The Fukushima Daiichi Incident

1. Plant Design
2. Accident Progression
3. Radiological releases
4. Spent fuel pools
5. Sources of Information

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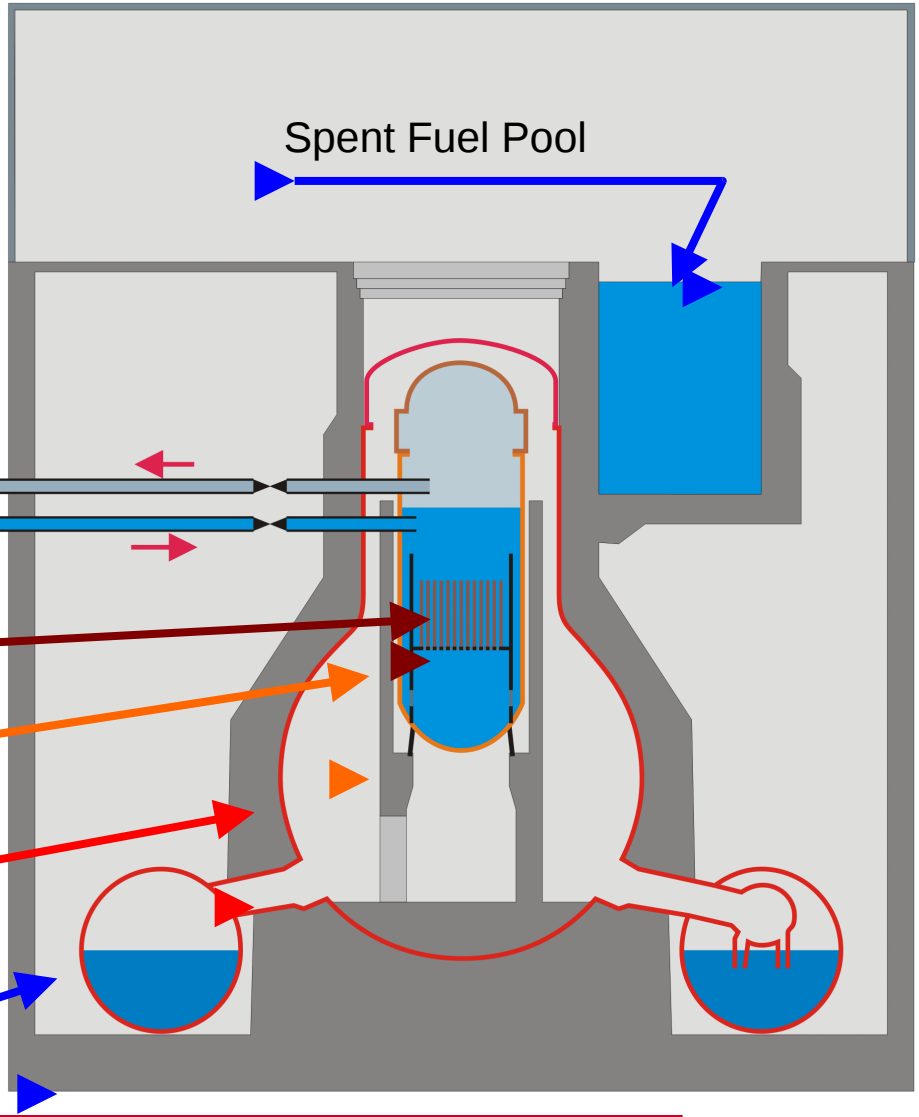
The Fukushima Daiichi Incident
1. Plant Design of Unit 1-4

- Fukushima Daiichi (Plant I)
  - Unit I
    - General Electric BWR3 (439 MW)
    - Containment MARK I
    - Operating since 1971
  - Unit II-III
    - General Electric BWR4 (760 MW)
    - Containment MARK I
    - Operating since 1974
  - Unit IV
    - Outage for regular inspection
  - Unit V-VI
    - Outage for regular inspection

The Fukushima Daiichi Incident

1. Plant Design of Unit 1-4

- Reactor Service Floor (Steel Construction)
- Concrete Reactor Building (secondary Containment)
- Reactor Core
- Reactor Pressure Vessel
- Containment (Dry well)
- Containment (Wet Well) / Condensation Chamber



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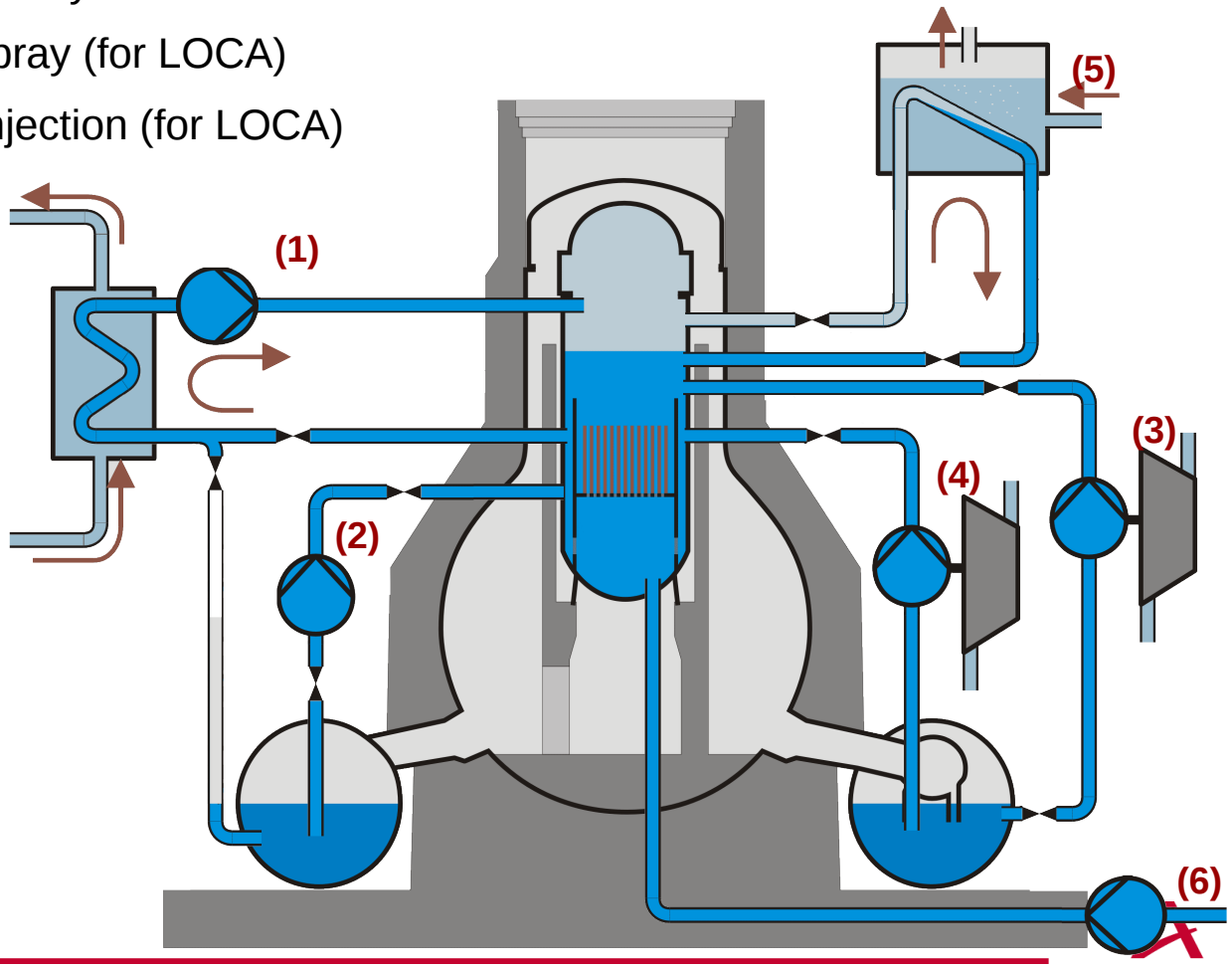
1. Plant Design of Unit 1-4

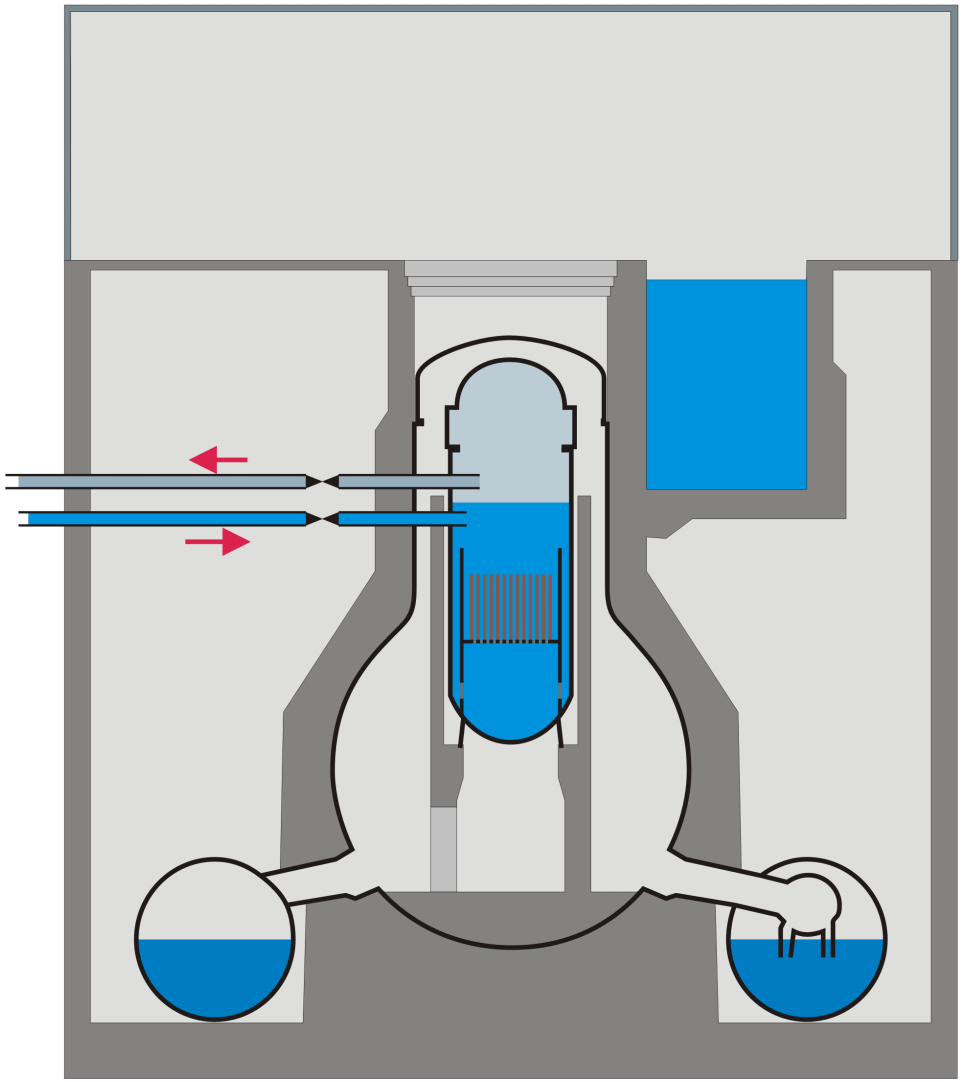
- Emergency Core Cooling Systems

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



The Fukushima Daiichi Incident
2. Accident progression

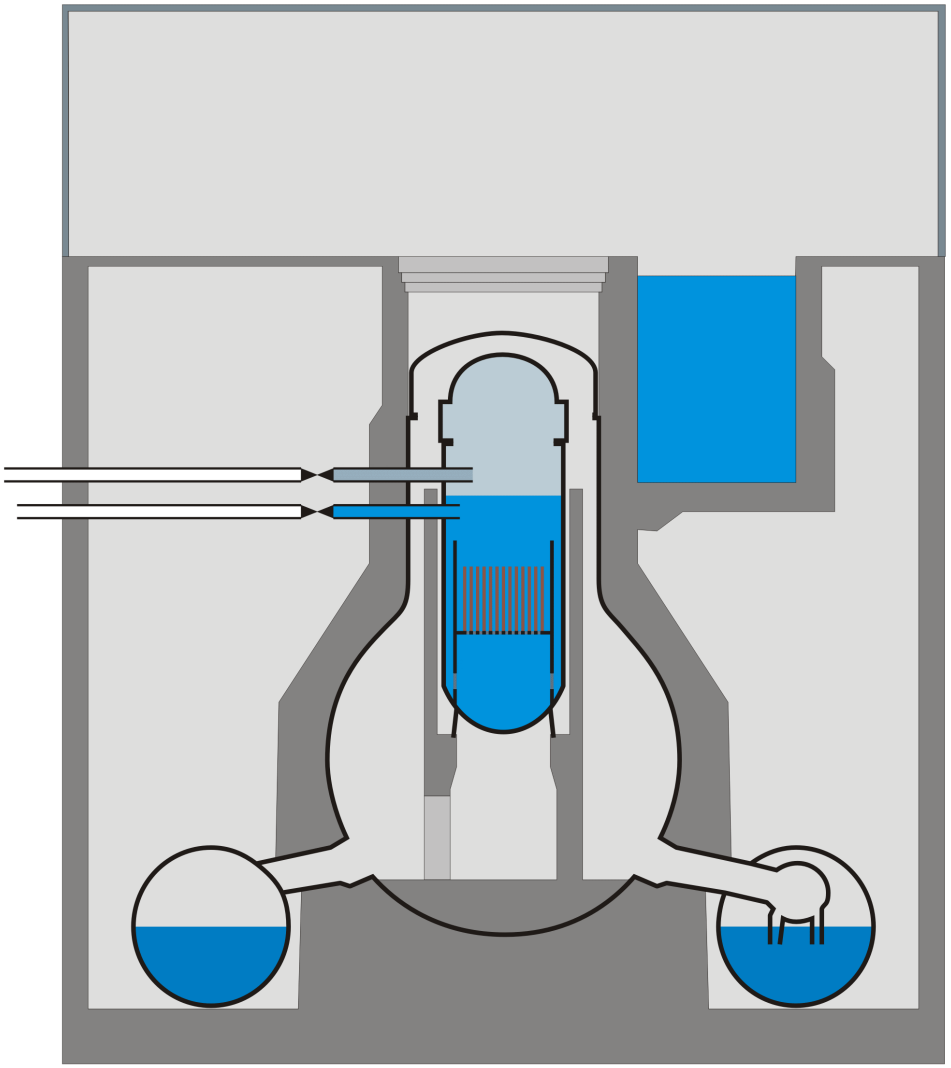
- 11.3.2011 14:46 - Earthquake
  - Magnitude 9
  - Power grid in northern Japan fails
  - Reactors itself are mainly undamaged
- SCRAM
  - Power generation due to Fission of Uranium stops
  - Heat generation due to radioactive Decay of Fission Products
    - After Scram ~6%
    - After 1 Day ~1%
   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



The Fukushima Daiichi Incident

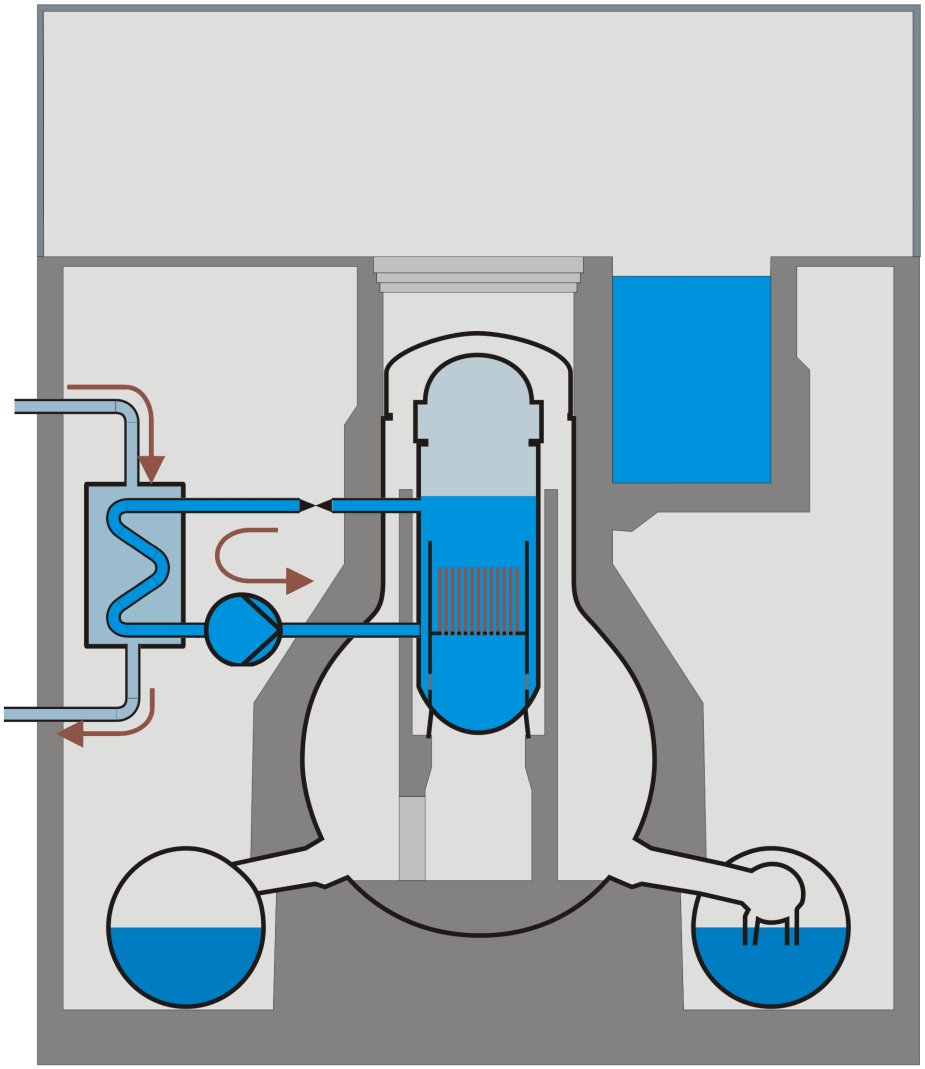
2. Accident progression

- 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



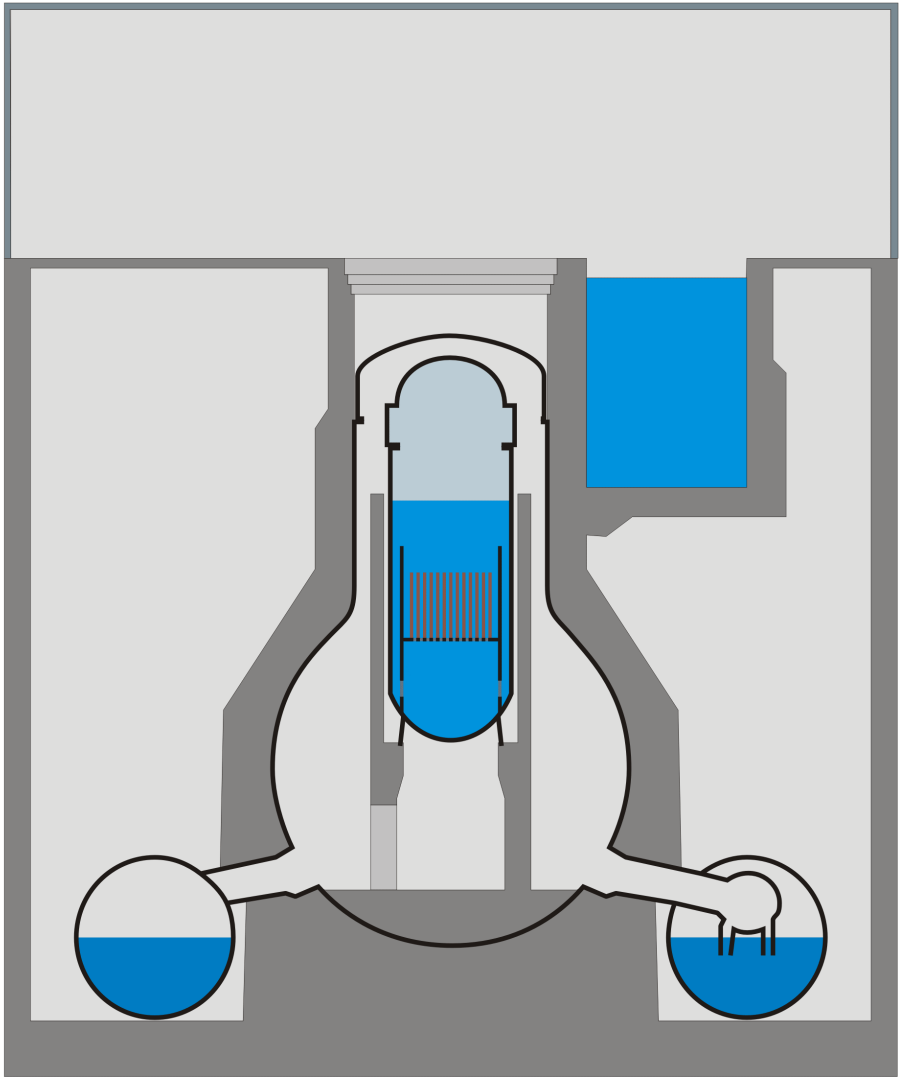
The Fukushima Daiichi Incident
2. Accident progression

- 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)



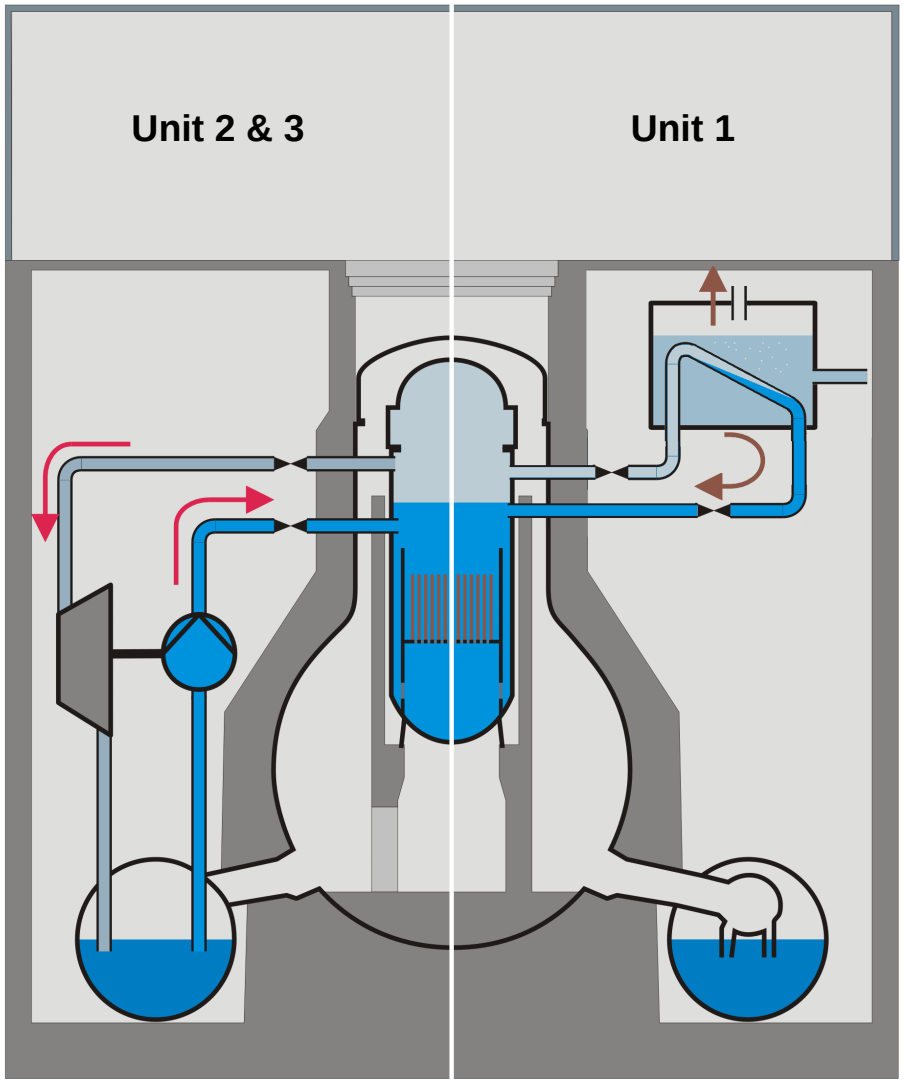
The Fukushima Daiichi Incident
2. Accident progression

- 11.3. 15:01(?) Tsunami hits plant
  - Plant Design for Tsunami height of up to 5.7-6.5m
  - Actual Tsunami height 7-11m
  - 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



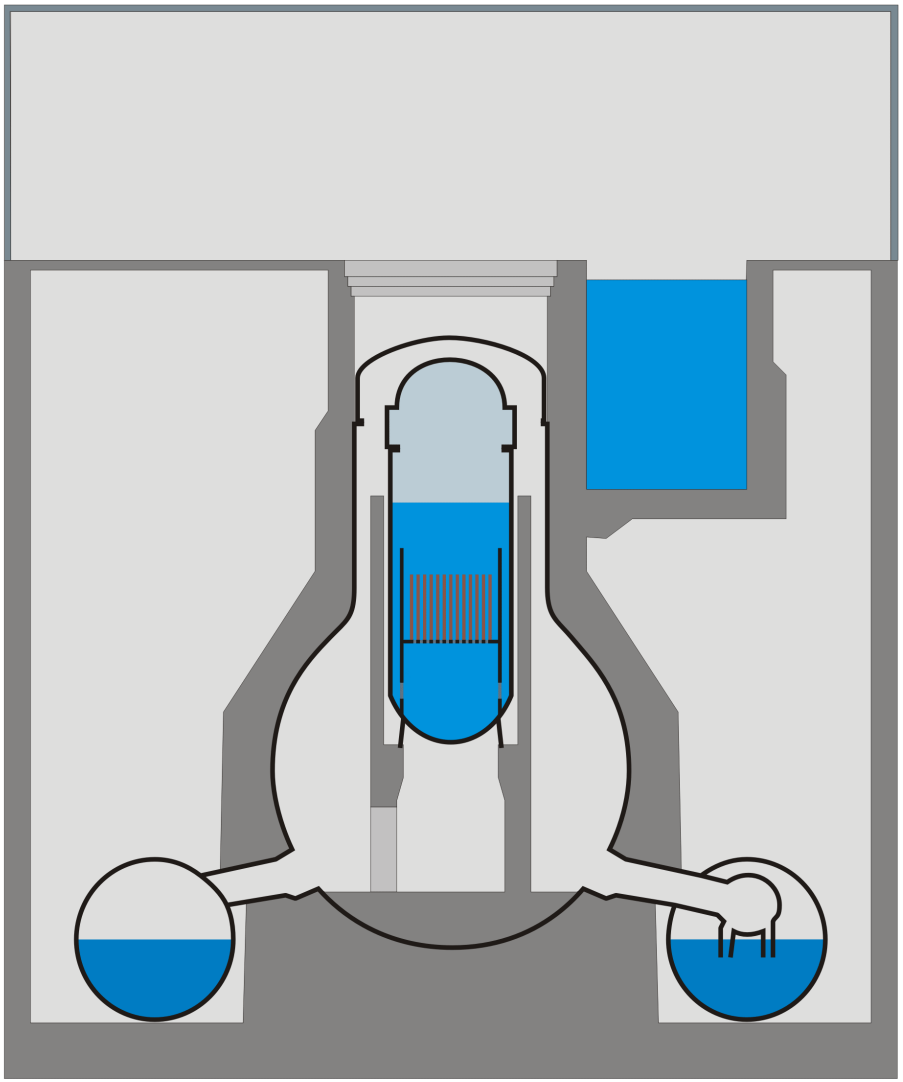
The Fukushima Daiichi Incident
2. Accident progression

- 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
    - Wet-Well Temperature < 100°C
  - No heat removal from the buildings



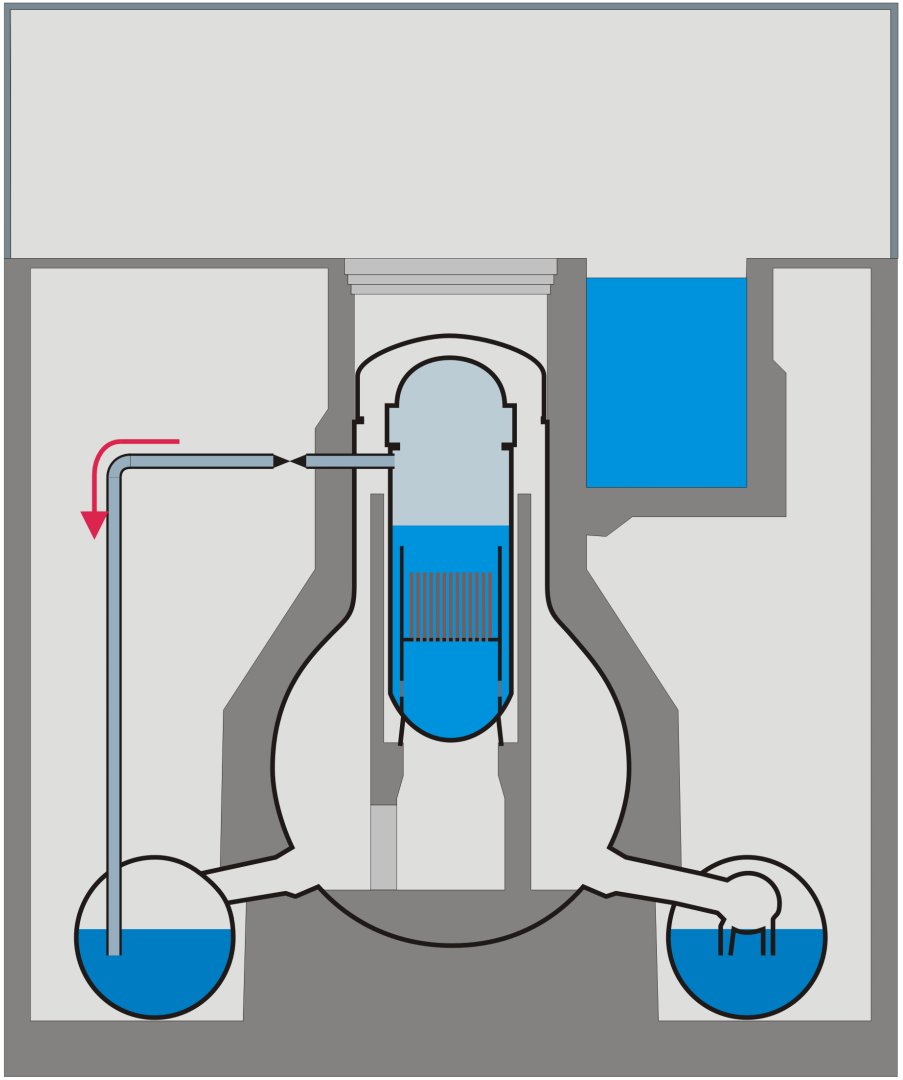
The Fukushima Daiichi Incident
2. Accident progression

- 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



The Fukushima Daiichi Incident
2. Accident progression

- 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



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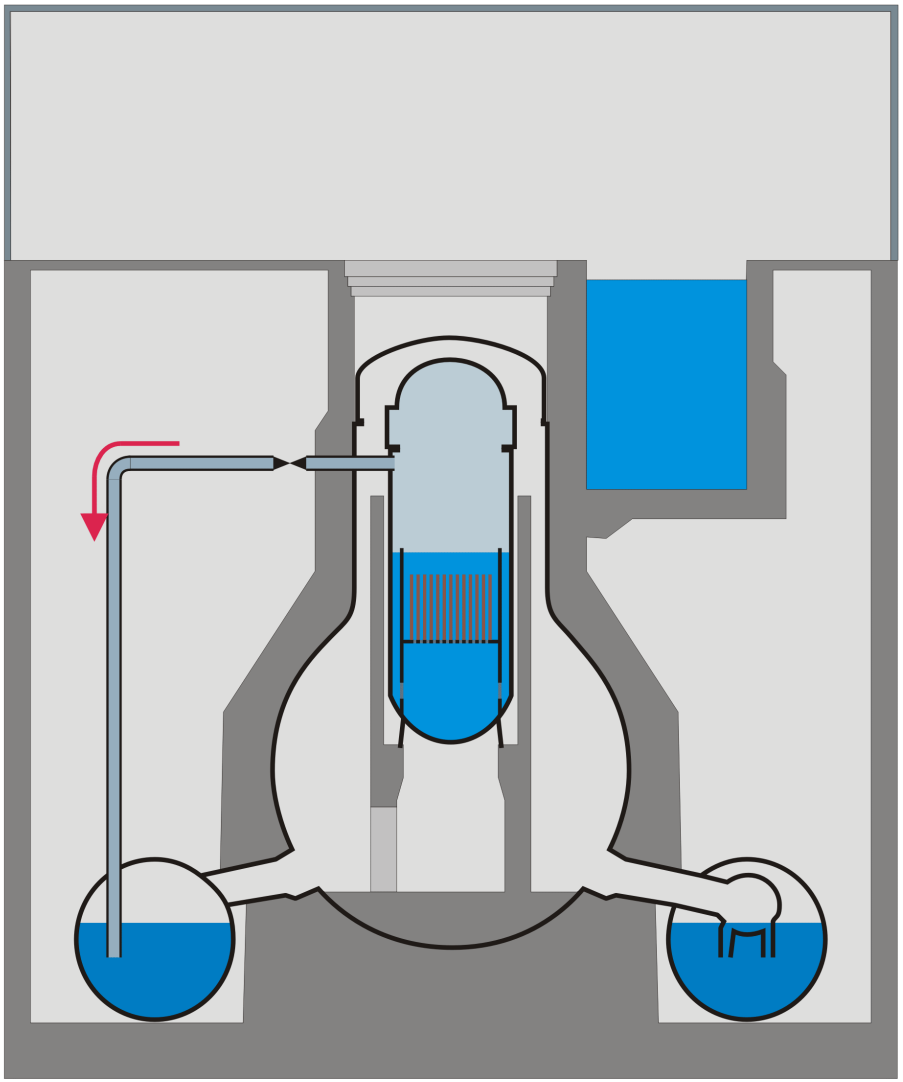

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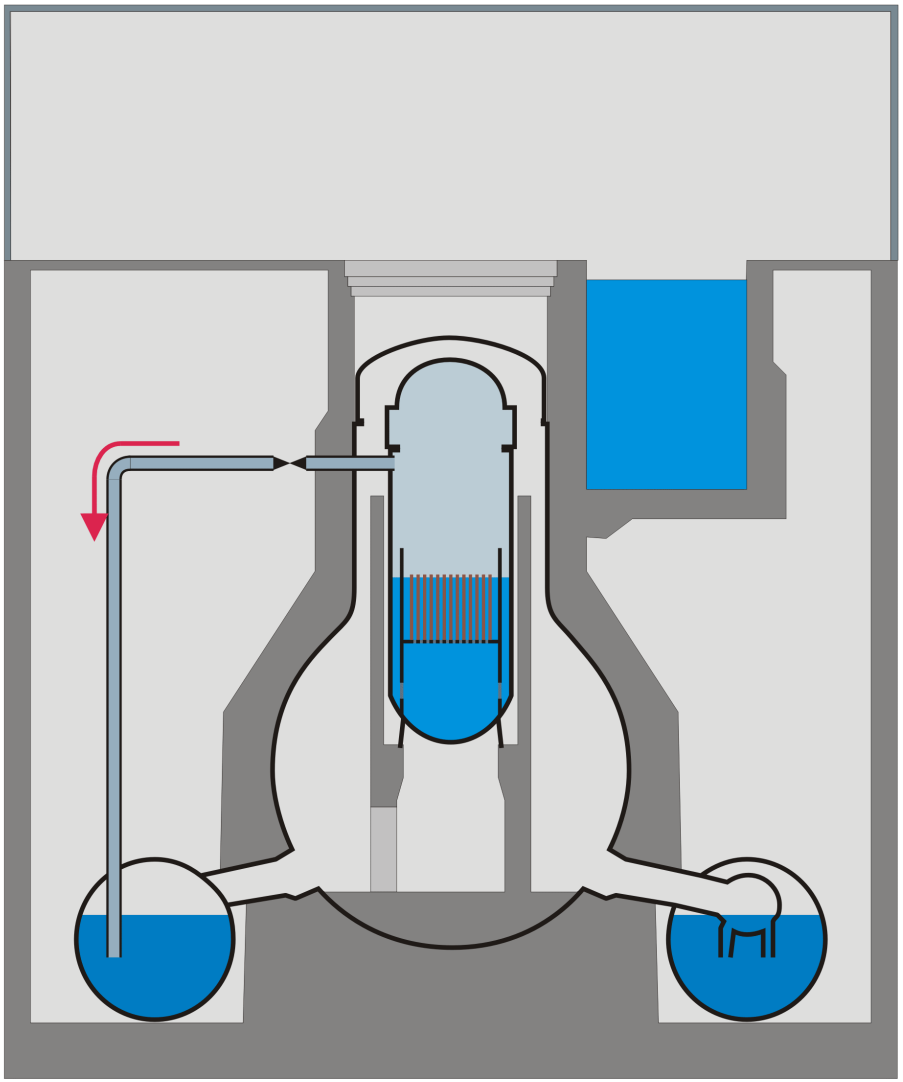

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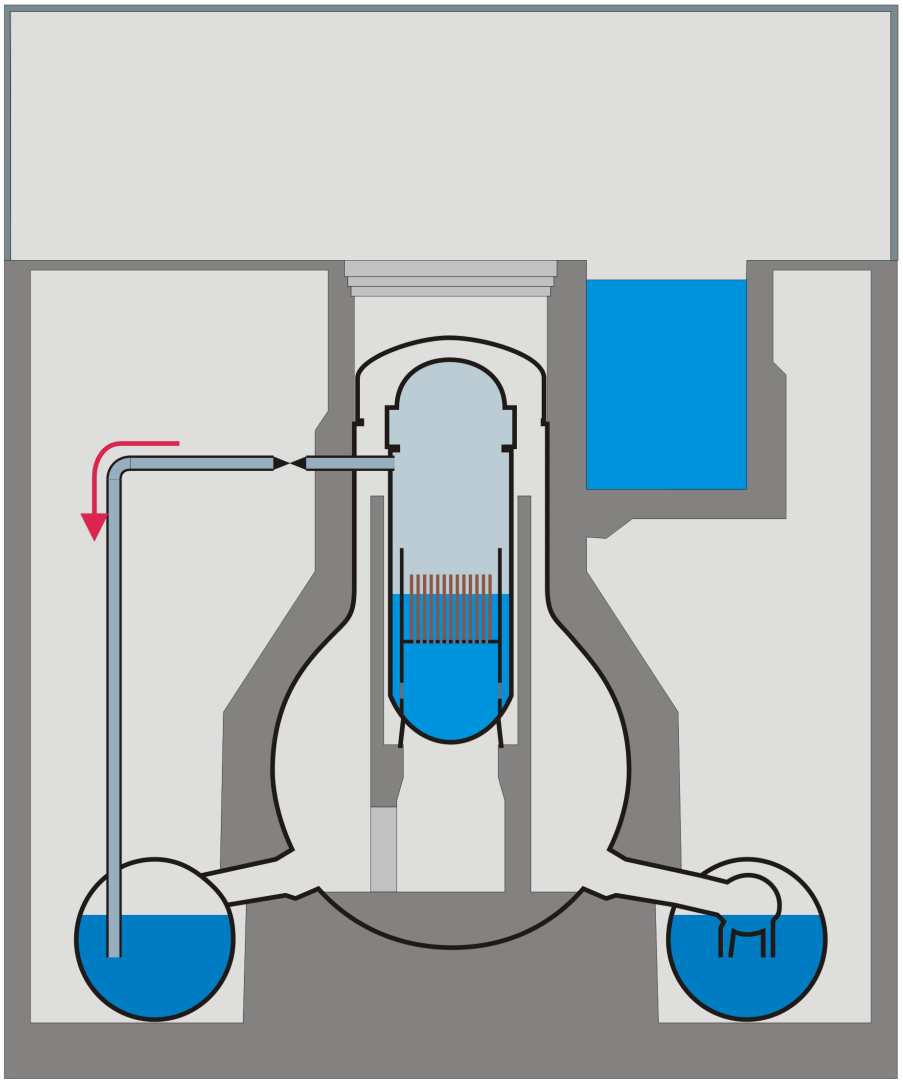
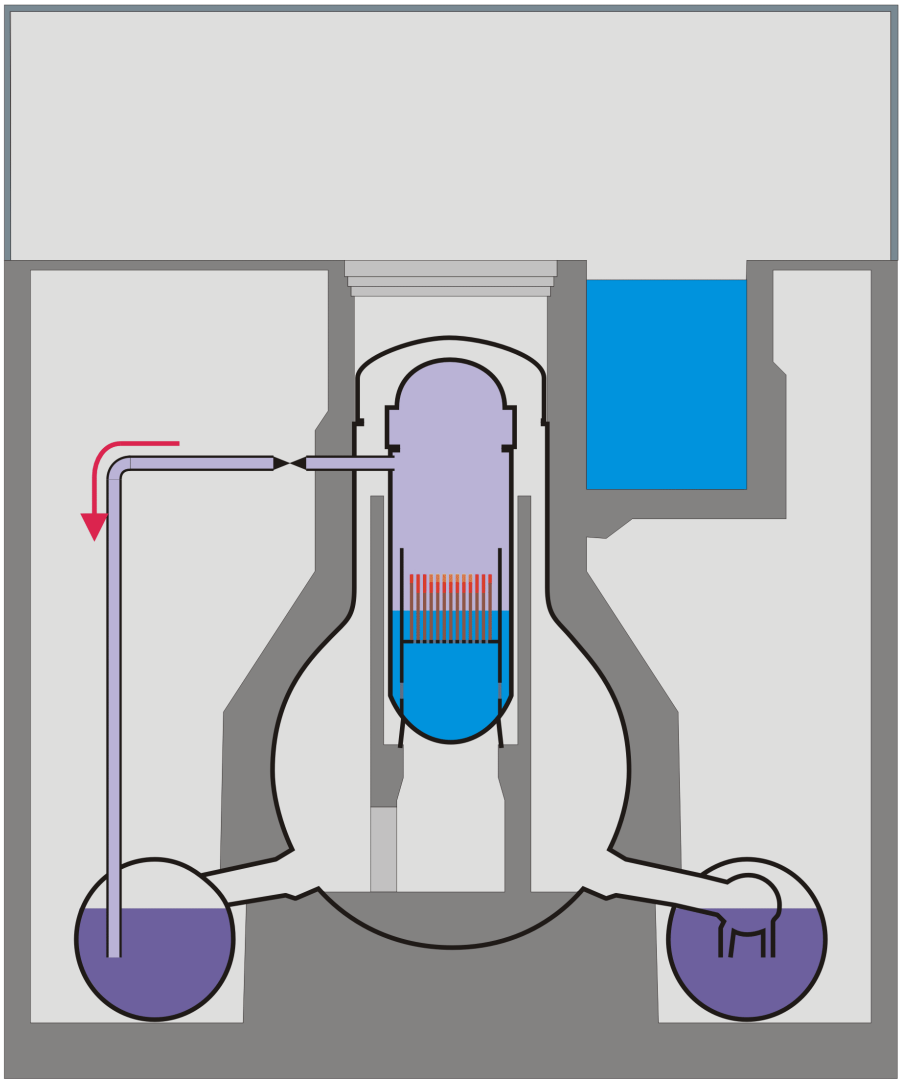


The Fukushima Daiichi Incident
2. Accident progression

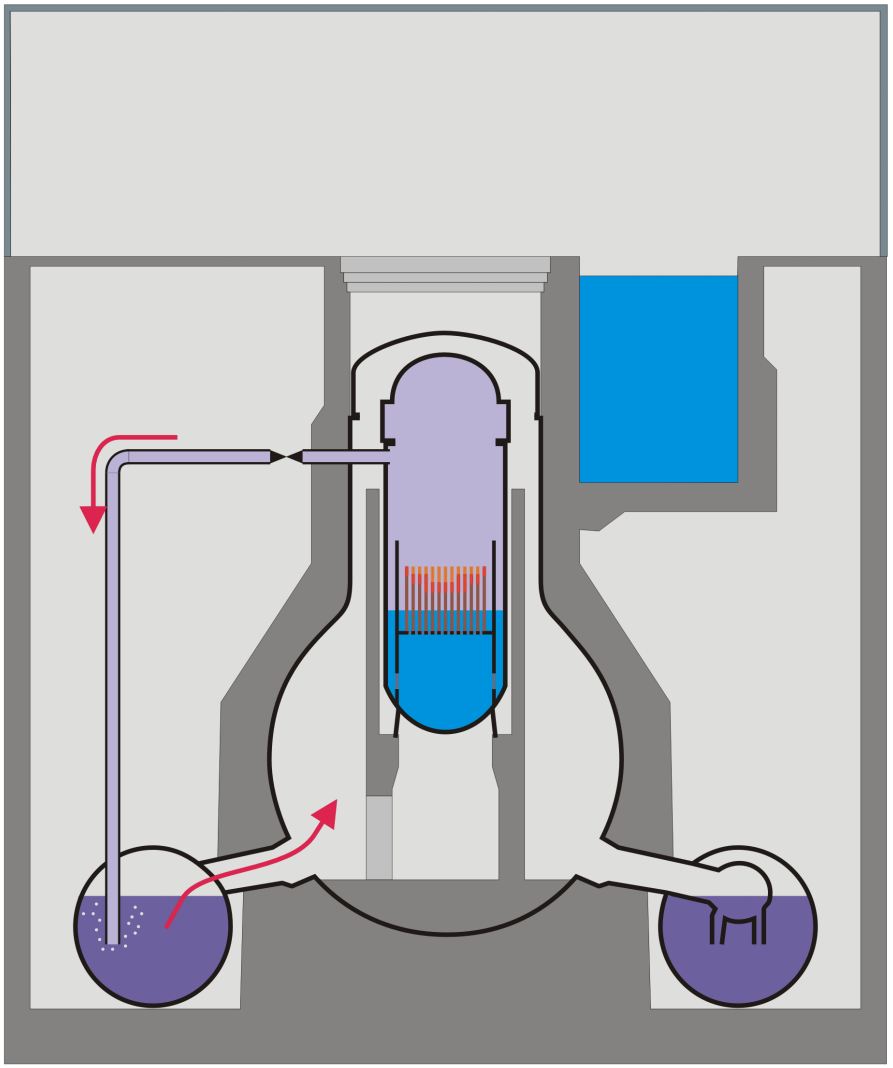
- ~50% of the core exposed
  - Cladding temperatures rise, but still no significant core damage
- ~2/3 of the core exposed
  - Cladding temperature exceeds ~900°C
  - Balooning / Breaking of the cladding
  - Release of fission products from the fuel rod gaps

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



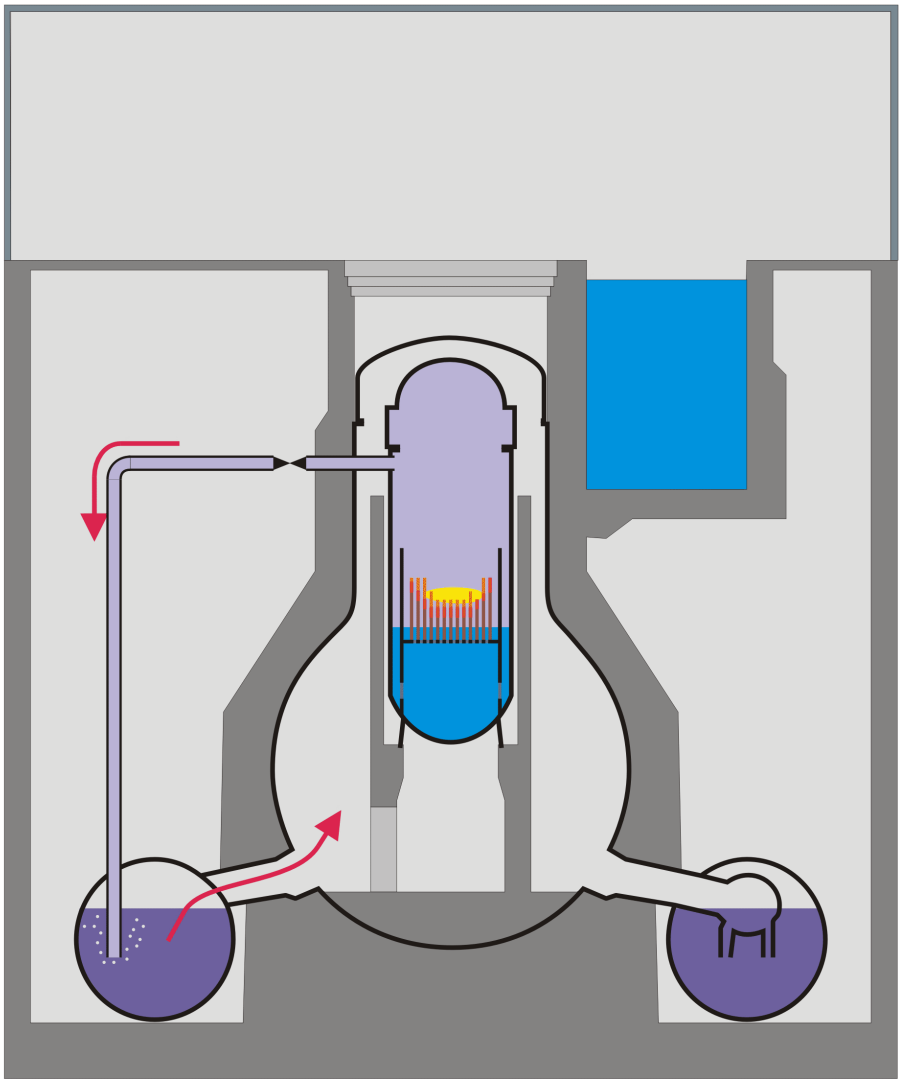
The Fukushima Daiichi Incident
2. Accident progression

- ~3/4 of the core exposed
  - Cladding exceeds ~1200°C
  - Zirconium in the cladding starts to burn under steam atmosphere
  - **$Zr + 2H_20 \rightarrow ZrO_2 + 2H_2$**
  - Exothermal reaction further heats the core
  - Estimated masses hydrogen
    - Unit 1: 300-600kg
    - Unit 2/3: 300-1000kg
  - Hydrogen gets pushed via the wet-well and the wet-well vacuum breakers into the dry-well



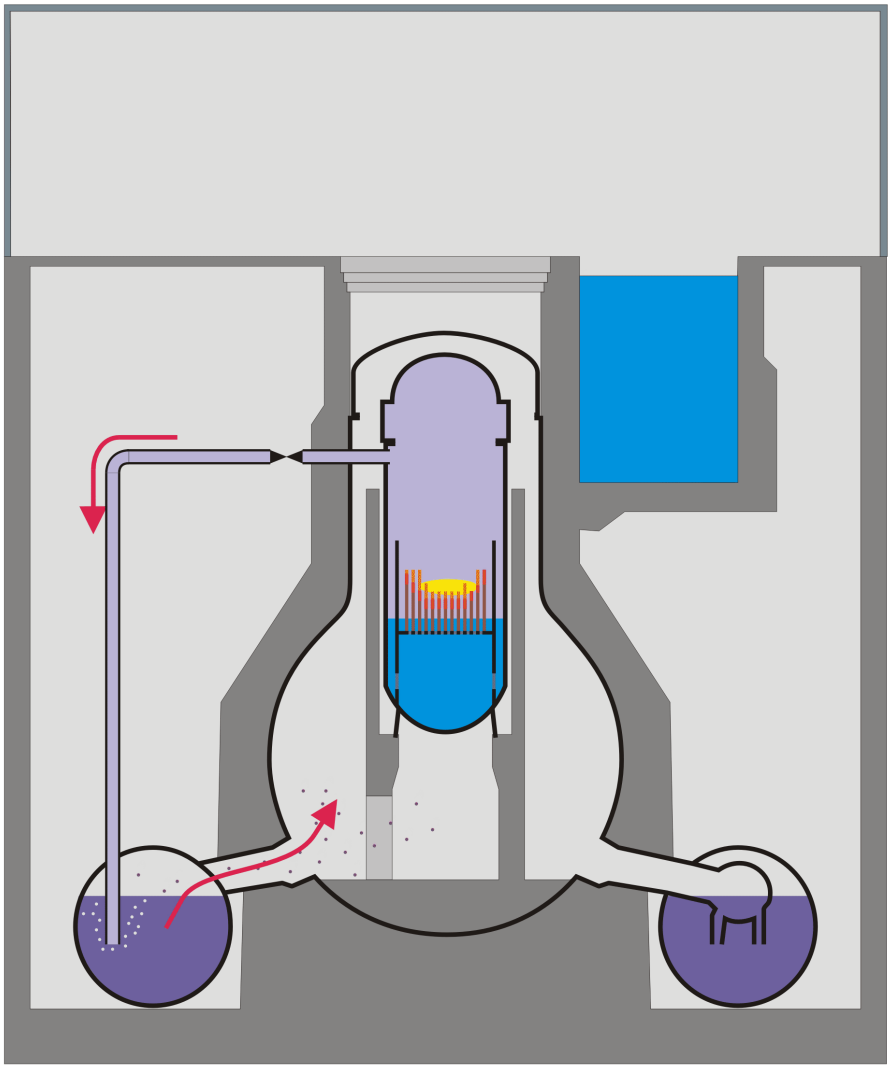
The Fukushima Daiichi Incident
2. Accident progression

- at ~1800°C [expected Unit 1,2,3]
  - Melting of the Cladding
  - Melting of the steel structures
- at ~2500°C [expected Unit 1,2]
  - Breaking of the fuel rods
  - debris bed inside the core
- at ~2700°C [maybe 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 (27h w.o. water)
  - Unit 2: 14.3. 20:33 (7h w.o. water)
  - Unit 3: 13.3. 9:38 (7h w.o. water)



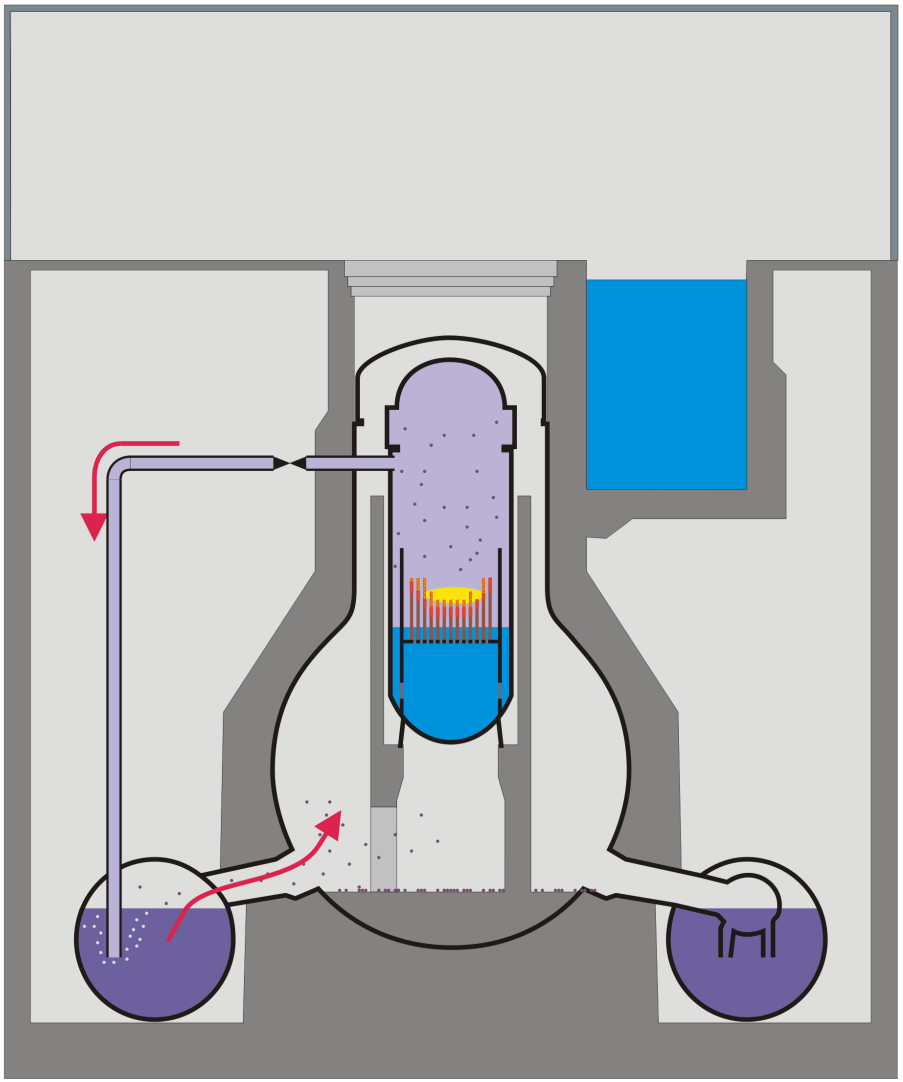
The Fukushima Daiichi Incident
2. Accident progression

- 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
  - Deposition of aerosols on surfaces further decontaminates air



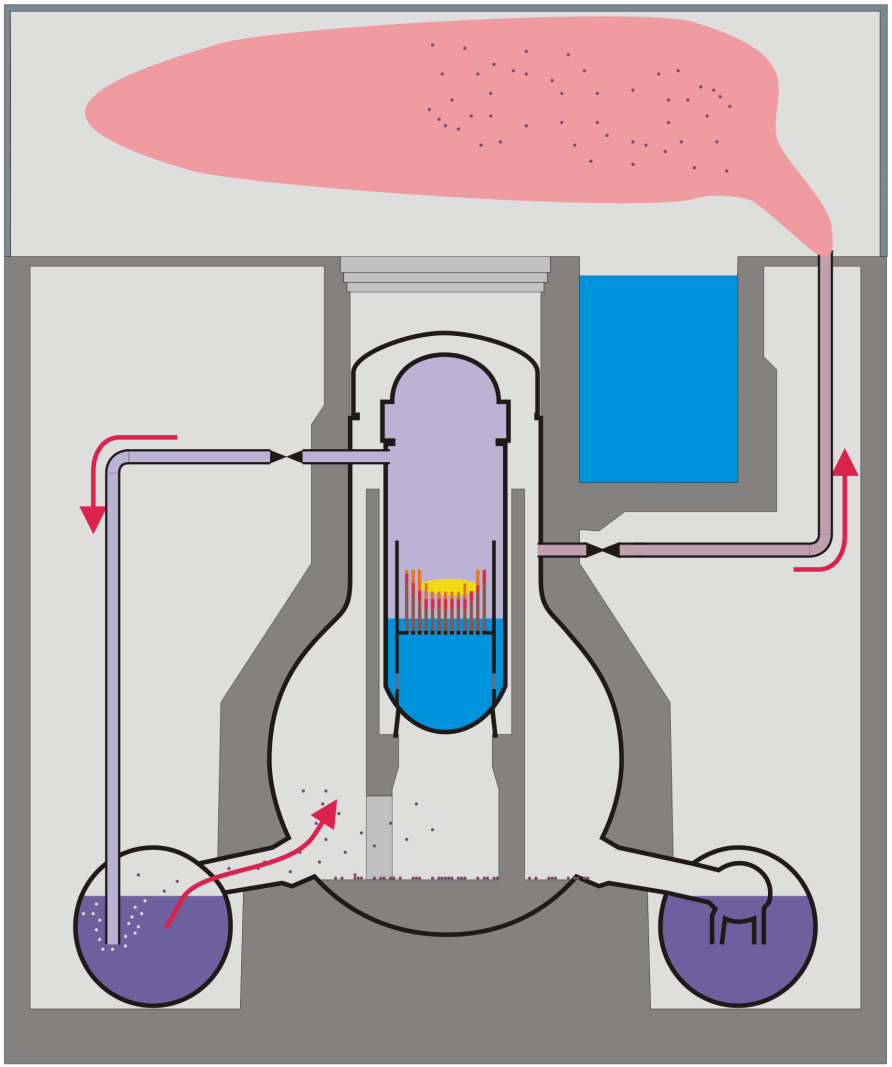
The Fukushima Daiichi Incident
2. Accident progression

- 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



The Fukushima Daiichi Incident
2. Accident progression

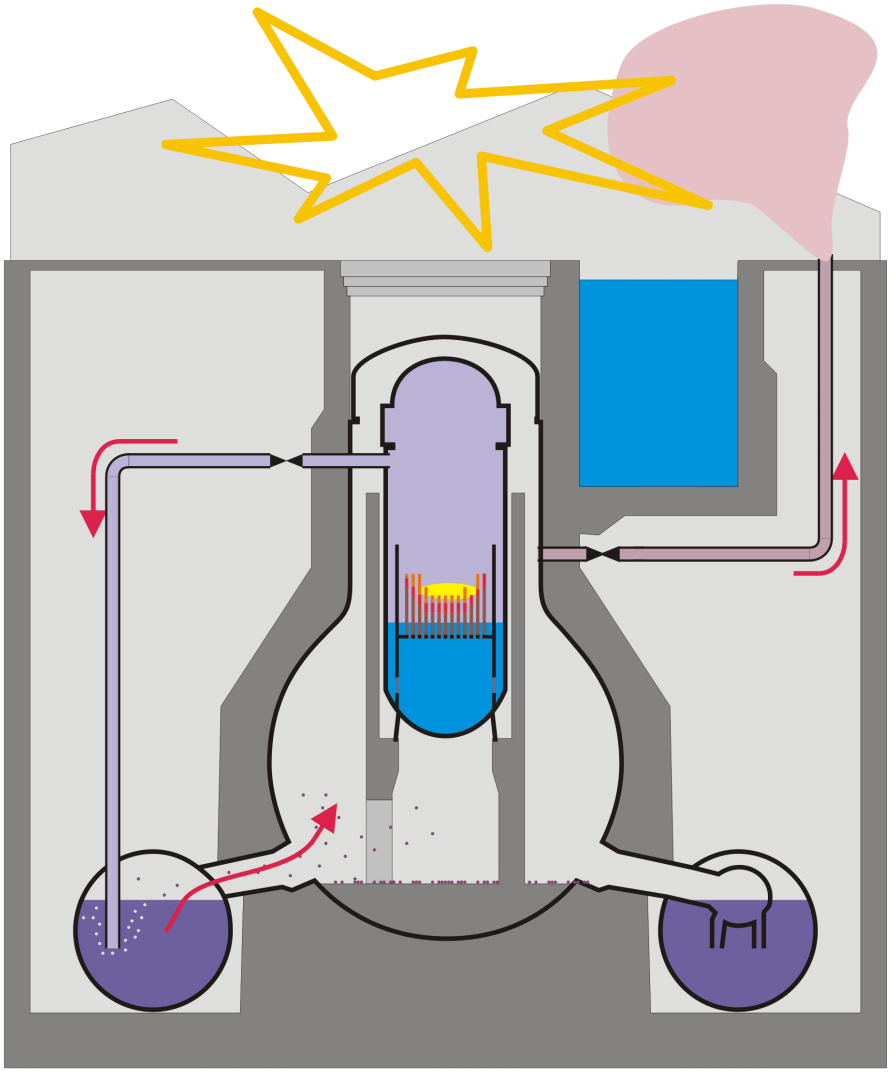
- Positive und negative Aspects of depressurizing the containment
  - Removes Energy from the Reactor building (only way left)
  - Reducing the pressure to ~4 bar
  - Release of small amounts of Aerosols (Iodine, Cesium…)
  - Release of all noble gases
  - Release of Hydrogen
- Release of unfiltered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



The Fukushima Daiichi Incident

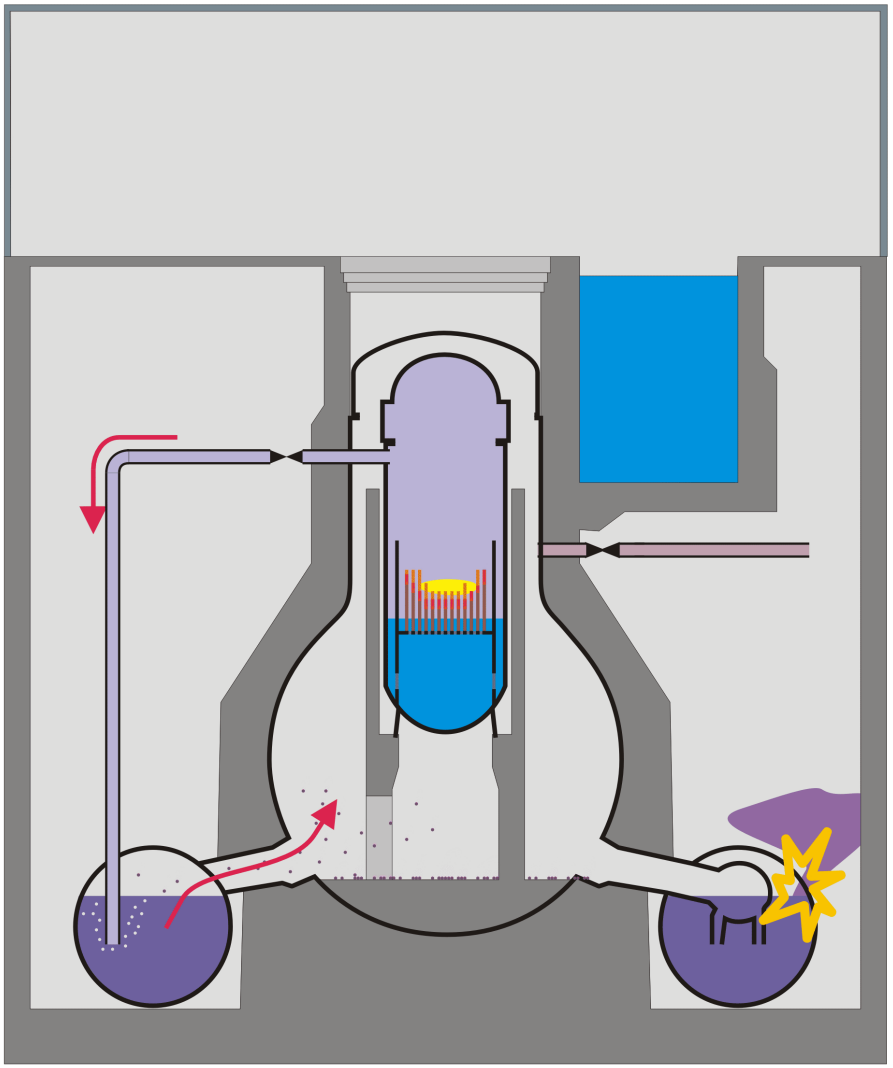
2. Accident progression

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



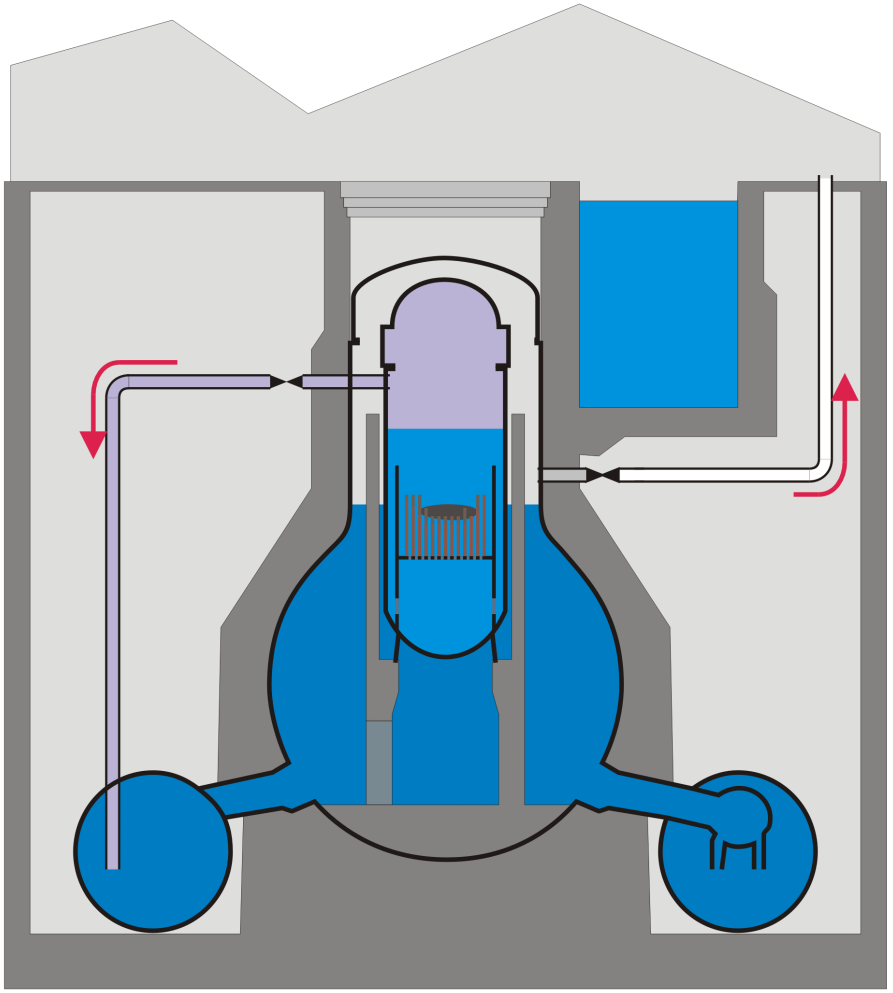
The Fukushima Daiichi Incident
2. Accident progression

- Unit 2
  - Probably Hydrogen leakage of the condensation chamber (actual pressure exceeds design pressure)
  - Burn 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



The Fukushima Daiichi Incident
2. Accident progression

- 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

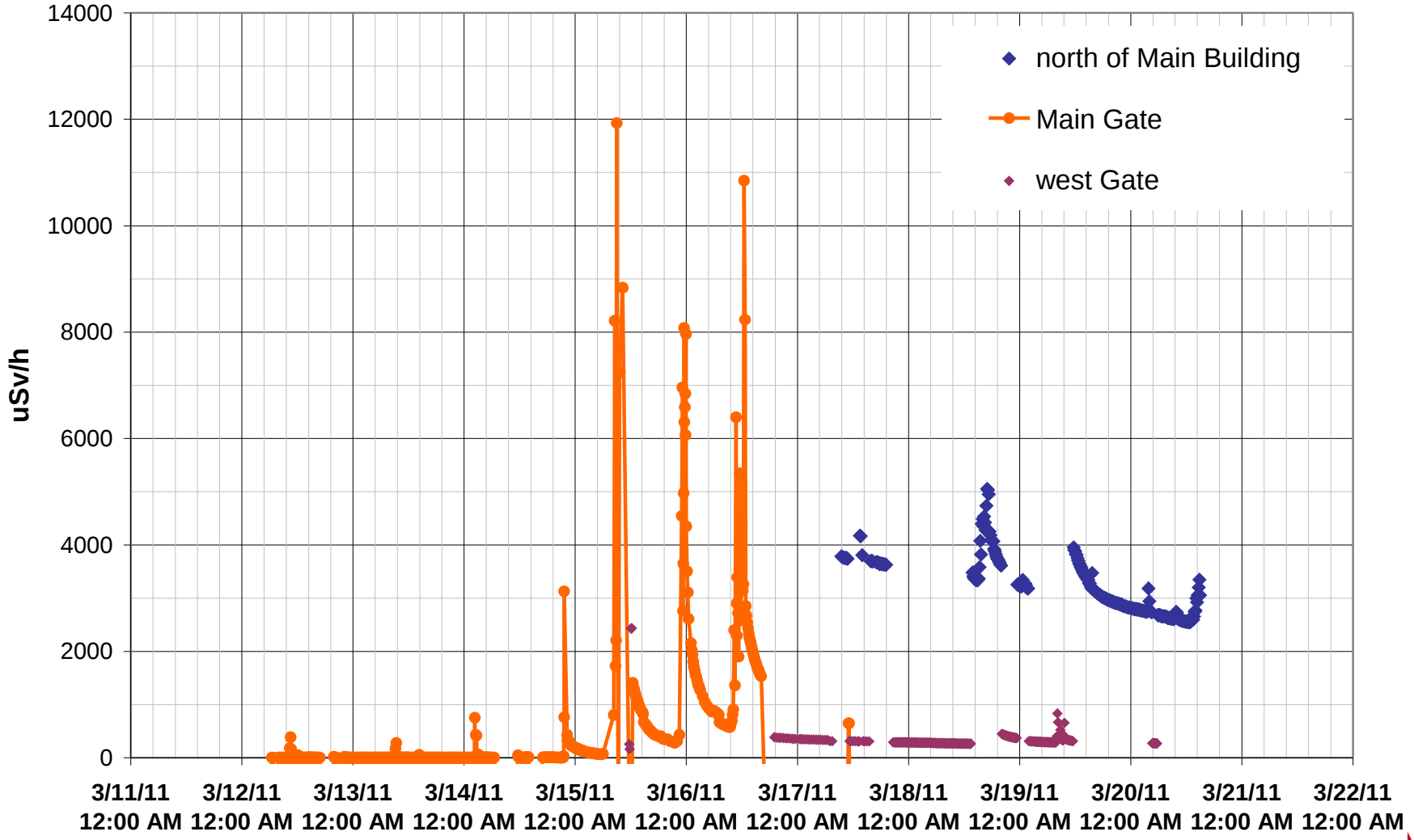


The Fukushima Daiichi Incident
3. Radiological releases

- Its not Chernobyl-like
- Directly on the plant site
  - Before Explosion in Unit 2
    - Below 2mSv / h
    - Mainly due to released radioactive noble gases
    - Measuring posts on west side. Maybe too small values measured due to wind
  - After Explosion in Unit 2 (Damage of the Containment)
    - Temporal peak values 12mSv / h (Origins not entirely clear)
    - Local peak values on site up to 400mSv /h (wreckage / Wet-Well inventory)
    - Currently stable dose on site at 5mSv /h
    - Inside the buildings a lot more
  - Limiting time of exposure of the workers necessary

The Fukushima Daiichi Incident

3. Radiological releases



The Fukushima Daiichi Incident

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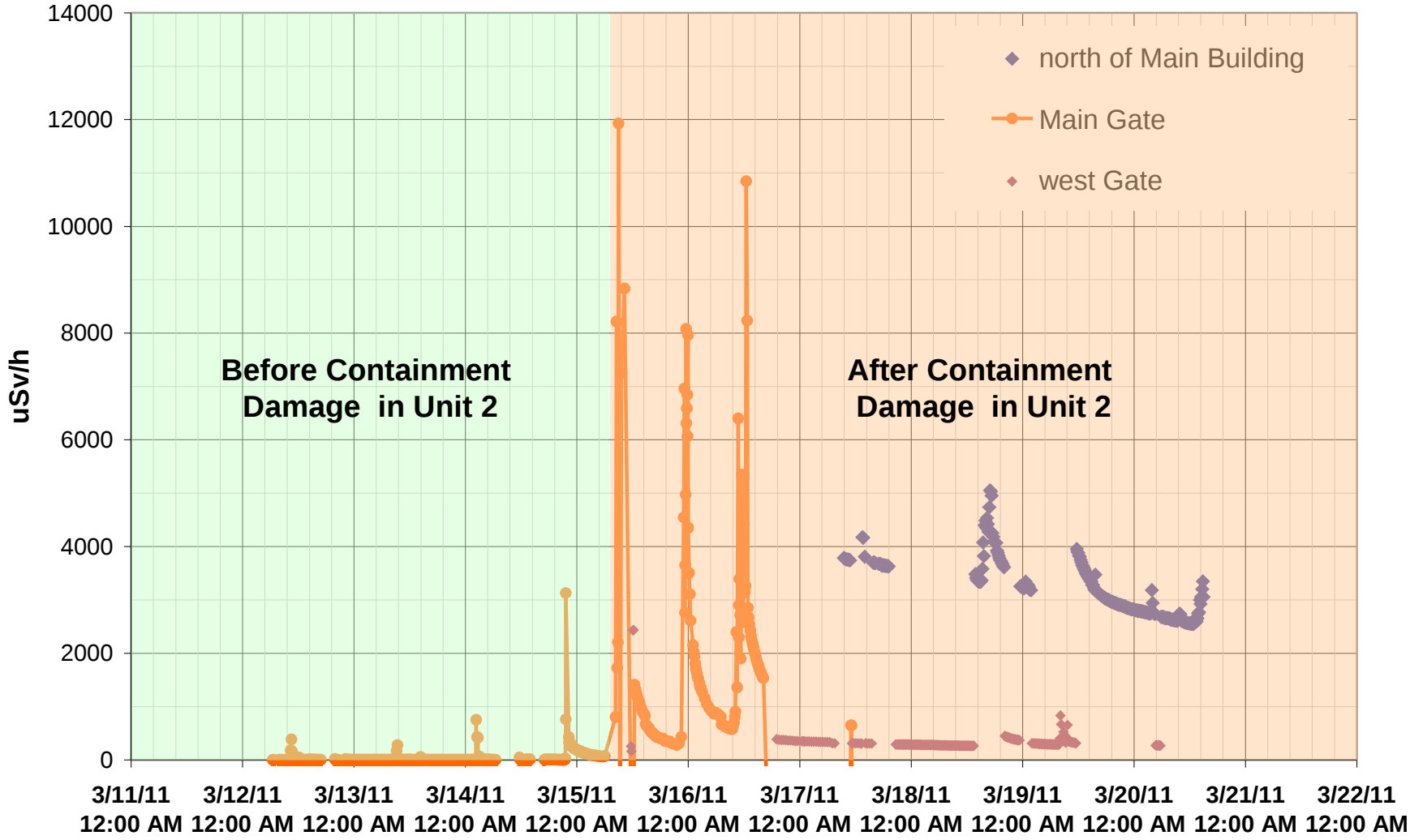

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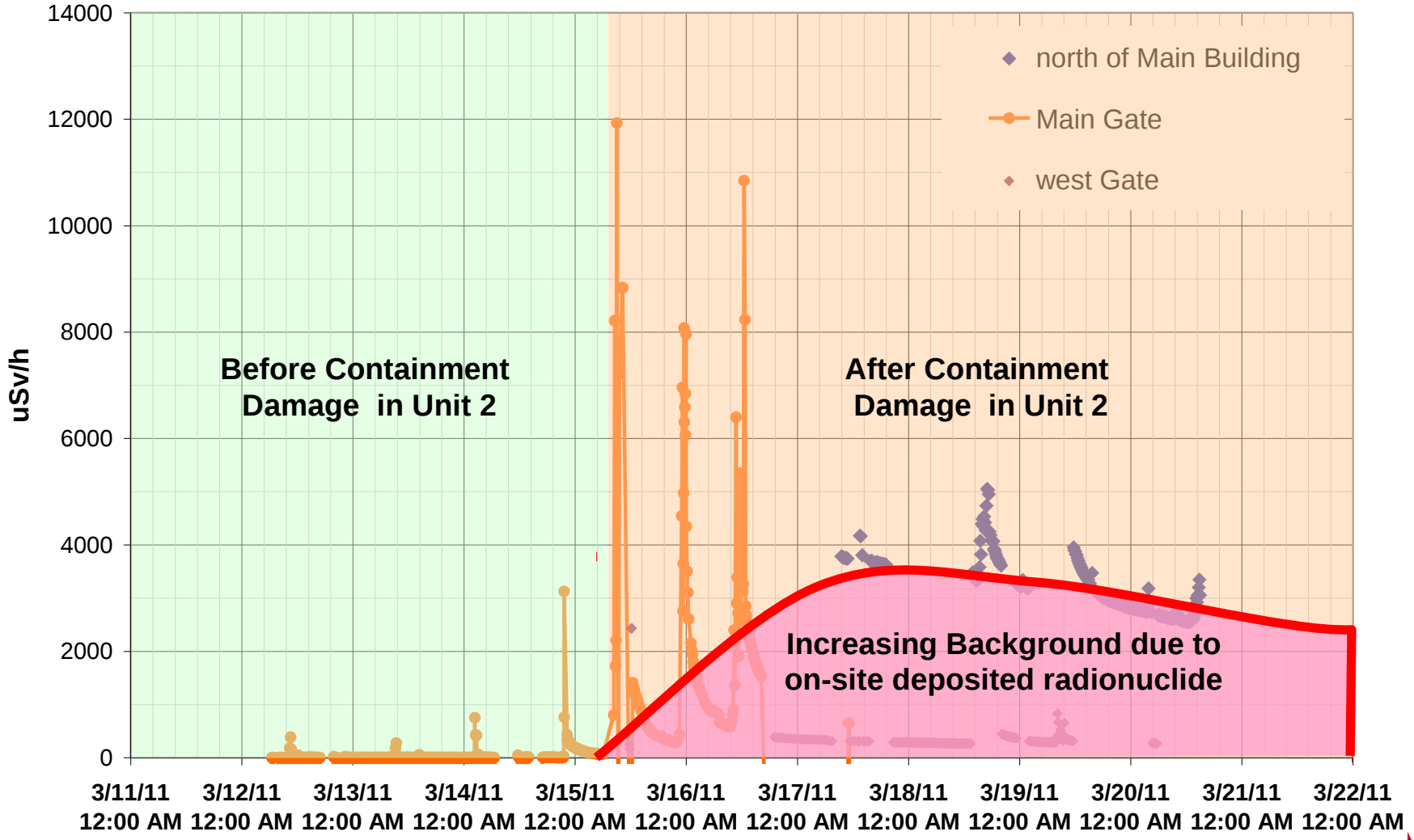


The Fukushima Daiichi Incident
3. Radiological releases

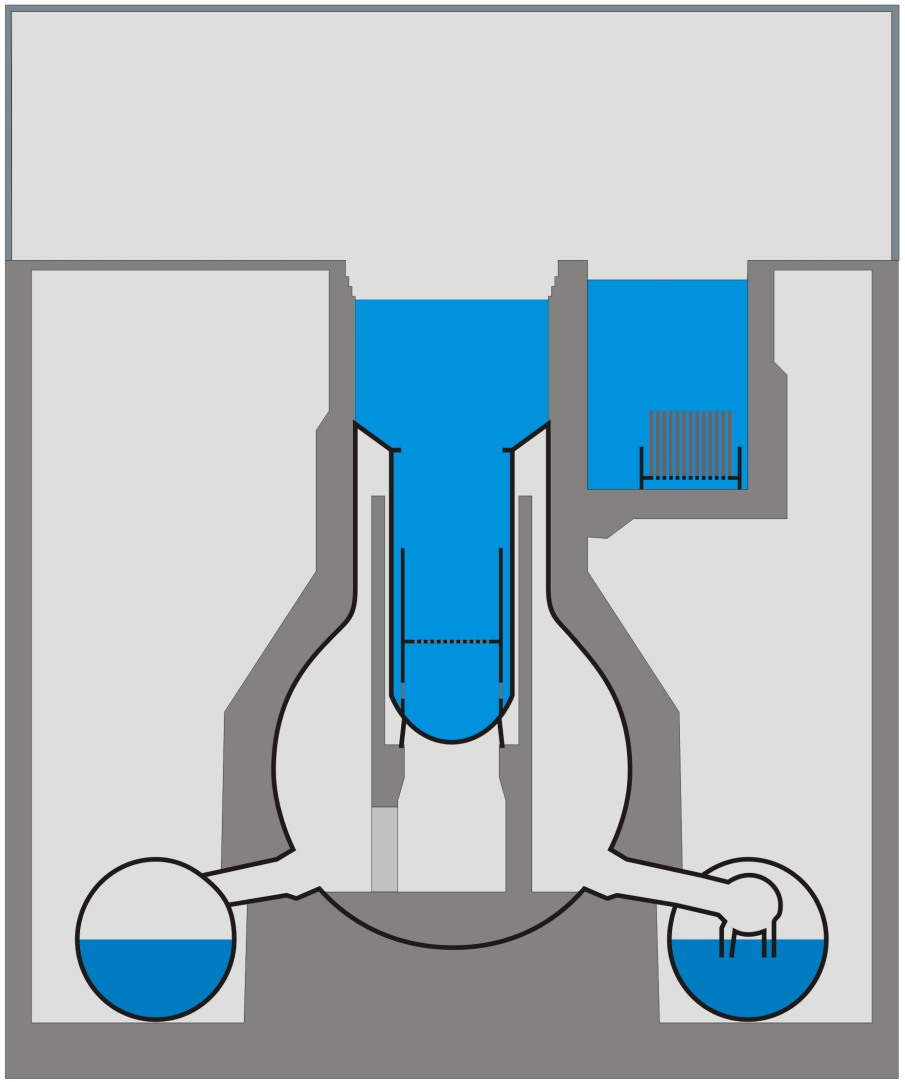
- Outside the Plant site
  - Reactor building mostly intact **=>** reduced release of Aerosols
  - Fission product release in steam **=>** fast Aerosol growth
  - Large fraction of Aerosols deposited in close proximity of plant
  - Main contribution to dose outside plant are the radioactive noble gases
    => No „Fall-out“ of the noble gases, so no local high contamination of soil

- ~20km around the plant
  - Evacuations were adequate
  - Measured dose up to 0.3mSv/h for short times
  - Maybe destruction of crops / dairy products this year
  - Probably no permanent evacuation of land necessary

- ~50km around the plant
  - Control of Crop / Dairy products
  - Distribution of Iodine pills, no usage recommended yet
    (Pills can interfere with heart medicine)

The Fukushima Daiichi Incident
4. Spend fuel pools

- Spend 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 „on fresh air “
  - Nearly no retention of fission products
  - Large release



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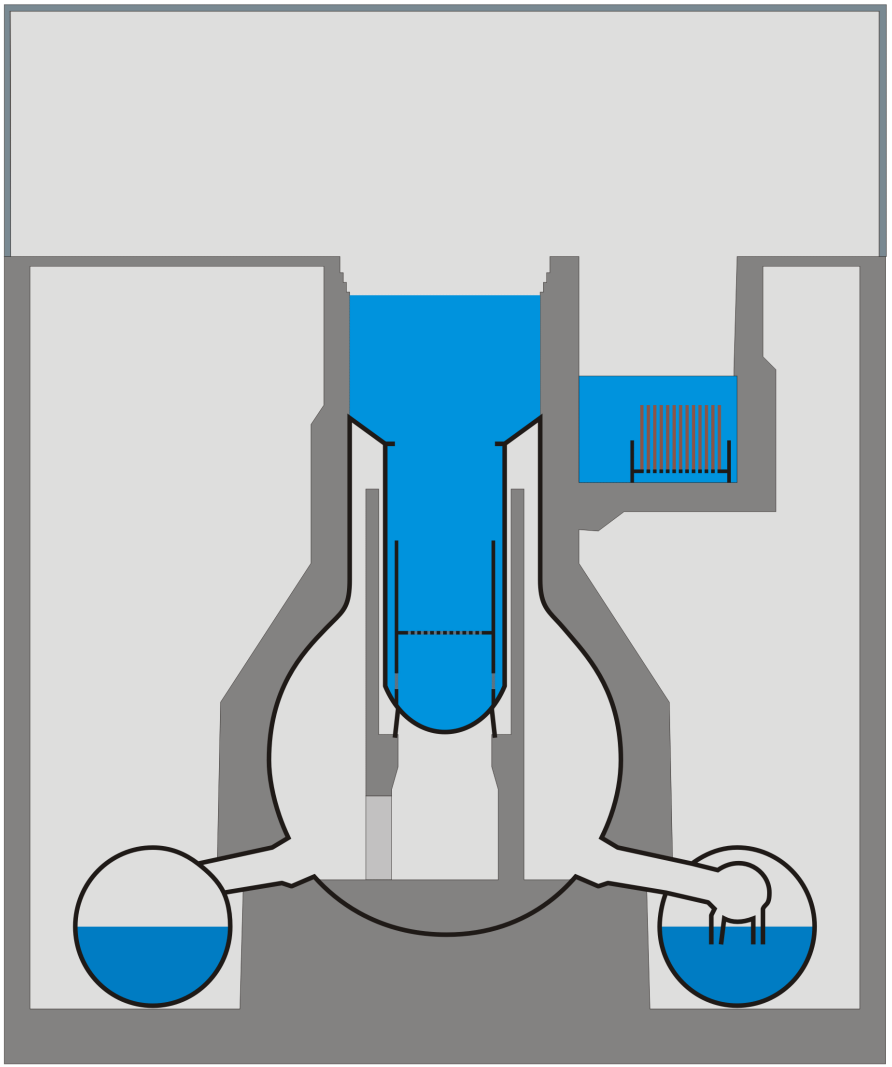

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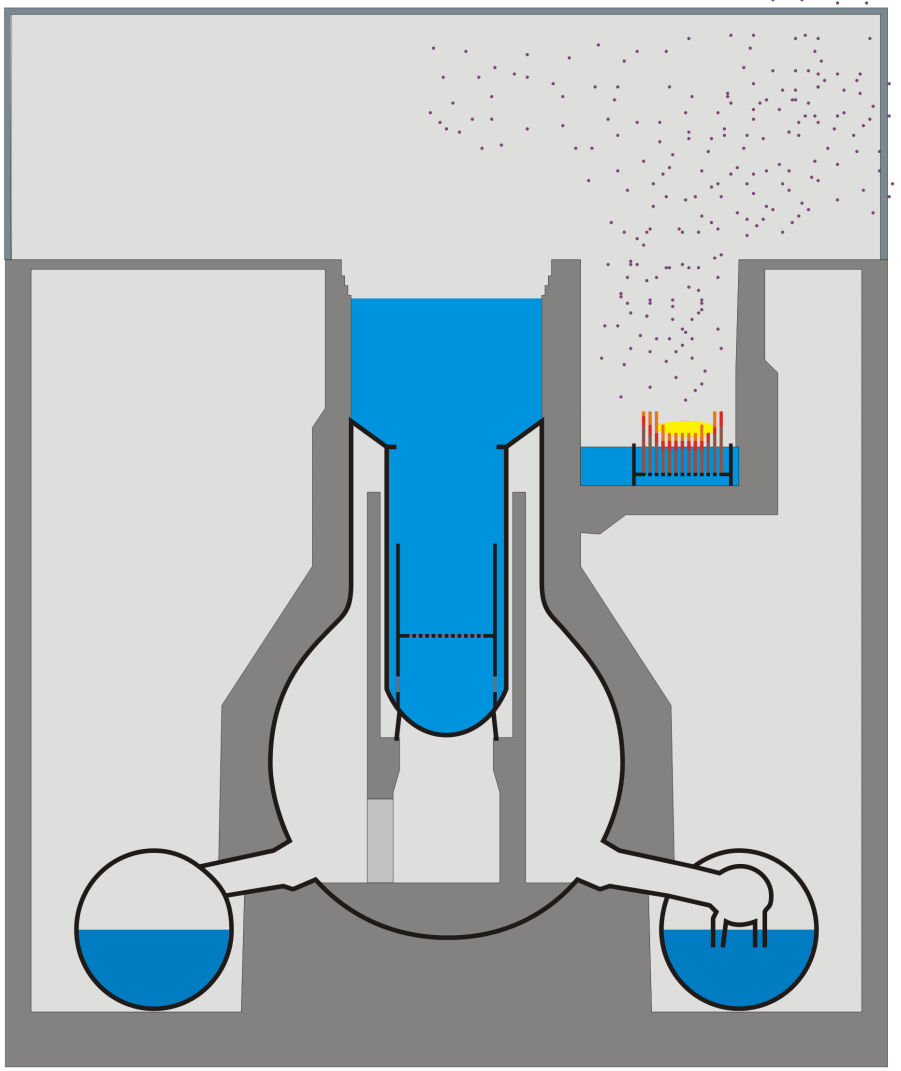
- **It is currently unclear if release from fuel pool already happened**



The Fukushima Daiichi Incident
5. Sources of Information

- Good sources of Information
  - Gesellschaft für Reaktorsicherheit [GRS.de]
    - Up to date
    - Radiological measurements presented
    - German translation of Japanese / English web pages
  - Japan Atomic Industrial Forum [jaif.or.jp/english/]
    - Current Status of the plants
    - Measurement values of the reactors (pressure liquid level)
  - Tokyo Electric Power Company [Tepco.co.jp]
    - Radiological measurements published
    - Status of the recovery work
    - Casualties