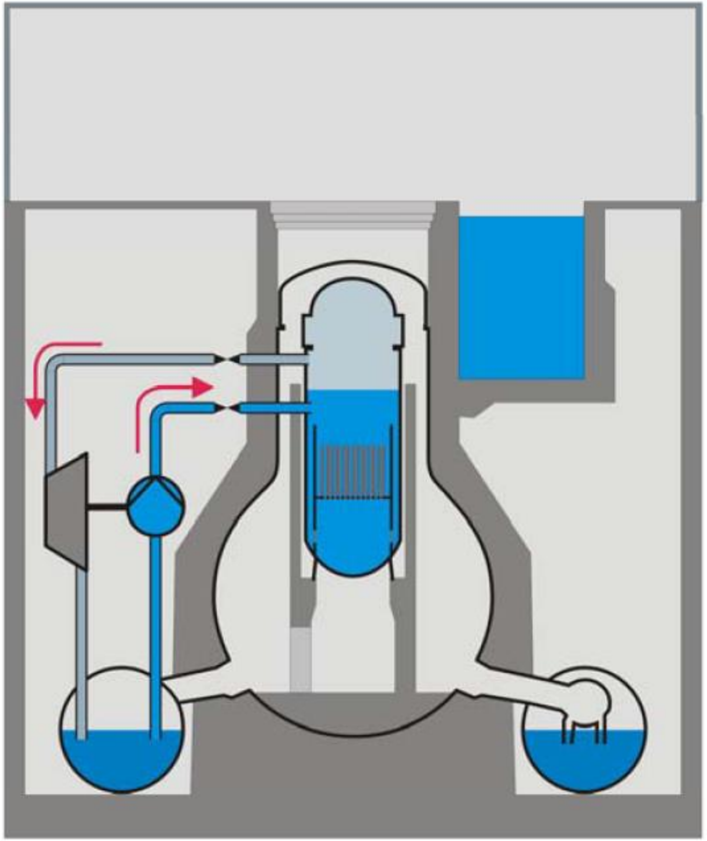
The Tsunami on March 11, 2011, 15:41



March 11, 2011, 15:41 - Tsunami hits the plant site

- Flooding of diesel generators.
  - All form of power supply – internal and external - are lost (common cause of failure!).
  - Only batteries are still available.

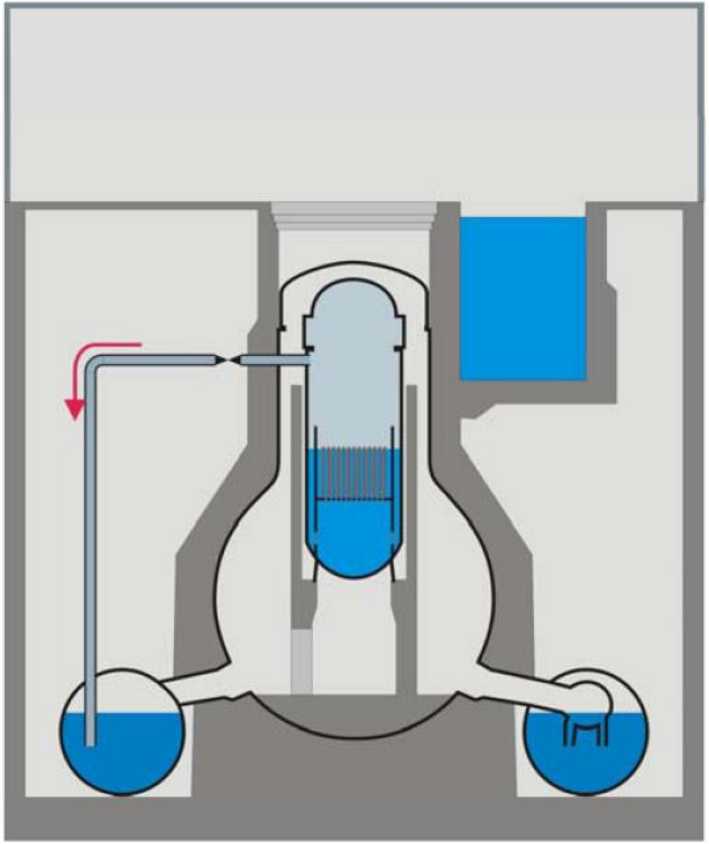
- ECCS is lost, only the ***reactor core isolation pump*** mechanically driven by a small steam turbine is available
  - Battery power still needed for turbine auxiliaries.
  - No heat removal from building → water heats up



Reactor isolation pumps stop

- Unit 1, Match 11 16:36 – Battery empty
- Unit 2, Match 14 13:25 – Pump failure
- Unit 3, Match 13 02:44 – Battery empty

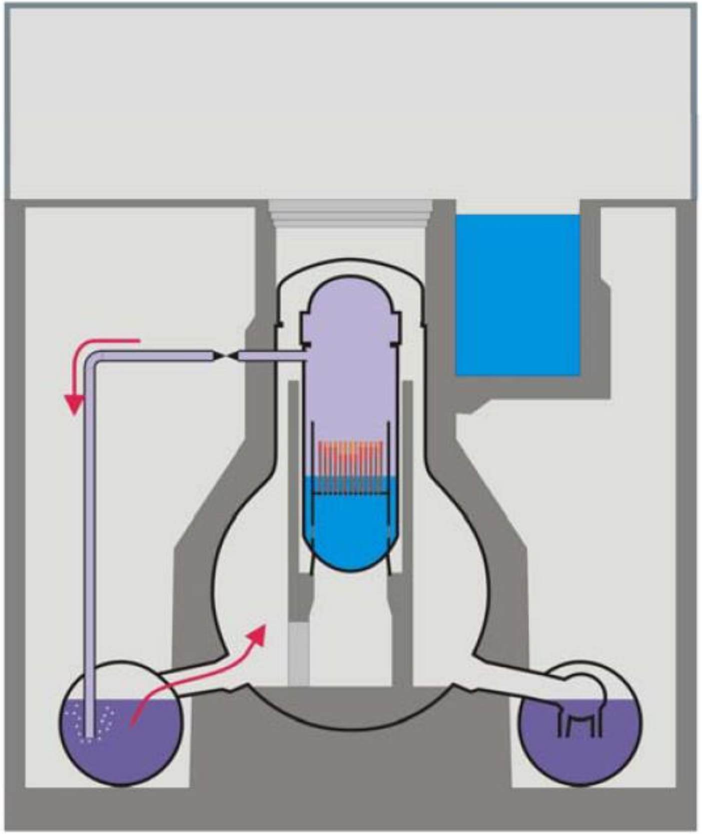
- Decay heat sill produces steam, leading to pressure rise:
  - Steam discharged into wet-well (relief valve opening).
  - Liquid level starts to decrease in RPV



Core Temperature Rises

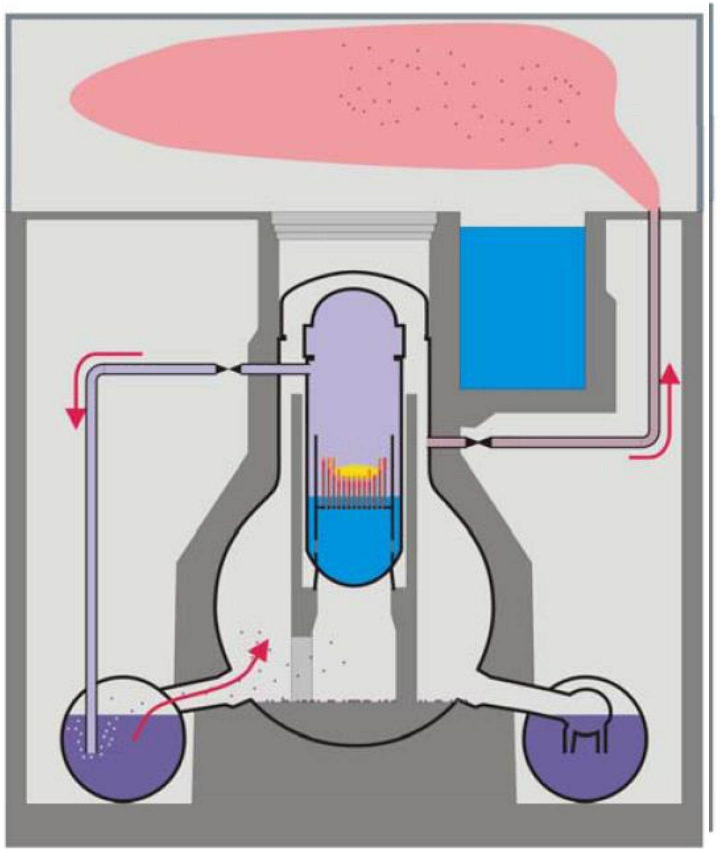
- **Core heat up phase:**
  - Clad temperature rises eventually reaching ~900°C.
  - Cladding burst and ballooning, release of volatile fission products.

- **Temperature escalation phase**
  - 75% of core cooled only by steam
  - Cladding temperature exceeds 1200°C.
  - Zr oxidation becomes exothermic (300kg to 1000kg of H produced).
  - Produced H is pushed into wetwell.



Core Melt and Containment Depressurization

- Significant core melt:
  - Uranium and actinides remain in core.
  - Gaseous and volatile fission products as well as H are released into wetwell and in part enter the drywell.
  - Drywell filled with inert Nitrogen (avoids H explosions)
- Pressure rise in drywell: it arrives at 8 bar against a design pressure of 5 bar.
- Containment depressurization (manually operated)
  - Unit 1, March 12 04:00
  - Unit 2, March 13 00:00
  - Unit 3, March 13 08:41



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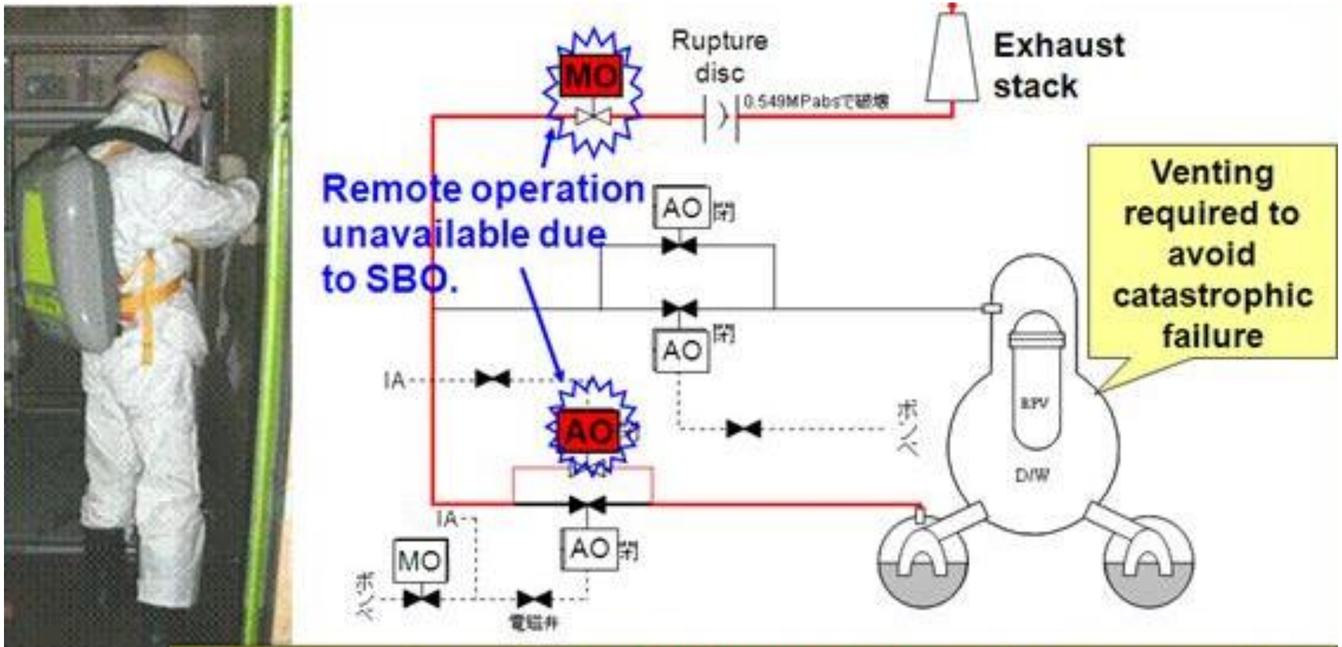
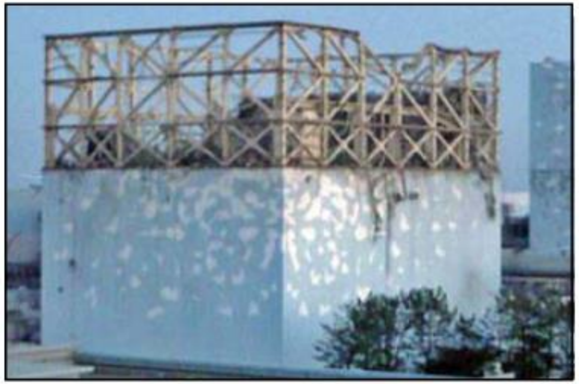
Containment Venting (Unit 1)

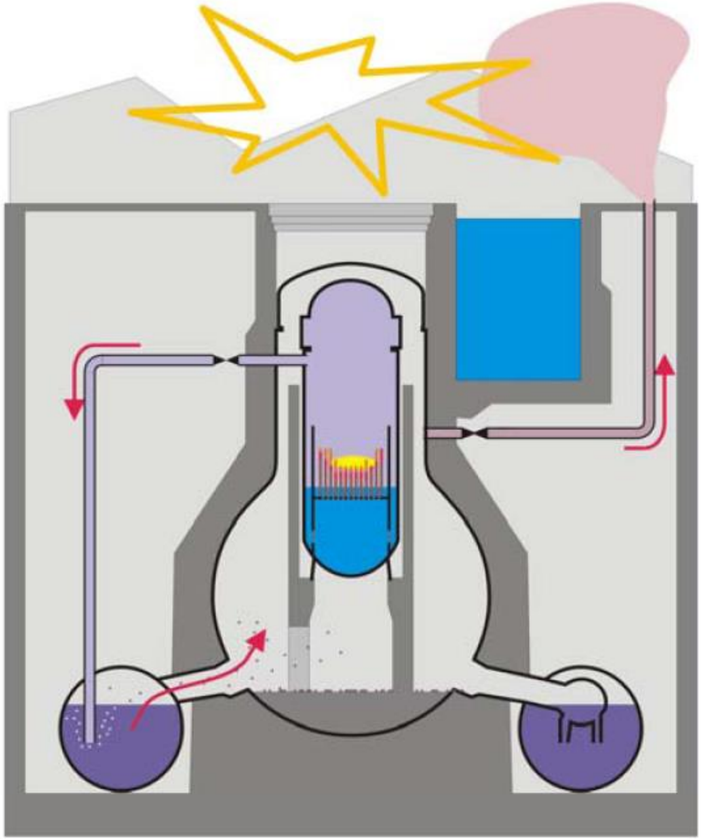


- Six men formed 3 “last-resort teams” to manually open 2 valves in highly-radioactive area
- Core damage already progressing by this time (3/12 9:04-9:30)

Unit 1 and 3 Explosions

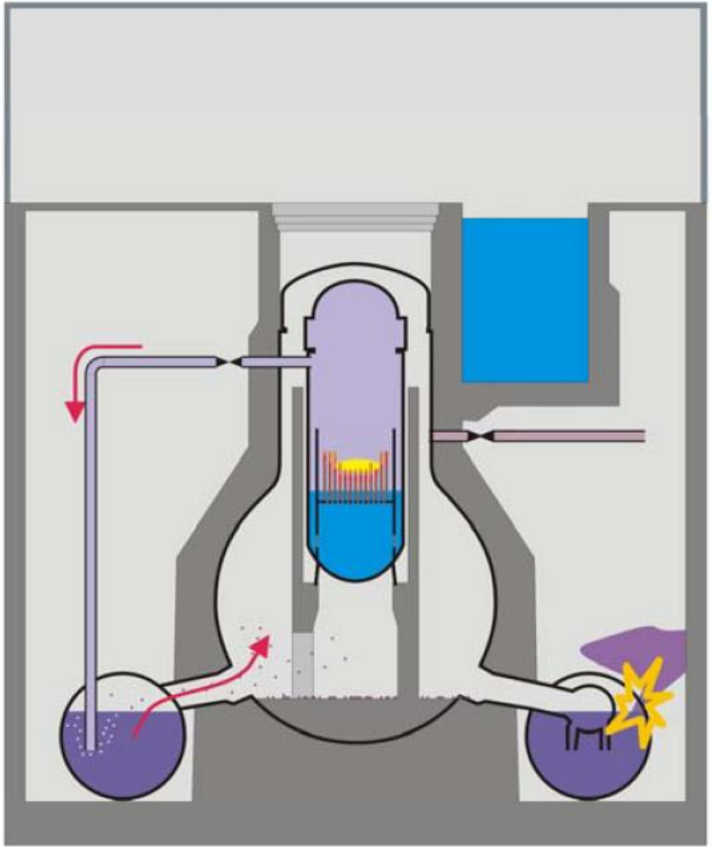
- H explosion inside the reactor service floor.
  - Unit 1 on March 12, 2011, 15:36 JST
  - Unit 3 on March 14, 2011, 11:00 JST
- No H-recombiners were installed.
- Destruction of steel-frame but concrete building remains undamaged.





Unit 2 Explosion

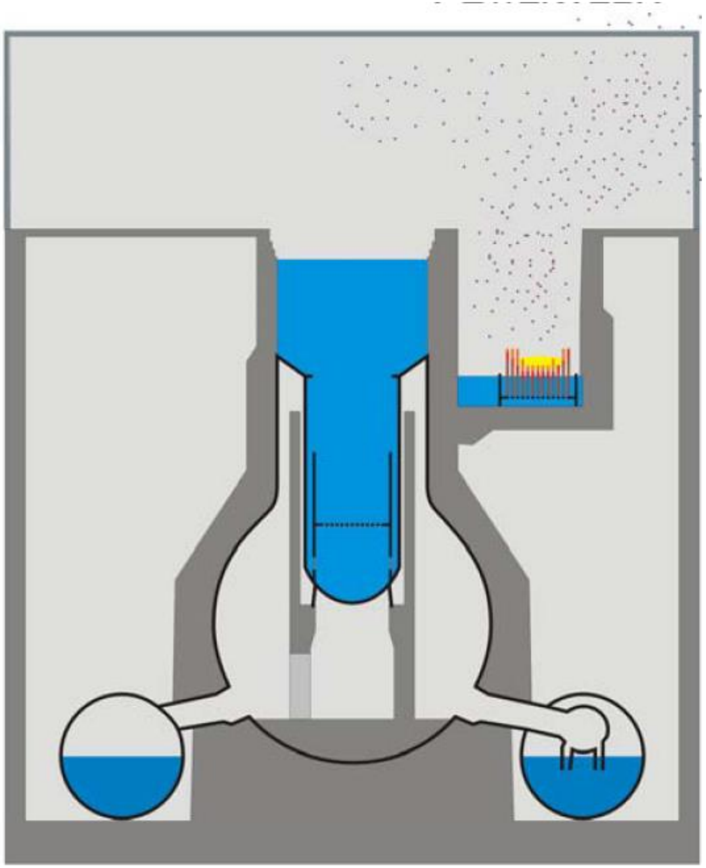
- Explosion with damage of the pressure suppression chamber in Unit 2 on March 15, 2011, 06:10 JST
- Probable damage of drywell due to pressure rise in containment.
- Highly contaminated water (required temporary evacuation).
- Uncontrolled release of gas from containment.



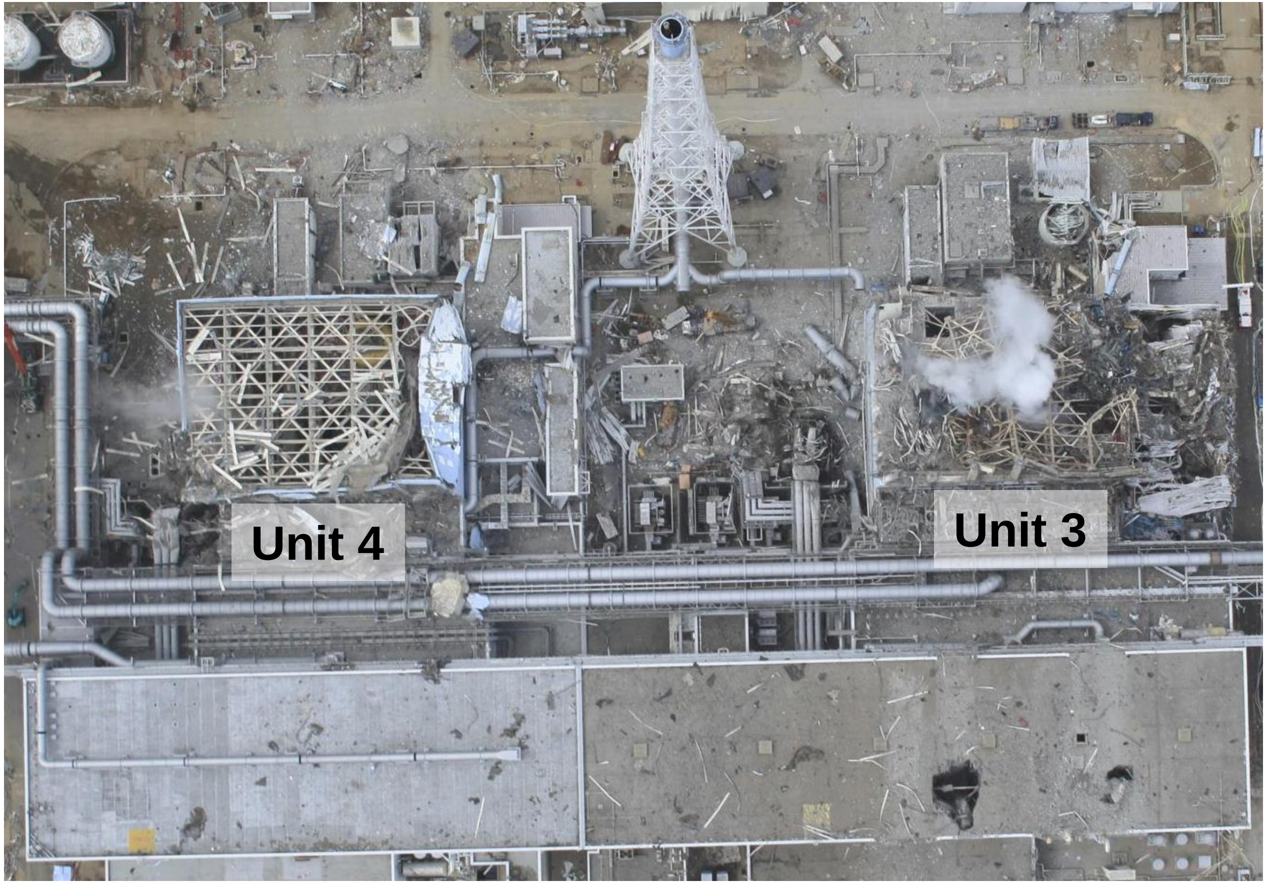
Unit 4 – Unexpected explosion with fire

- Explosion with fire in unit 4 close to the fuel assembly storage pool.
  - Not clear why.
  - H leaking from unit 3 through venting stack possible cause.

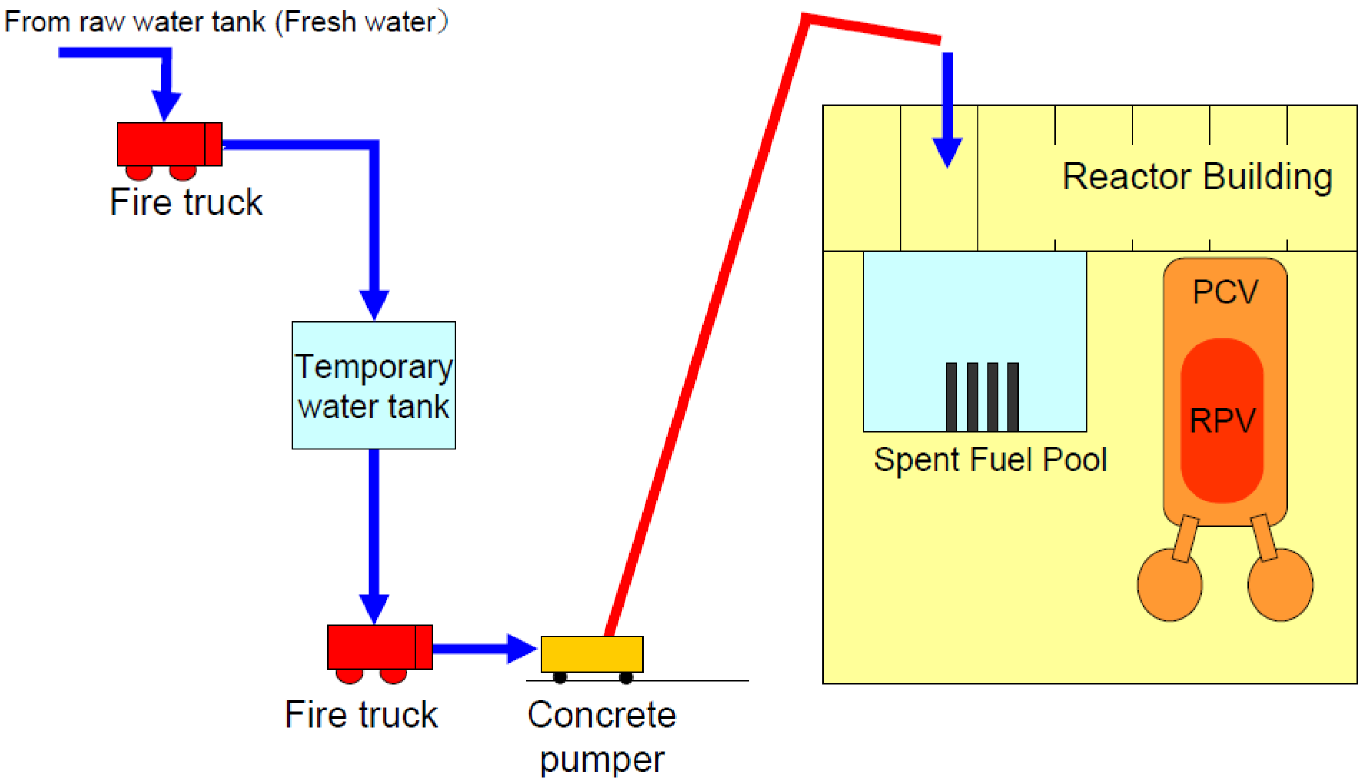
- Possible danger as entire core was in spent fuel:
  - Expected dryout in 10 days
  - No retention of fission products (no containment).
  - Risk of large releases into environment.



Venting Stacks of Units 3 and 4



Feeding Water into Spent Fuel Storage



Feeding Water into Spent Fuel Storage

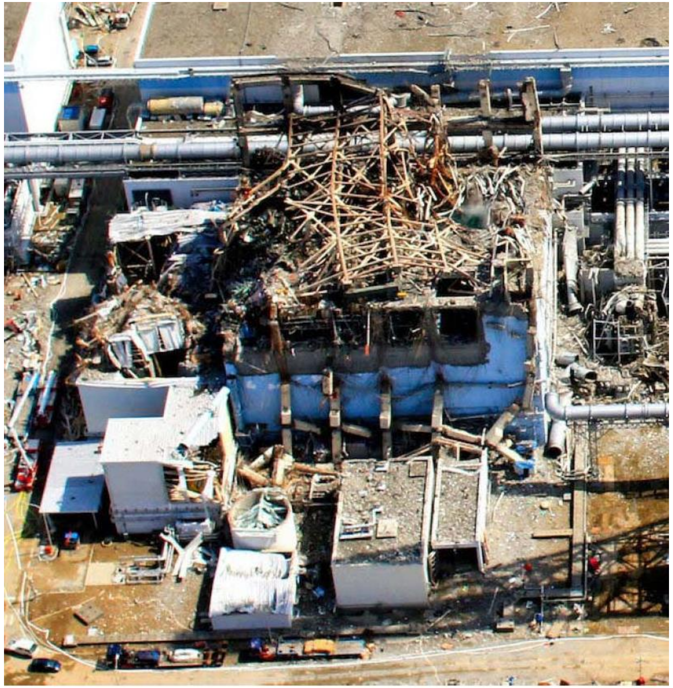
No Serious Damage to Fuel in Spent Fuel

Spent fuel pond apparently showing no serious damage

[Nuclear Emergency Response Headquarters, Government of Japan]

Destruction of reactor building roof by hydrogen explosion

[AREVA]

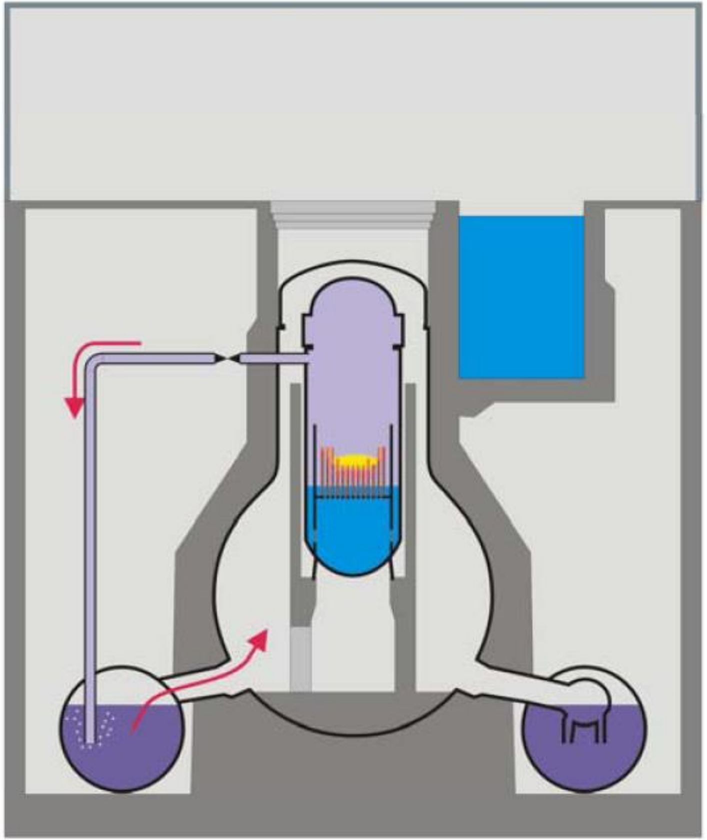


General view of damaged reactor building

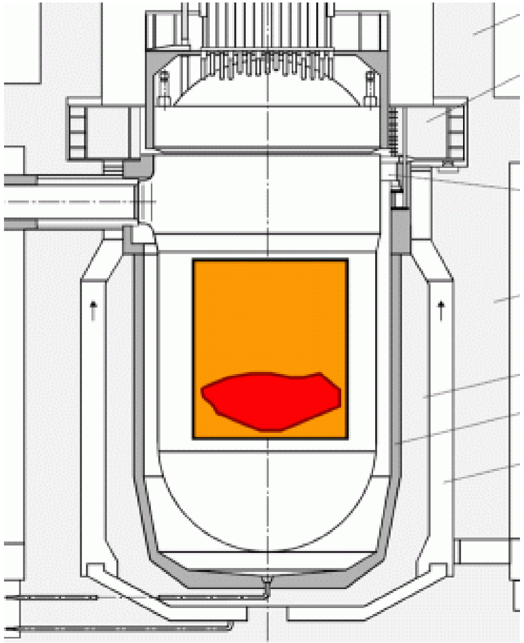
Core Melt Progression

- Eventually temperature keeps rising and core melt progresses:
  - At 1800°C cladding melts.
  - At 2500°C core debris bed formation.
  - At 2700°C melting of $(U,Zr)O_2$ eutectics

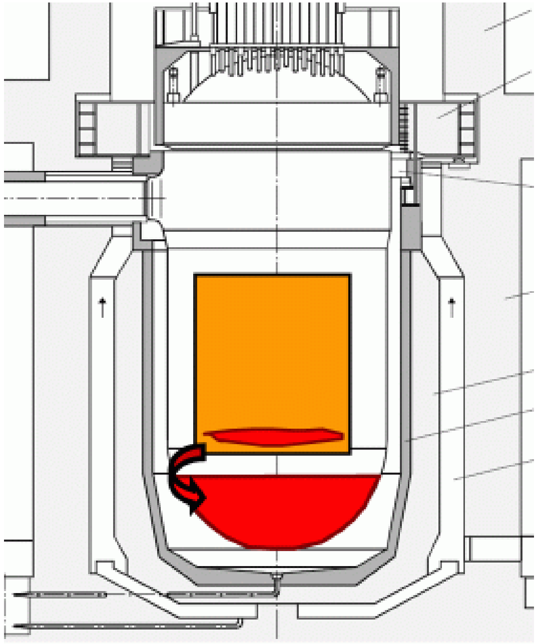
- TEPCO decides (maybe too late) to reflood core with seawater to stop melt progression
  - Unit 1, March 12 20:20 → **27h w/o water**
  - Unit 2, March 14 20:33 → **7h w/o water**
  - Unit 3, March 13 09:38 → **7h w/o water**



Phases of Core Degradation

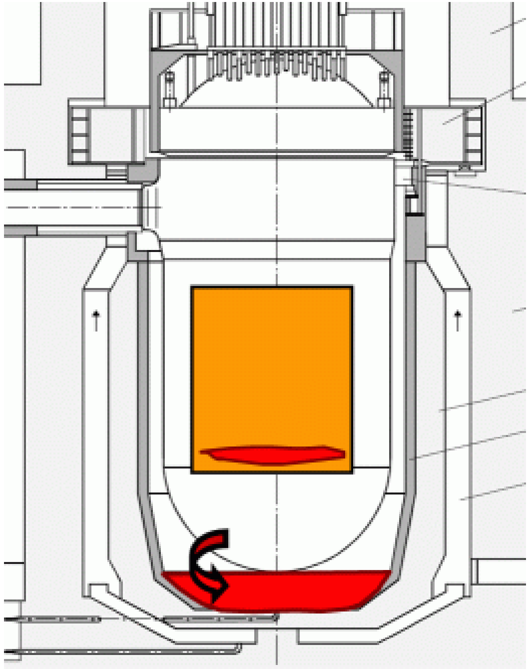


Melting of Reactor Core

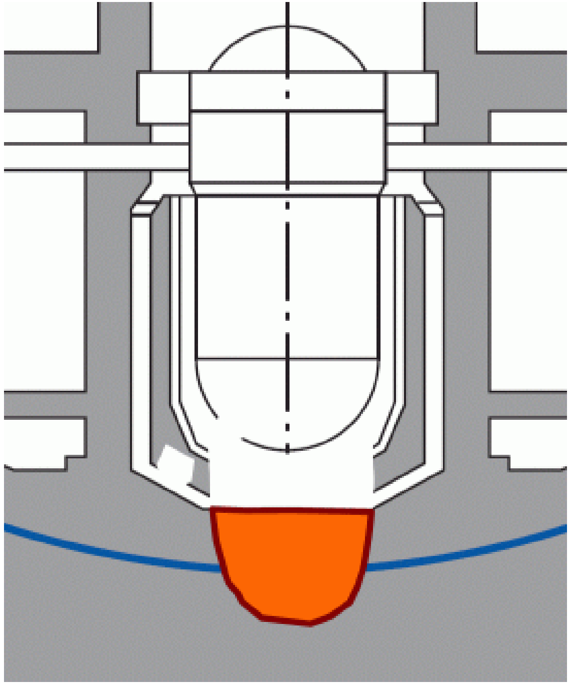


Relocation of Molten Core into lower plenum of RPV

Phases of Core Degradation



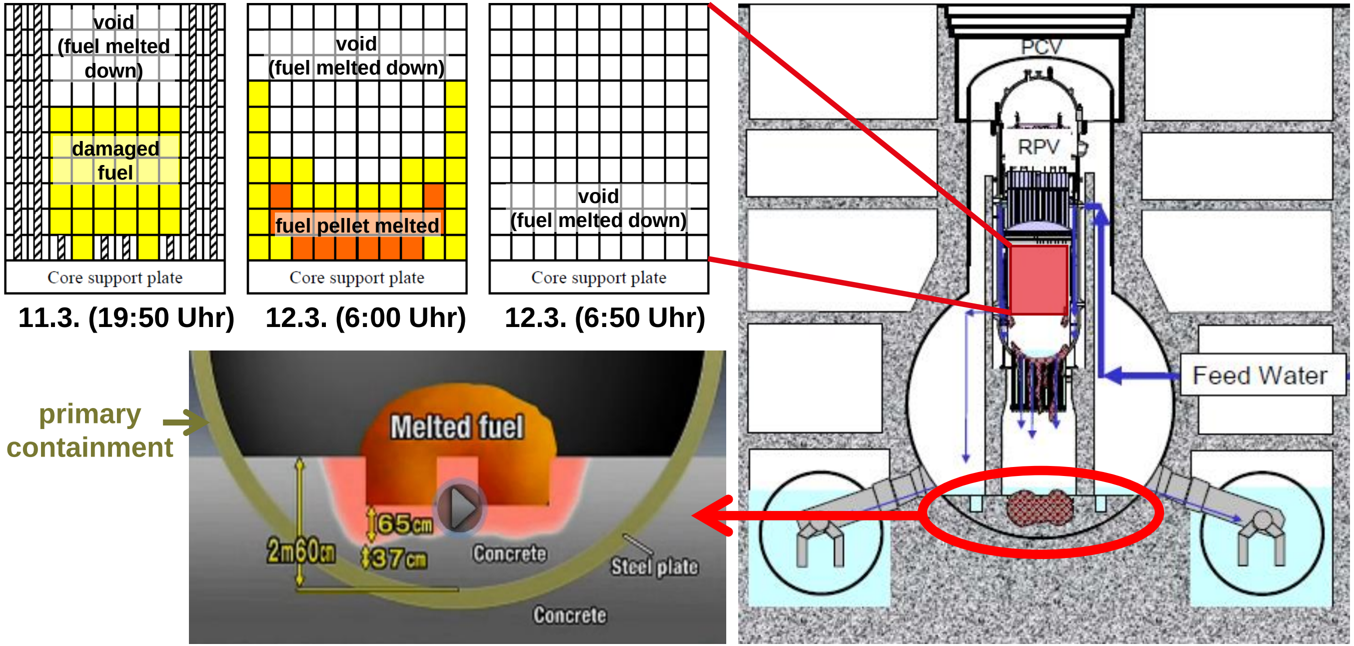
RPV failure and relocation into containment



Molten Core breaks through Containment

Status of the reactor core (unit 1) – results by TEPCO

- Calculations estimate that core did not go all through the bottom.
- However lateral leakage paths are possible so some water might be leaking in the soil.



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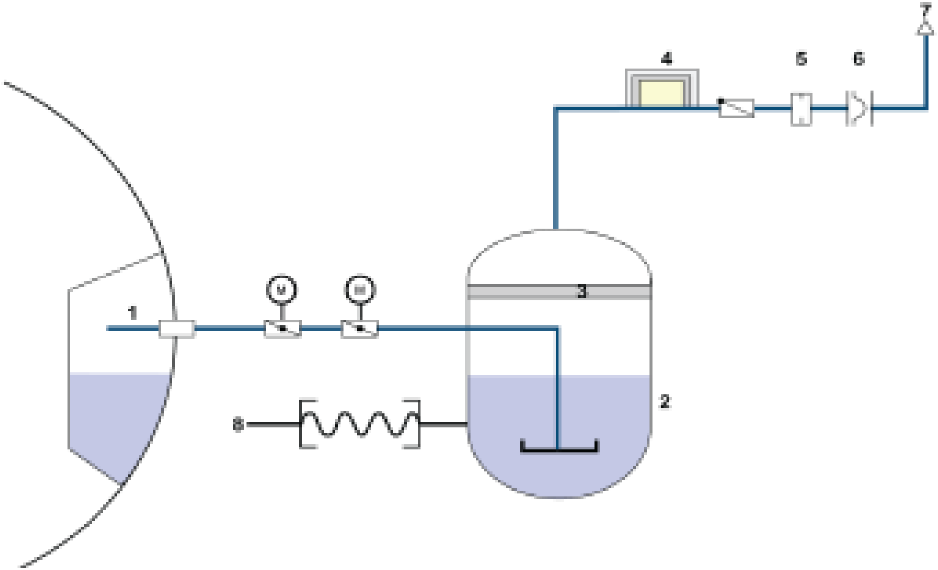
Lessons Learned

- Power Plants must be protected against ***simultaneous*** external hazards
- The management of Severe Accidents must take into account **extensive destruction of the surrounding** infrastructure.
- Neighbouring plants can aggravate the situation and physical protection of spent fuel pools must be secured (Unit 4).
- The grace time of a power plant before operator interaction is required should at least be several days (instead of hours)
- Long-term station blackout must be considered, and emergency equipment (mobile pumps, etc.) must be available on-site
- Management of **venting and H-control** is of paramount importance

BWR safety systems: Filtered Venting

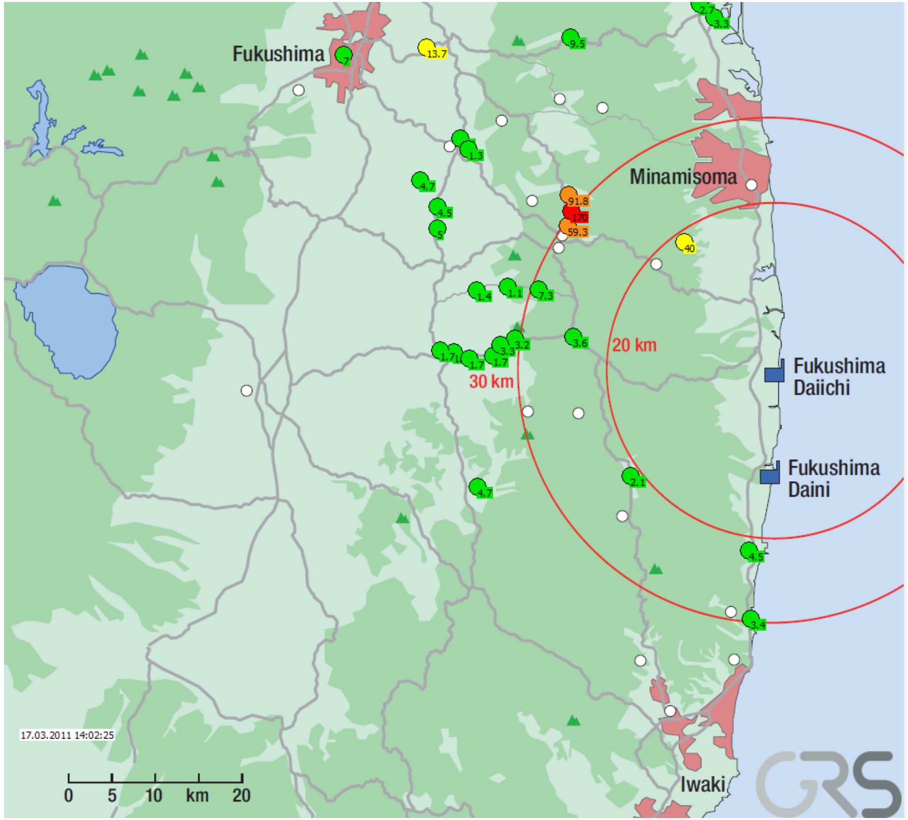


Containment Pressure Relief System

1. Condensation Chamber
2. Venturi Washer
3. Metal Fiber Filter
4. Dose Measurement Station
5. Orifice
6. Blow-Out Disk
7. Venting Stack
8. External Feed Water System (Fire Feed Line)

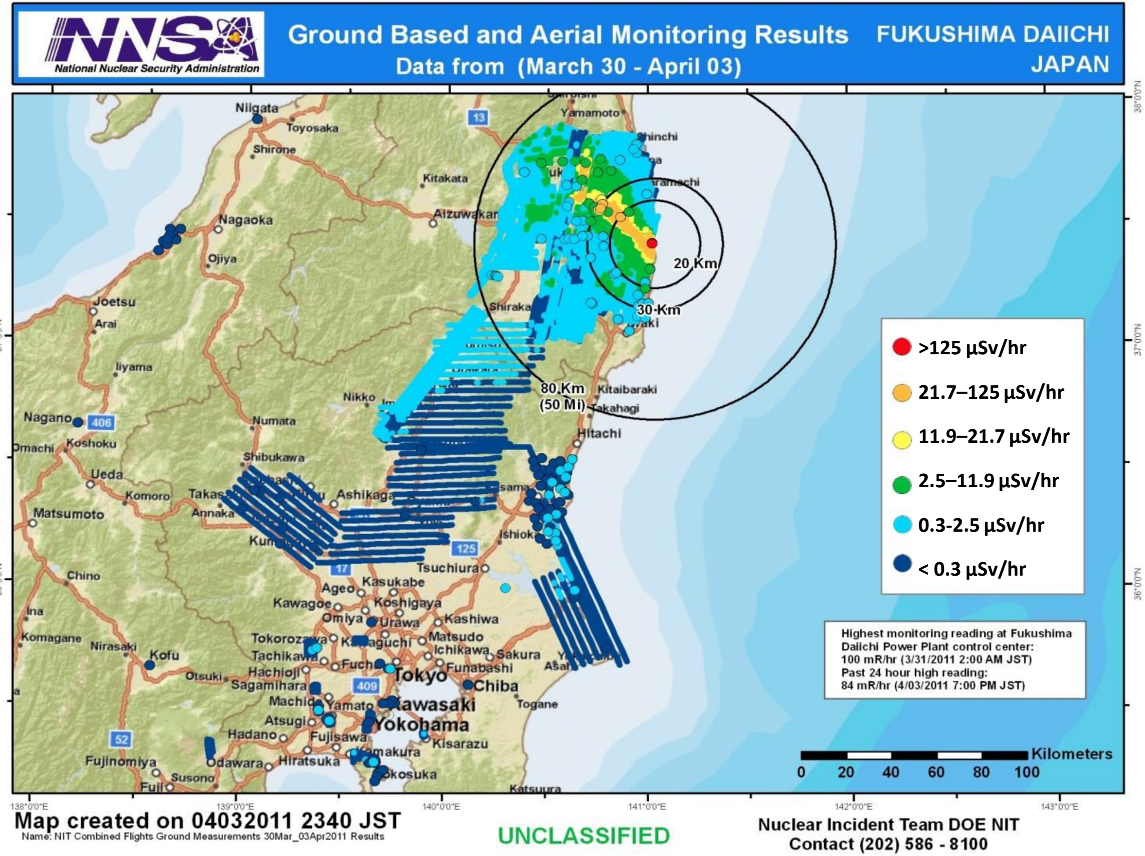
Picture of the Fort Calhoun Flooding (June 2011)

Radiologcal Situation around the Fukushima NPP

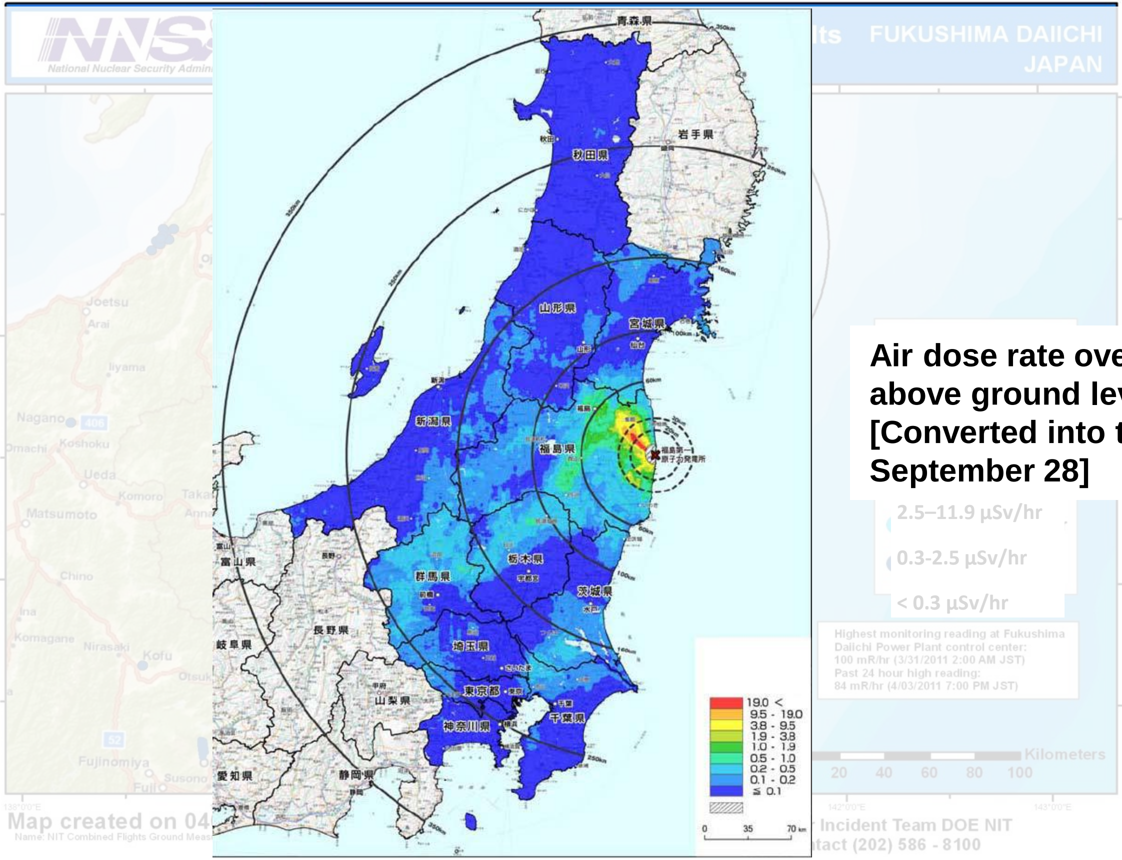


- Maximal local dose rate of 180 µSv/h at the outer limit of the30 km-Zone
- Mostly I-131 and Cs-134/137
- Measures
  - Evacuation (20 km)
  - Sheltering (30 km)
  - Restriction on food for the whole Fukushima prefecture

Radiologcal Situation in Japan



Radiologcal Situation in Japan



Air dose rate over 1 meter above ground level (μSv/h) [Converted into the value as of September 28]