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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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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

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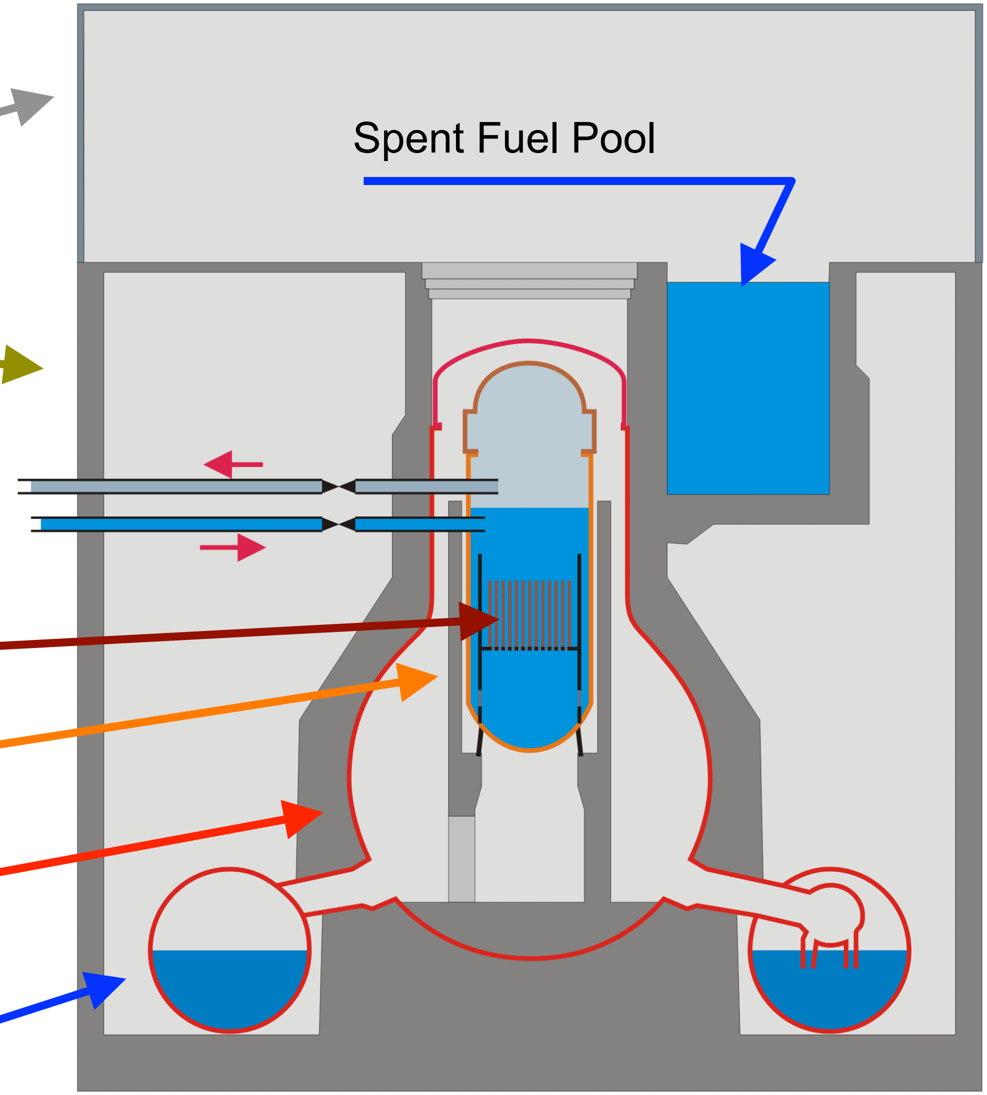
The Fukushima Daiichi Incident
1. Plant Design of Unit 1-4

- 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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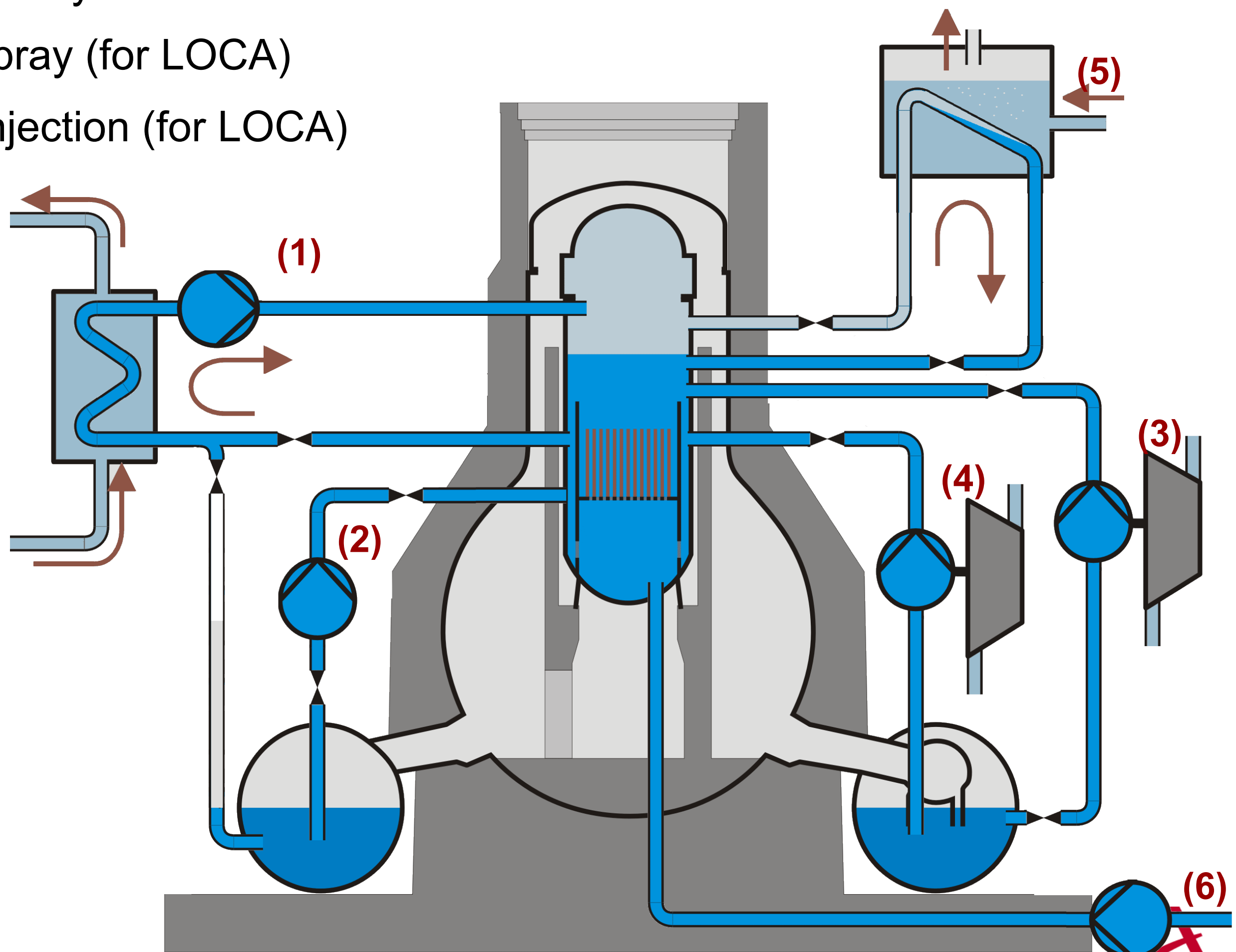
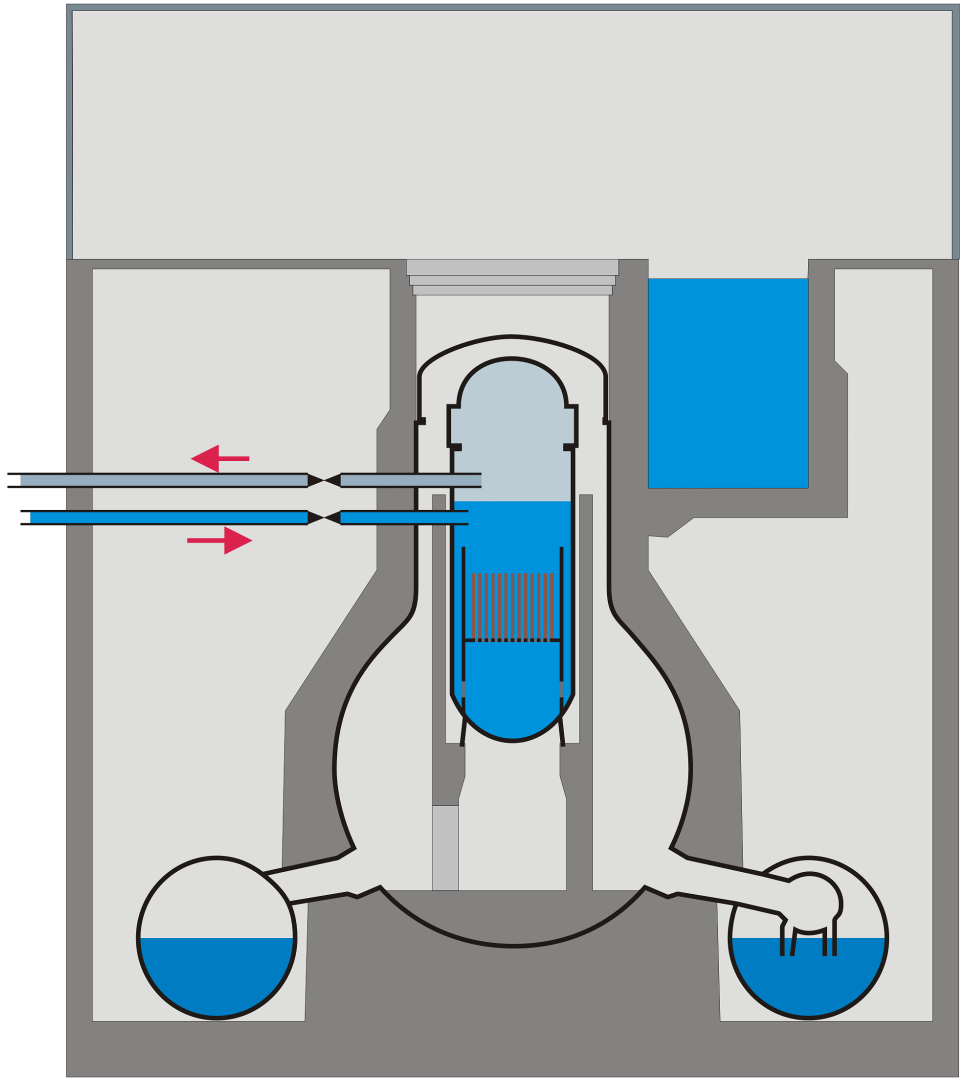
- Emergency Core Cooling Systems

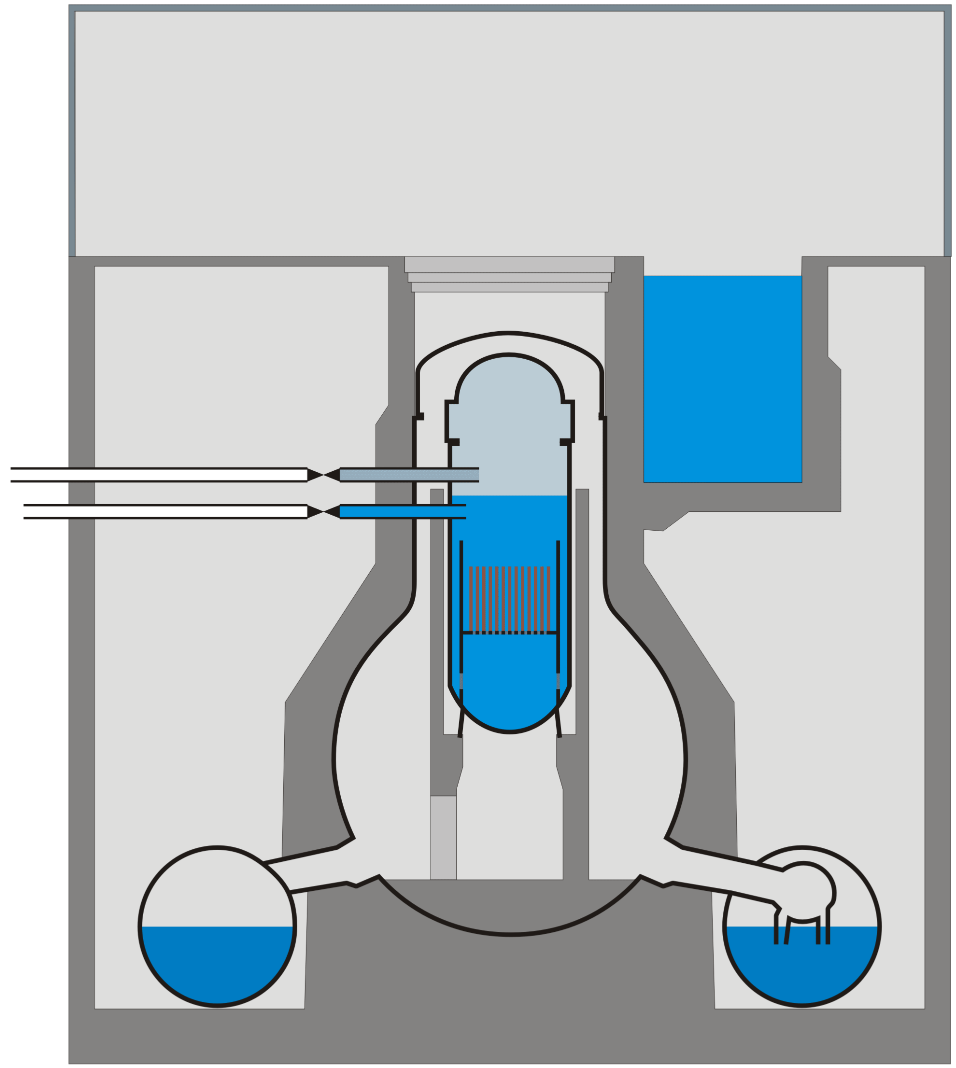
1) Residual Heat Removal System
2) Low-Pressure Core Spray (for LOCA)
3) High-Pressure Core Injection (for LOCA)
4) Reactor Core isolation cooling (Unit 2,3 [BWR4])
5) Isolation Condenser (Unit 1 [BWR3])
6) Borating System



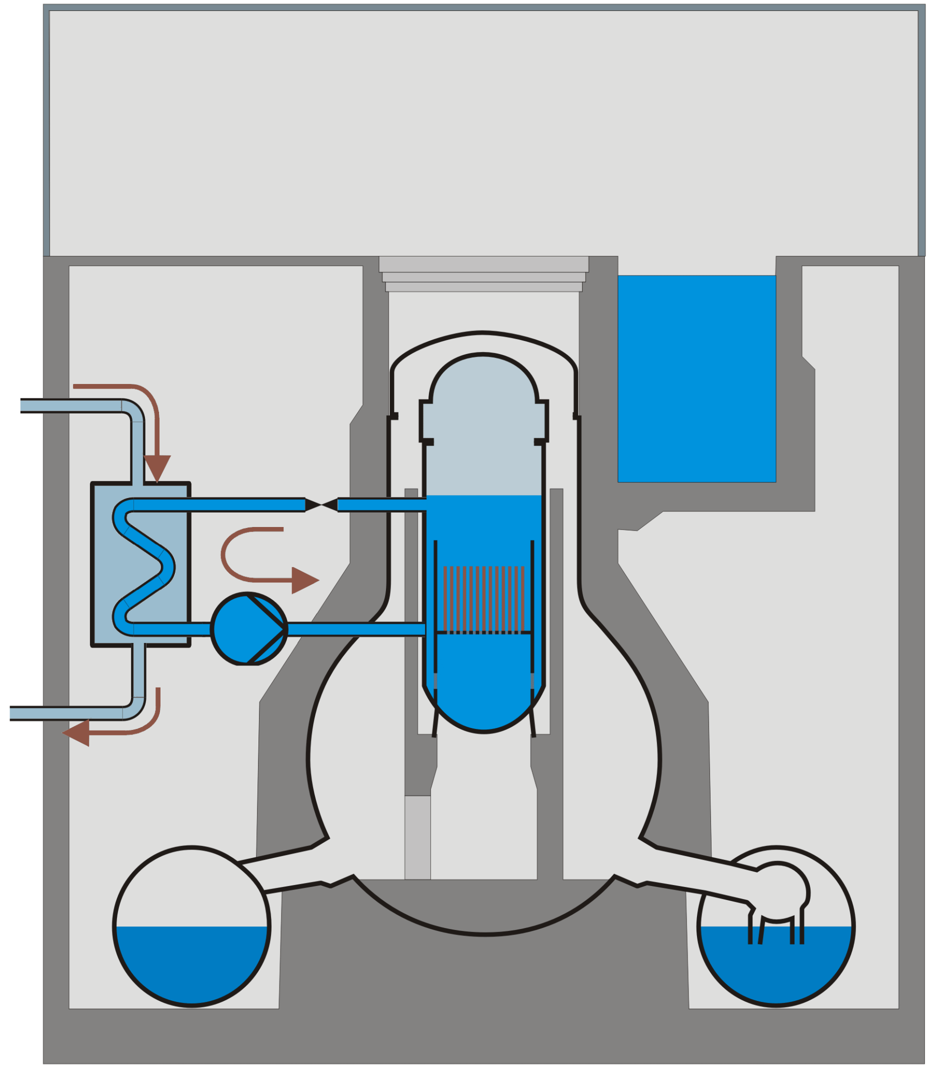
- 11.3.2011 14:46 - Earthquake
  - Magnitude 9
  - Power grid in northern Japan fails
  - Reactors itself are mainly undamaged
- SCRAM
  - Power generation due to Fission of Uranium stops
  - Heat generation due to radioactive Decay of Fission Products
    - After Scram ~6%
    - After 1 Day ~1%
   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

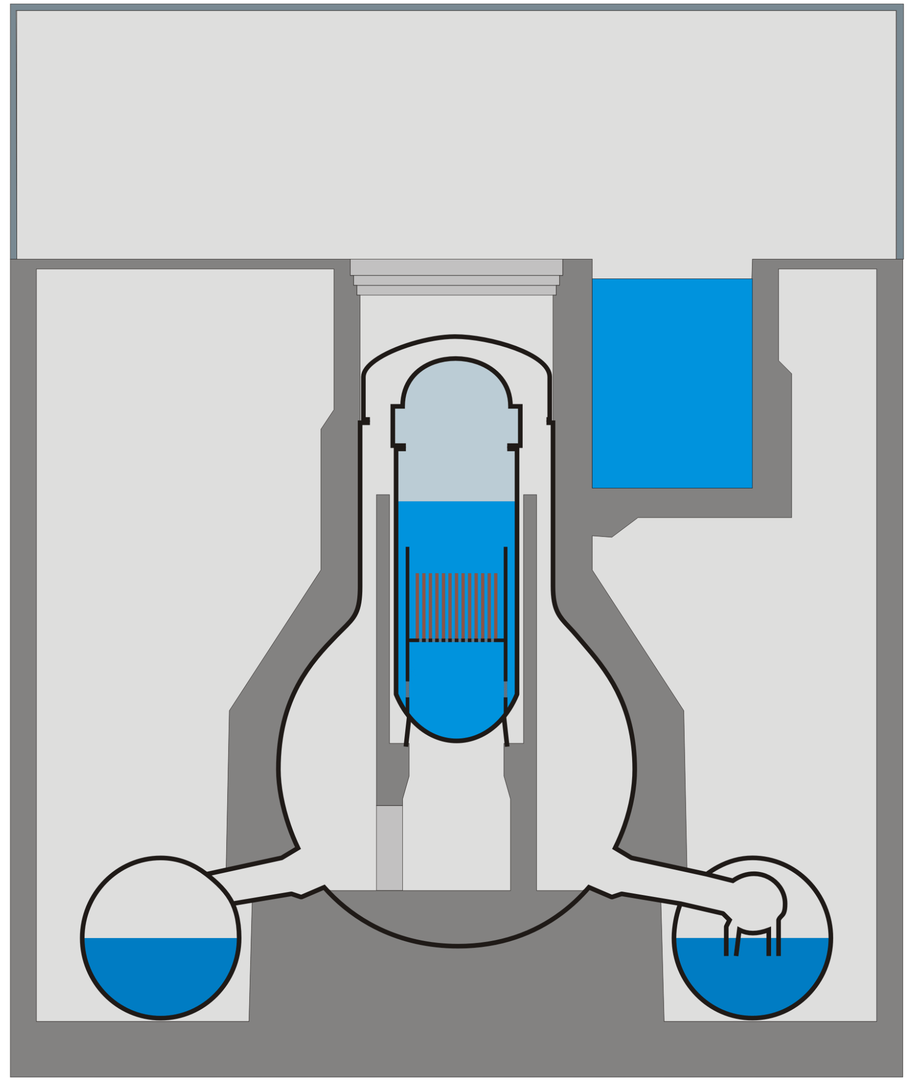


- Containment Isolation
  - Closing of all non-safety related Penetrations of the containment
  - Cuts off Machine hall
  - Due to successful containment isolation, a large early release of fission products is highly unlikely
- Diesel generators start
  - Emergency Core cooling systems are supplied
-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



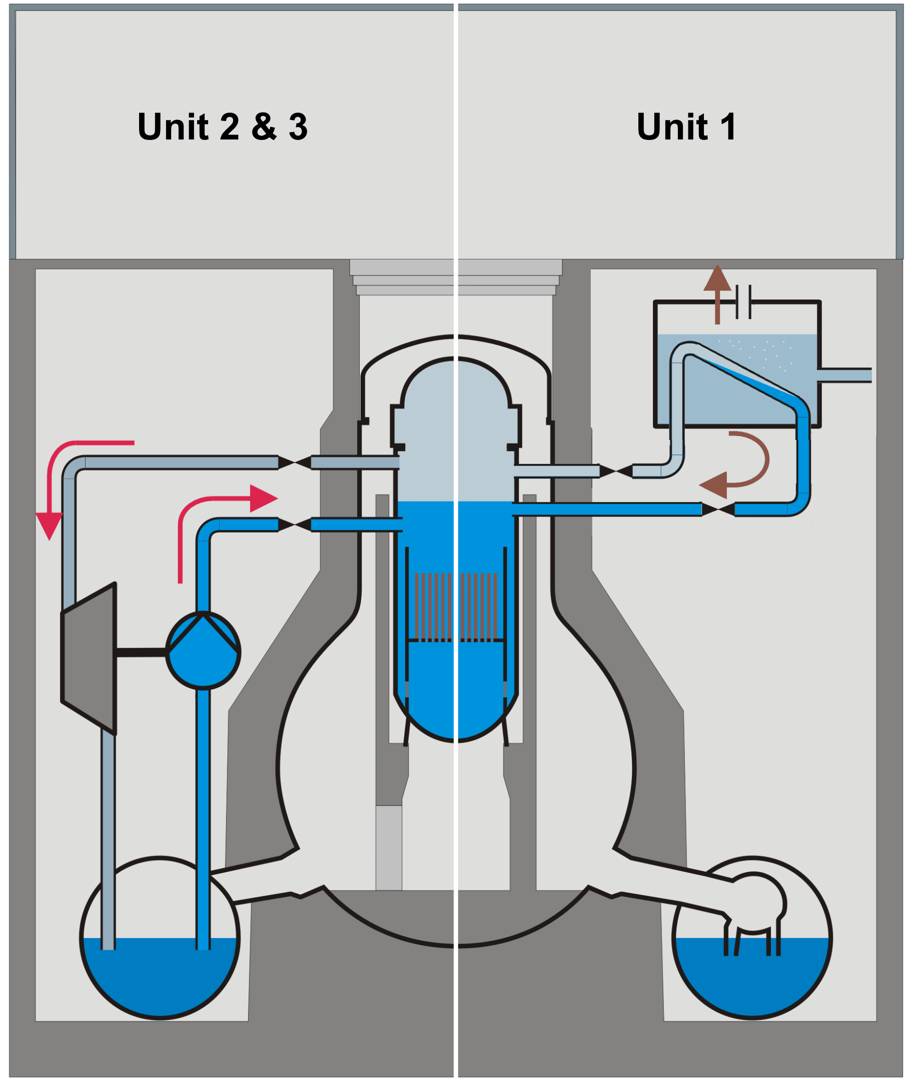
- Usual course of action:
  - Cooling reactor by Residual Heat Removal Systems
  - Active spend fuel pool cooling
  - Active containment heat removal
- Necessary
  - Electricity for pumps
  - Heat sink outside Reactor building (Service Water)





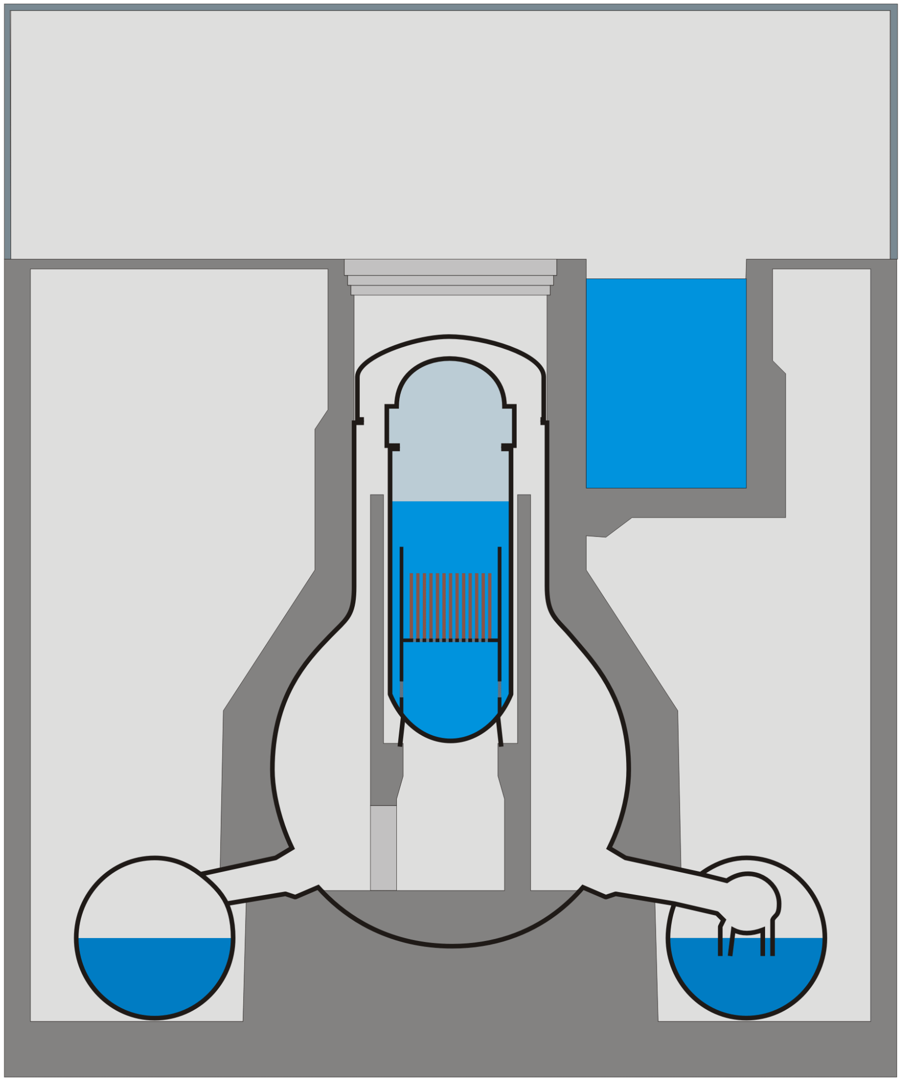
- 11.3. 15:01(?) Tsunami hits plant
  - Plant Design for Tsunami height of up to 5.7-6.5m
  - Actual Tsunami height 7-11m
  - Flooding of
    - Diesel and/or
    - Switchgear building and/or
    - Fuel Tanks and/or
    - Essential service water buildings
- 11.3. 15:41 Station Blackout
  - Common cause failure of the power supply
  - Only Batteries are still available
  - Failure of all but one Emergency core cooling system

- 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

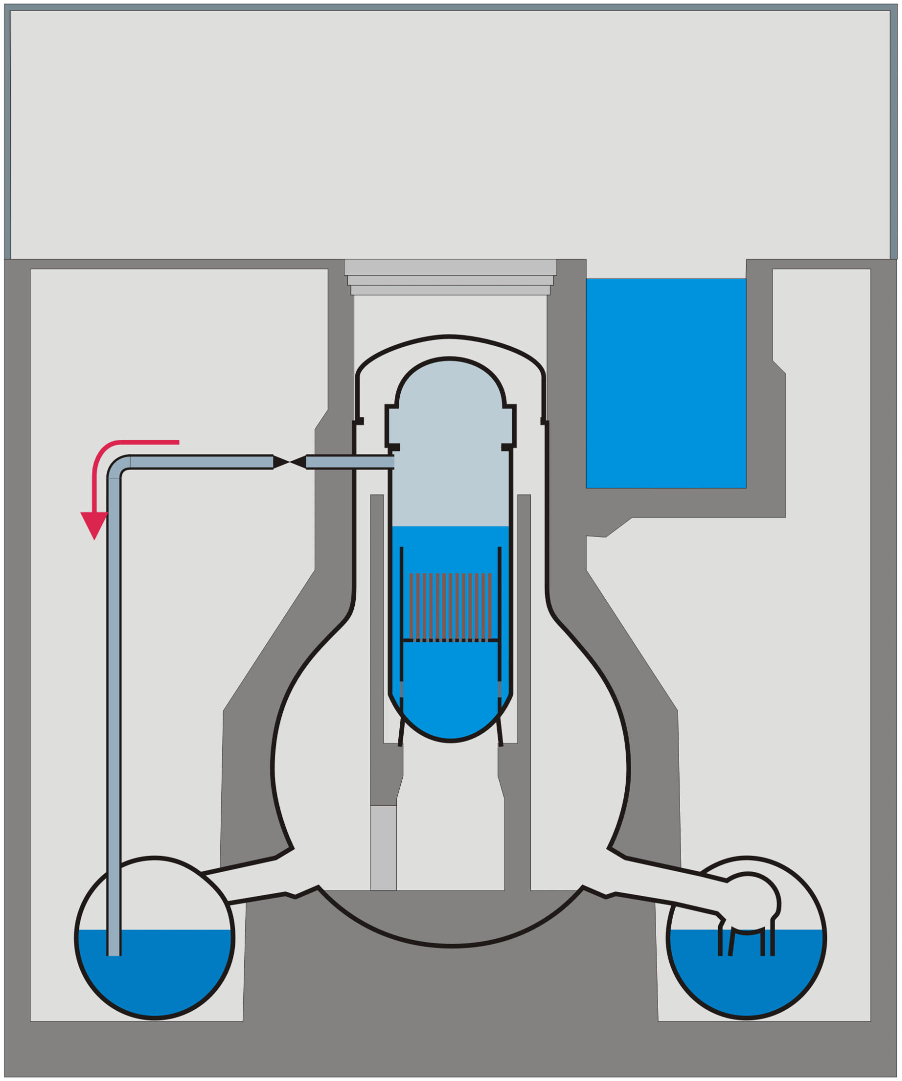


2. Accident progression

- 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



- 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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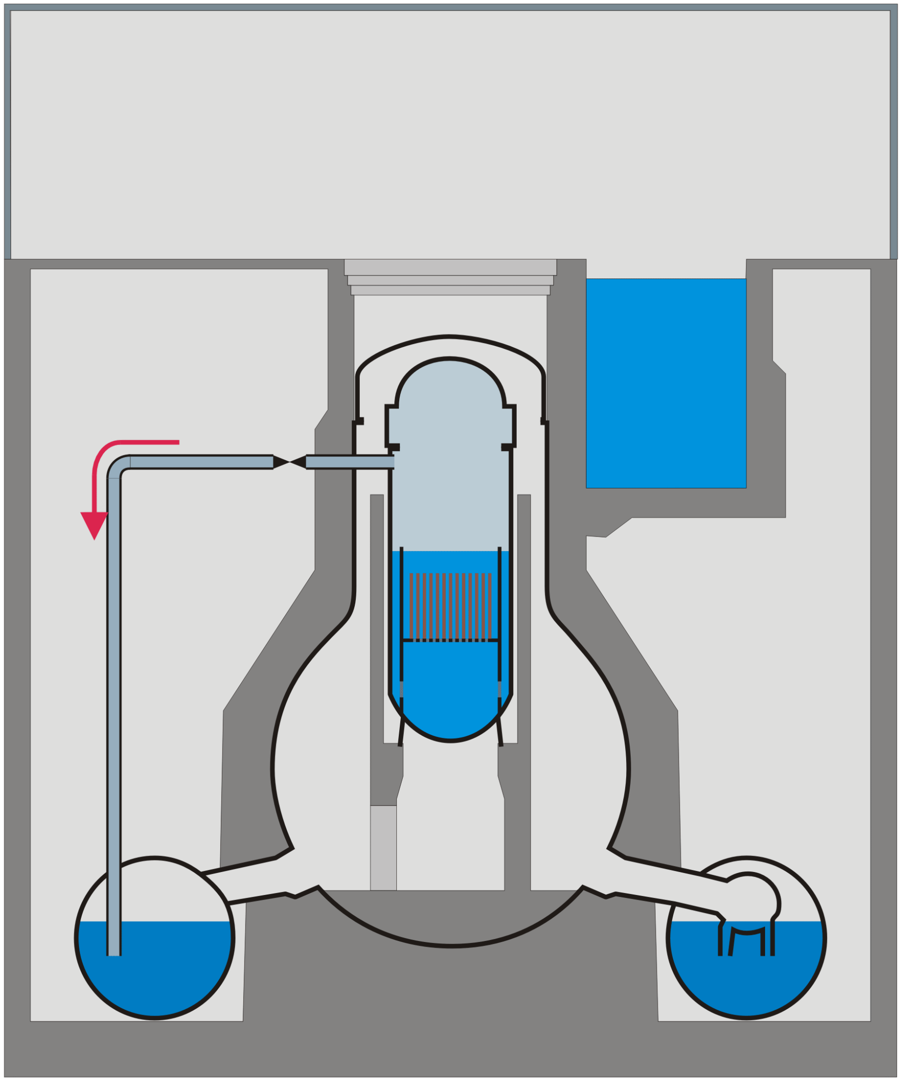

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The Fukushima Daiichi Incident
2. Accident progression

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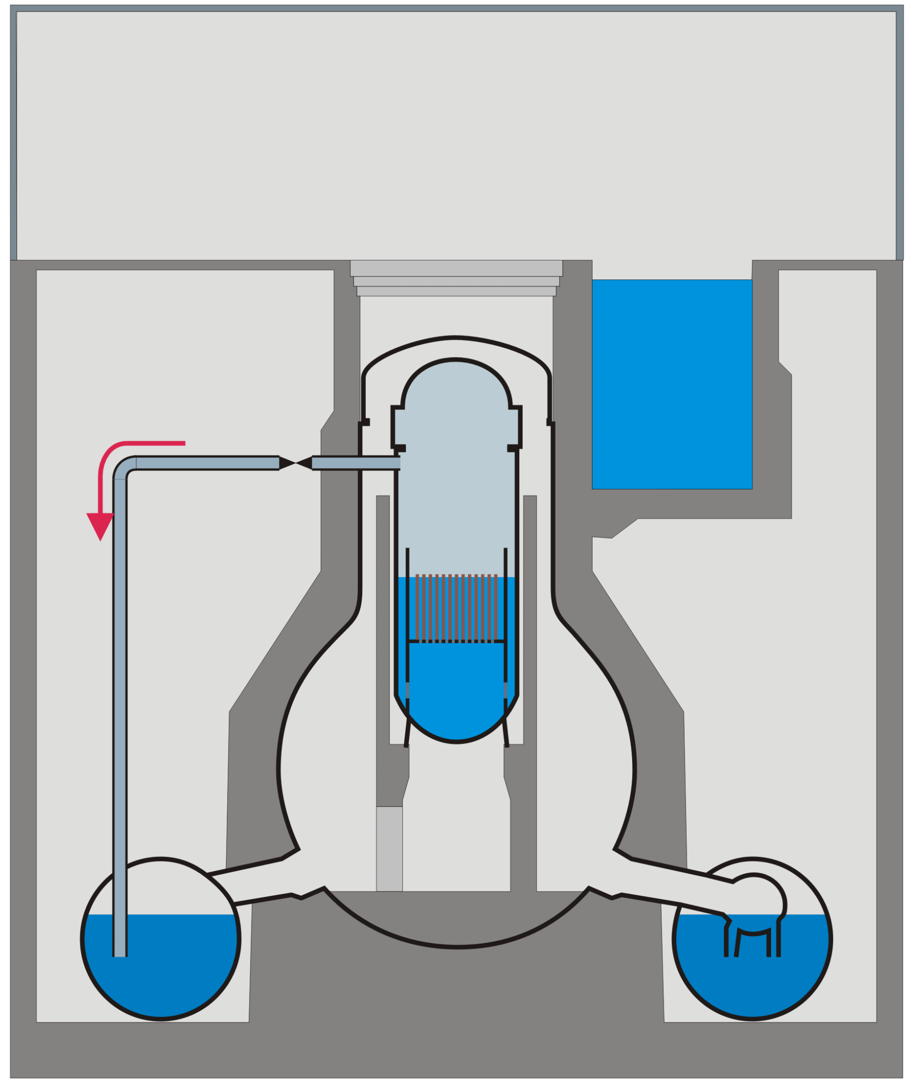

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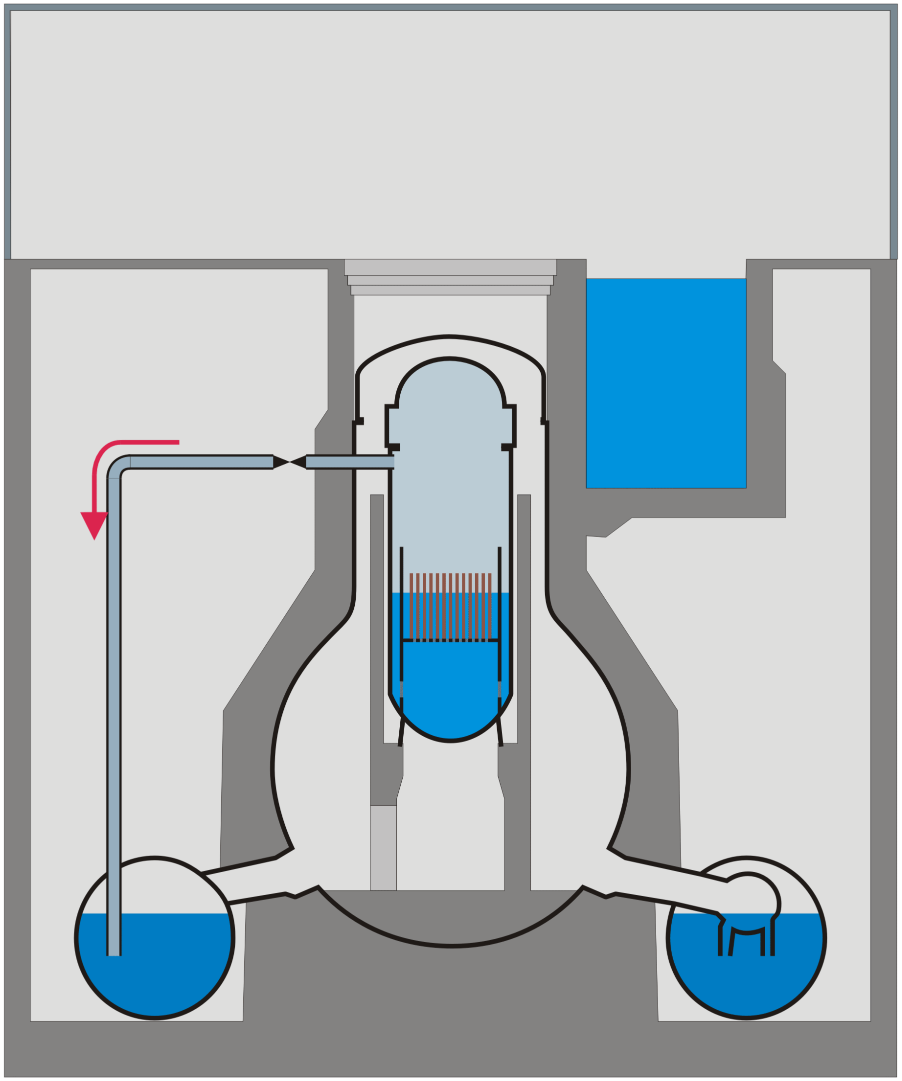
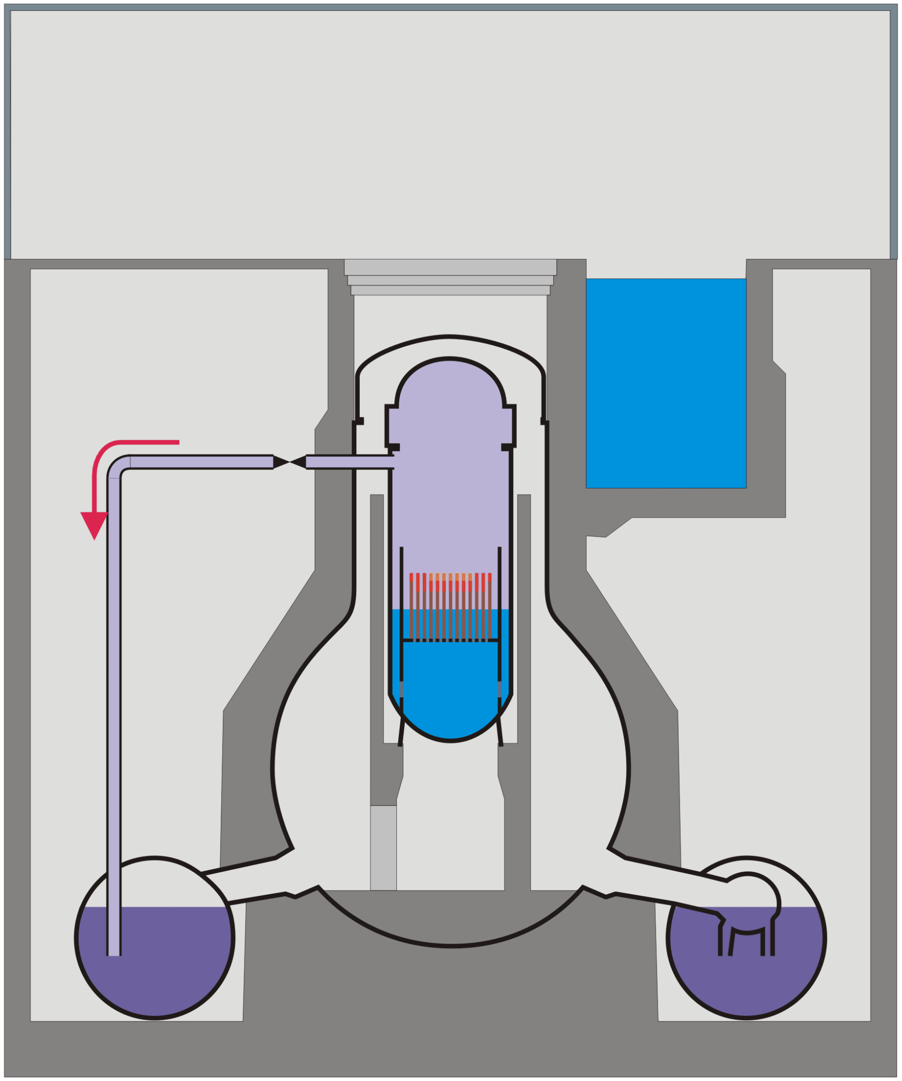


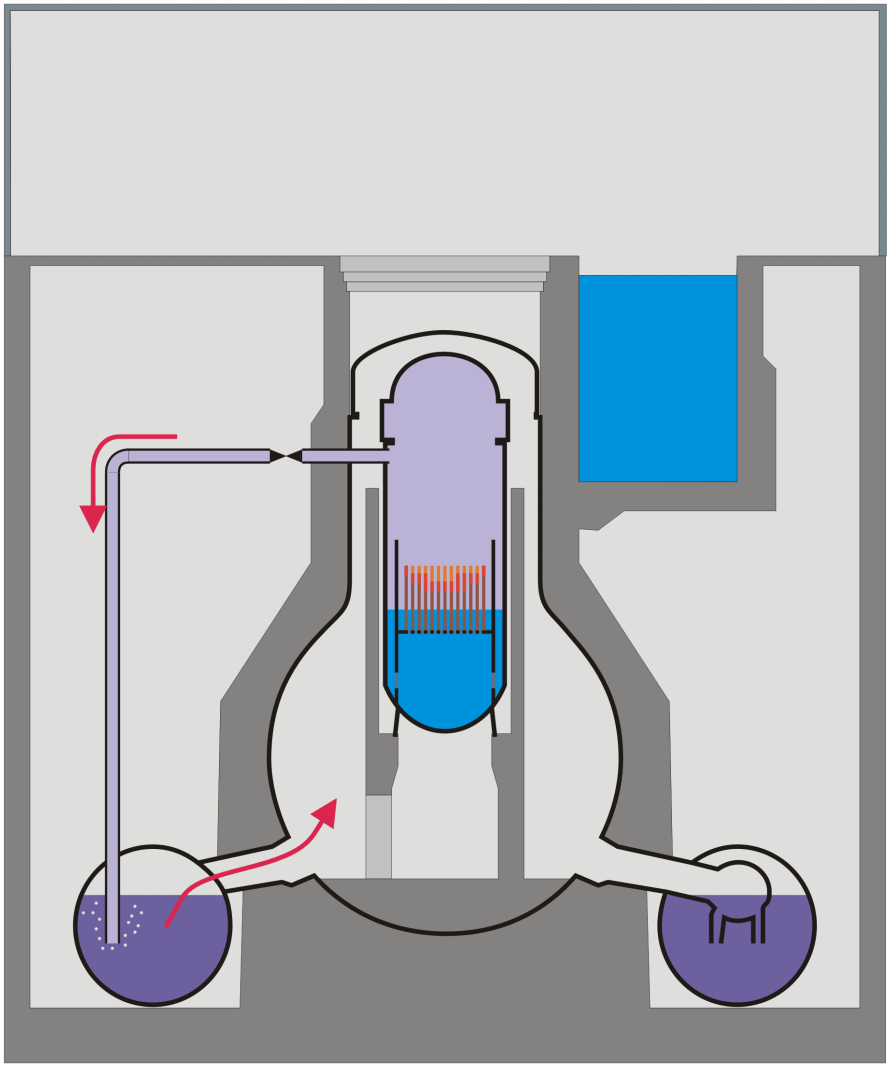
- ~50% of the core exposed
  - Cladding temperatures rise, but still no significant core damage

- ~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

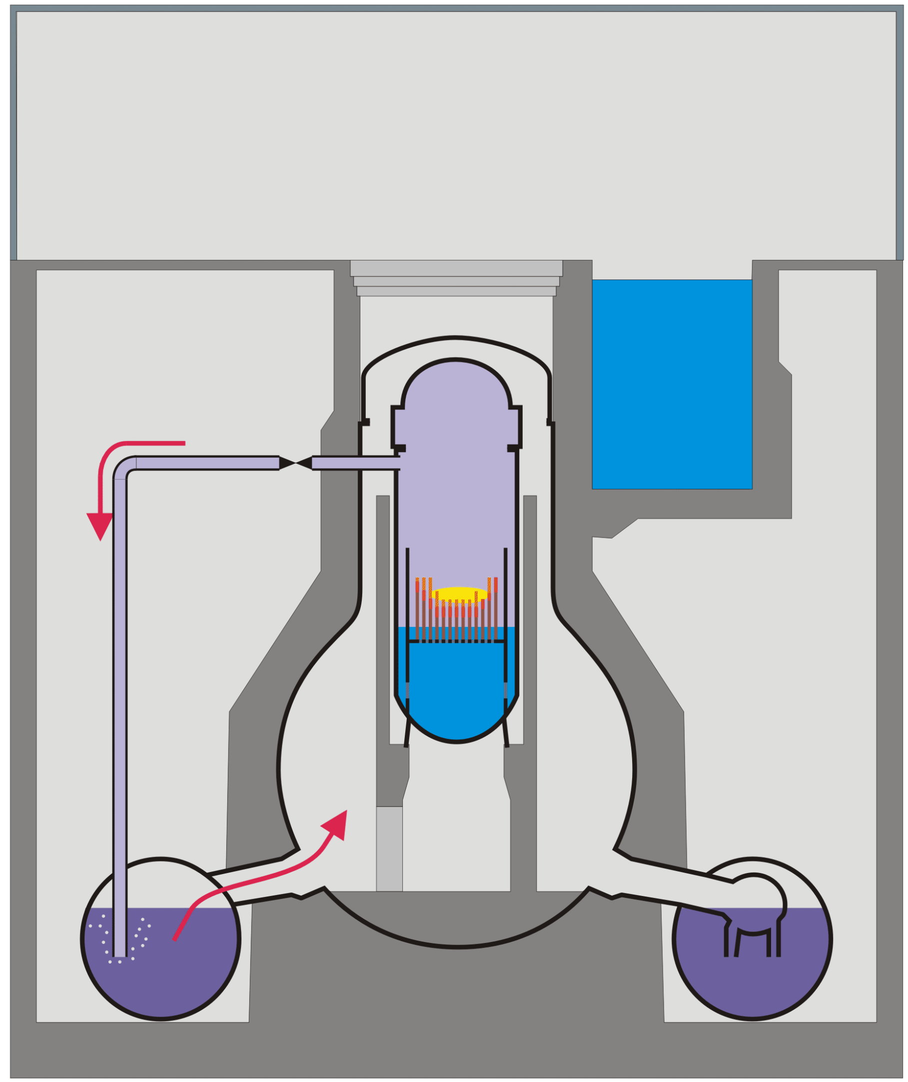
(Measured levels are collapsed level. The actual liquid level lies higher due to the steam bubbles in the liquid)



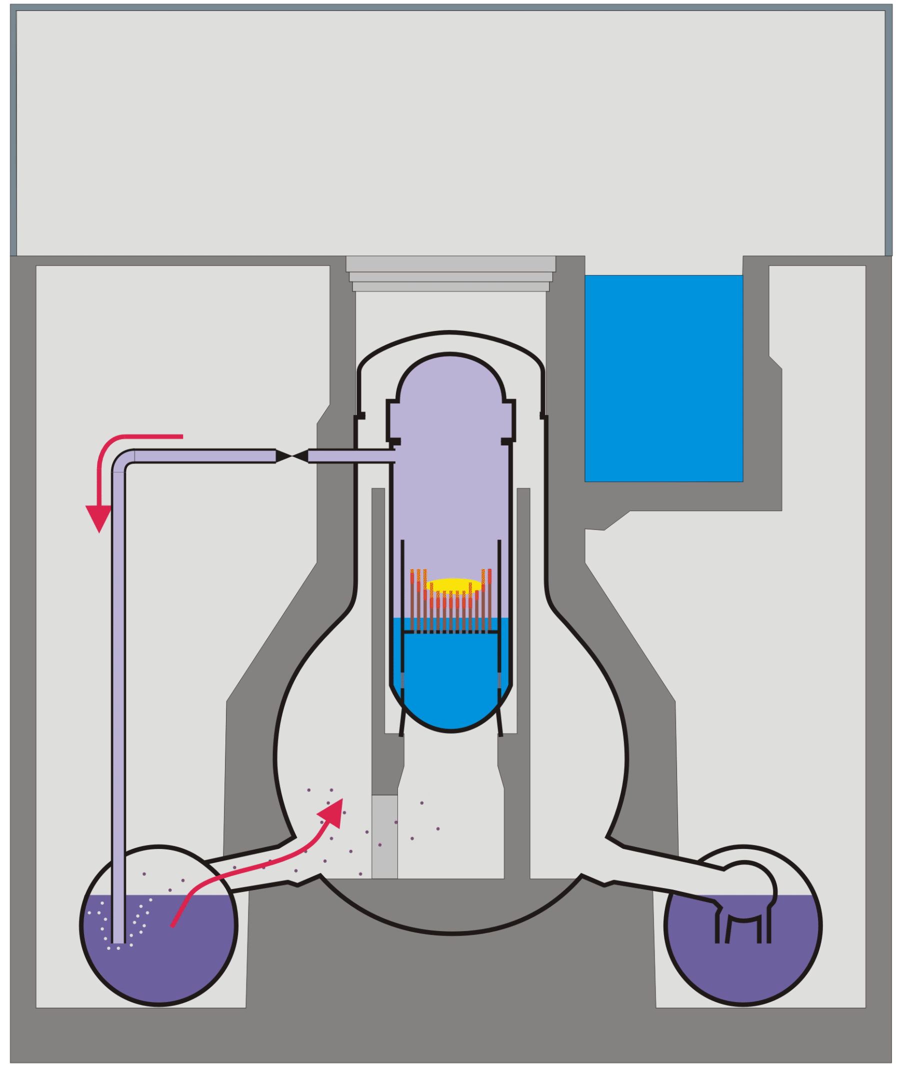
- ~3/4 of the core exposed
  - Cladding exceeds ~1200°C
  - Zirconium in the cladding starts to burn under steam atmosphere
  - **$Zr + 2H_20 \rightarrow ZrO_2 + 2H_2$**
  - Exothermal reaction further heats the core
  - Estimated masses hydrogen
    - Unit 1: 300-600kg
    - Unit 2/3: 300-1000kg
  -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



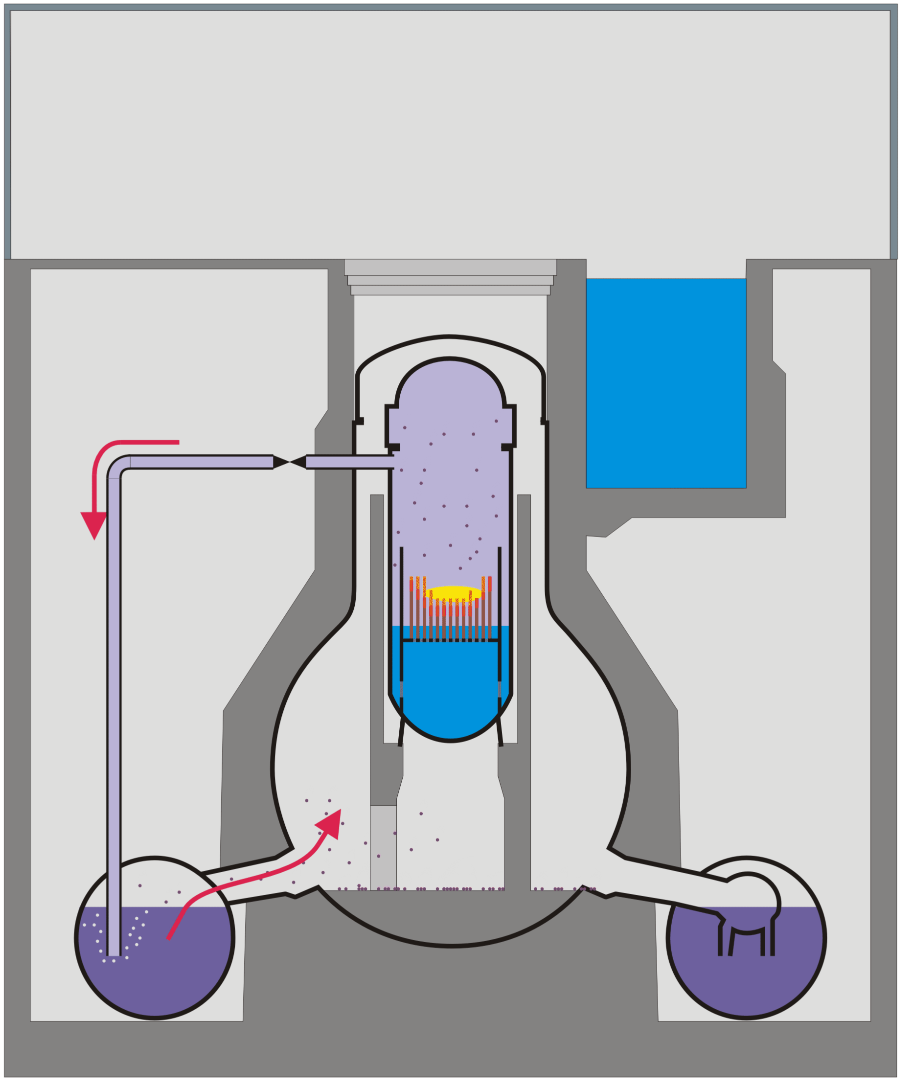
- at ~1800°C [expected Unit 1,2,3]
  - Melting of the Cladding
  - Melting of the steel structures
- at ~2500°C [expected Unit 1,2]
  - Breaking of the fuel rods
  - debris bed inside the core
- at ~2700°C [maybe Unit 1]
  - Significant melting of Uranium-Zirconium-oxides
- Restoration of the water supply 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)



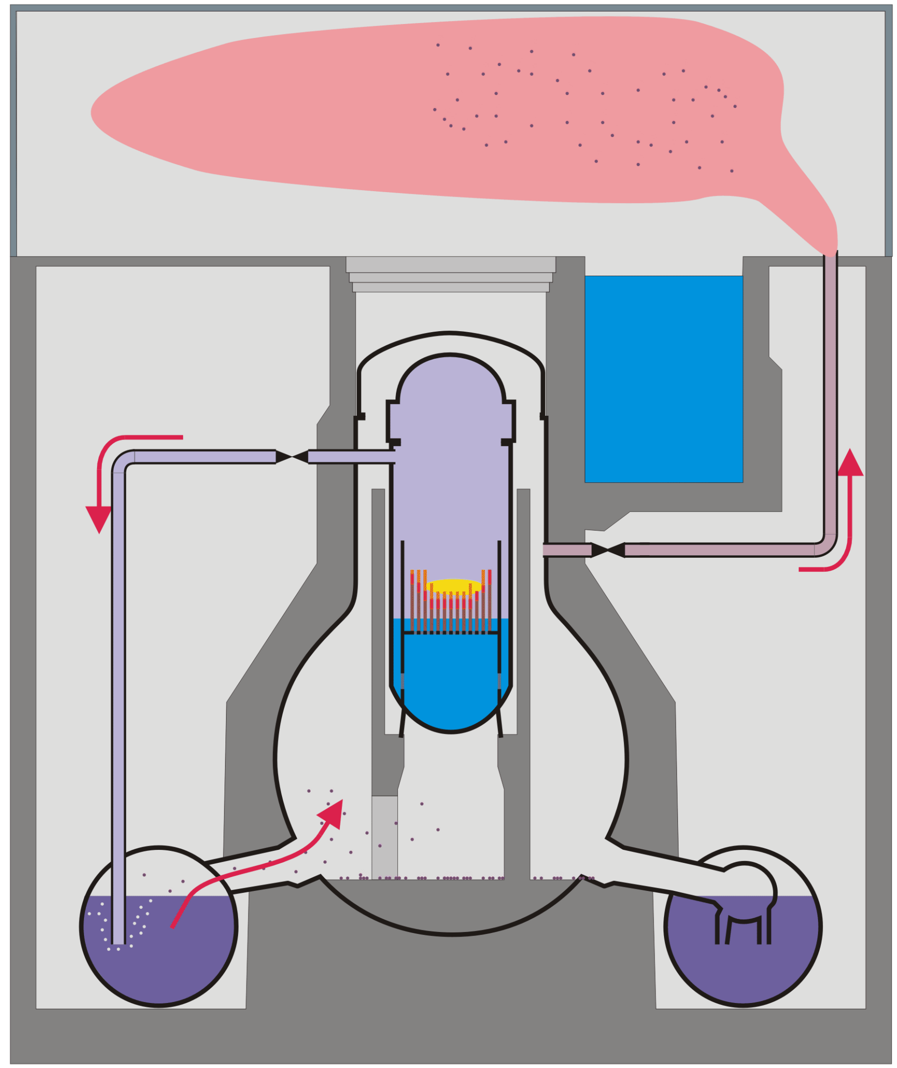
- Release of fission products during melt down
  - Xenon, Cesium, Iodine,…
  - Uranium/Plutonium remain in core
  - Fission products condensate to airborne Aerosols
- Discharge through valves into water of the condensation chamber
  - Pool scrubbing binds a fraction of Aerosols in the water
- Xenon and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



- 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



- 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



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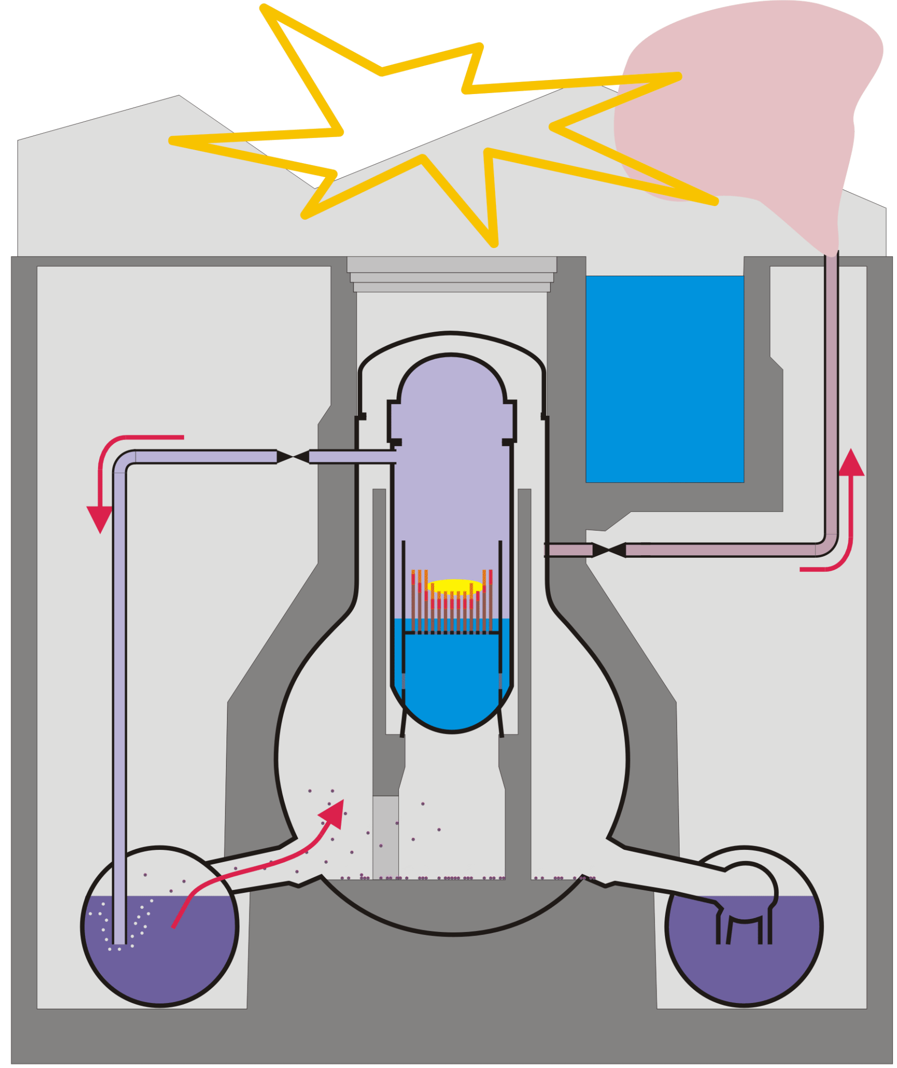
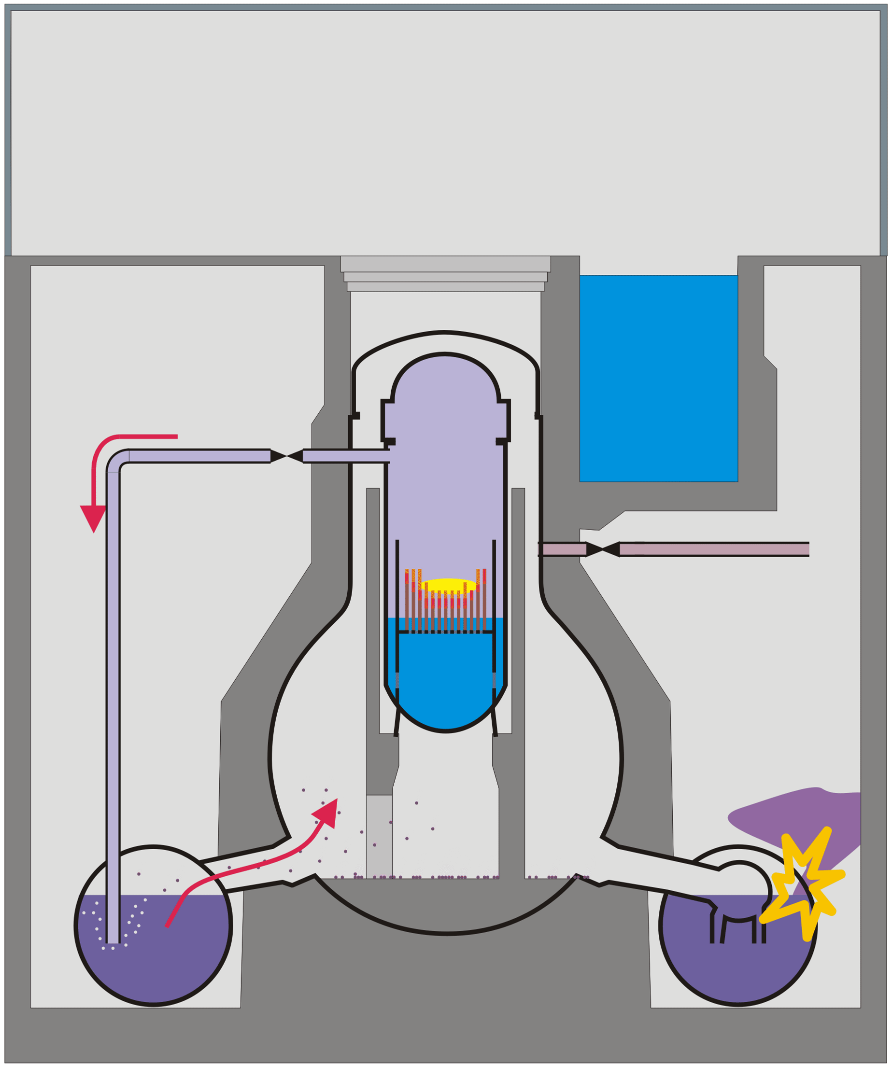
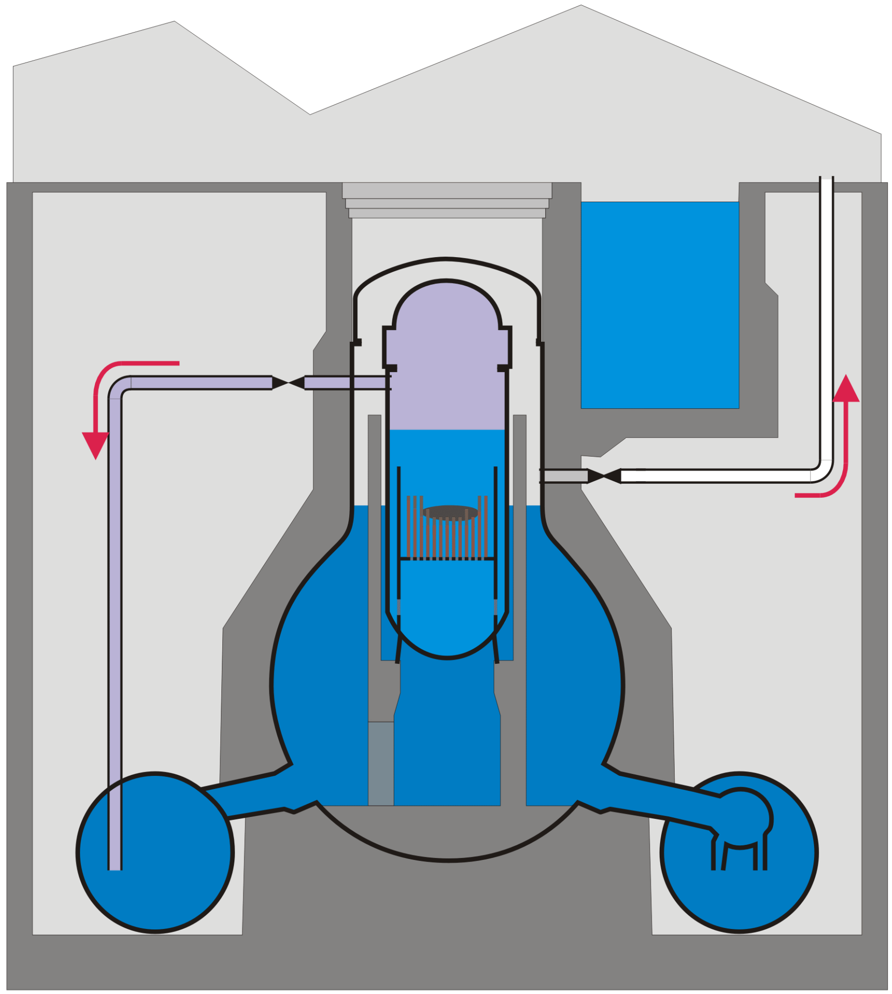
- Unit 1 and 3
  - Hydrogen burn inside the reactor service floor
  - Destruction of the steel-frame roof
  - Reinforced concrete reactor building seems undamaged
  - Spectacular but minor safety relevant



- 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



- 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

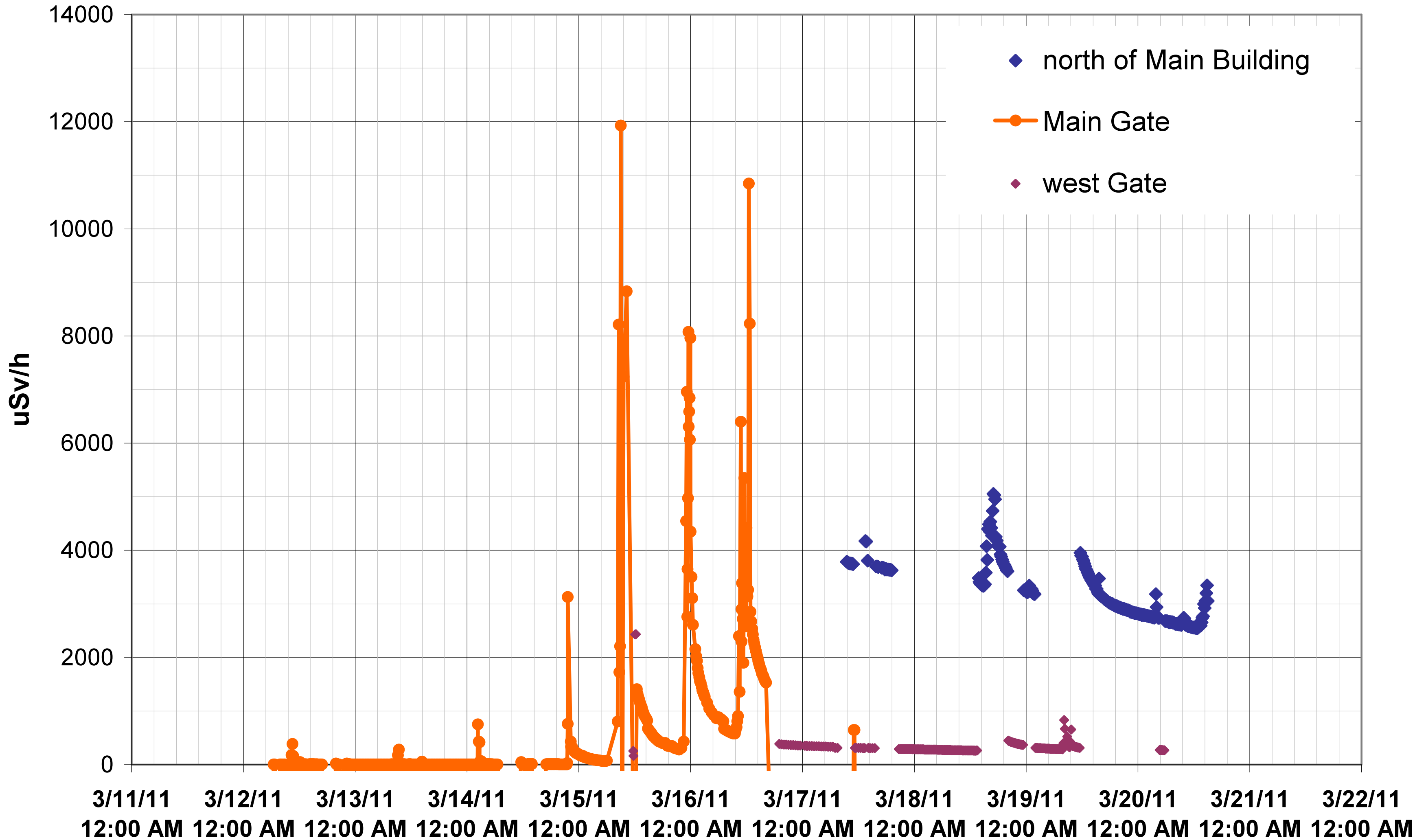


- Its not Chernobyl-like

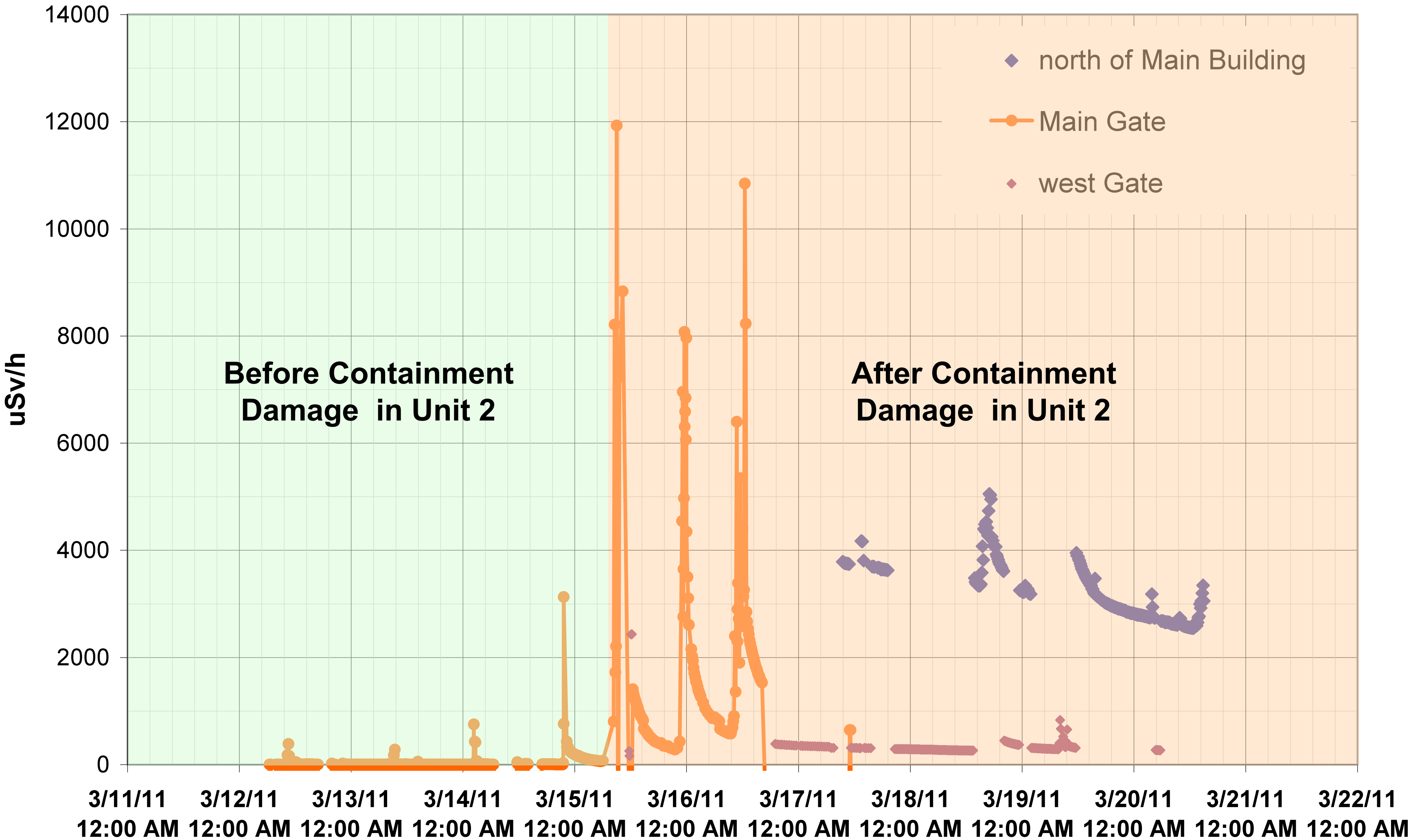
- Directly on the plant site
  - Before Explosion in Unit 2
    - Below 2mSv / h
    - Mainly due to released radioactive noble gases
    - Measuring posts on west side. Maybe too small values measured due to wind
  - After Explosion in Unit 2 (Damage of the Containment)
    - Temporal peak values 12mSv / 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
3. Radiological releases



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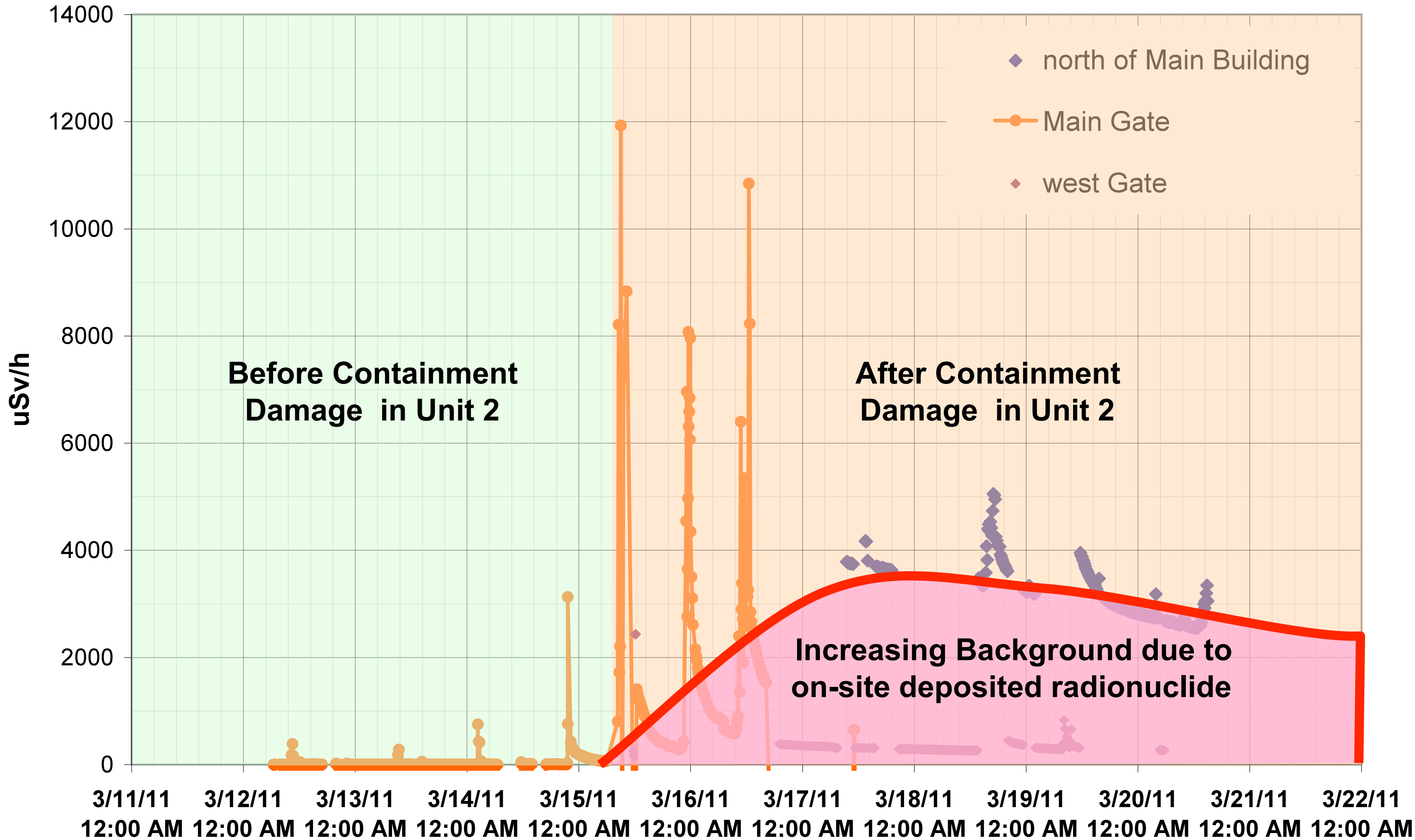
The Fukushima Daiichi Incident
3. Radiological releases



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- 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)

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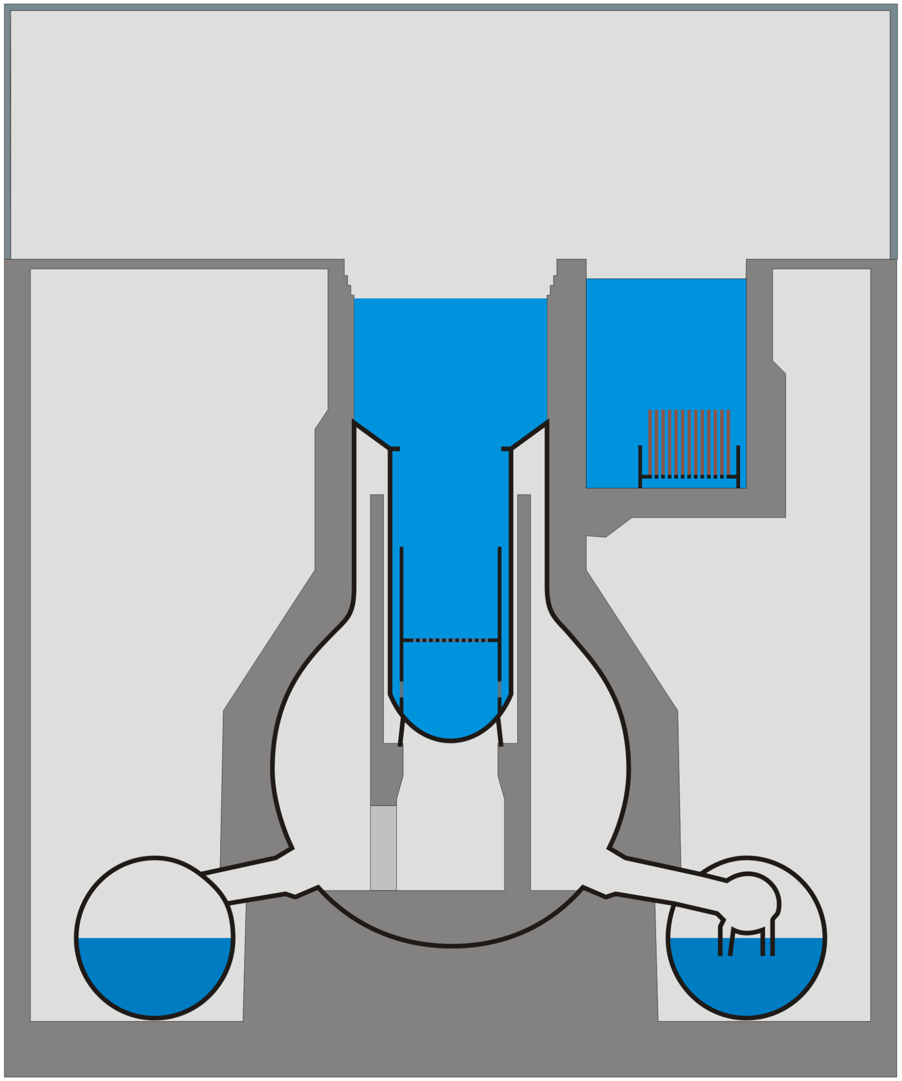
4. Spend fuel pools

- 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



The Fukushima Daiichi Incident
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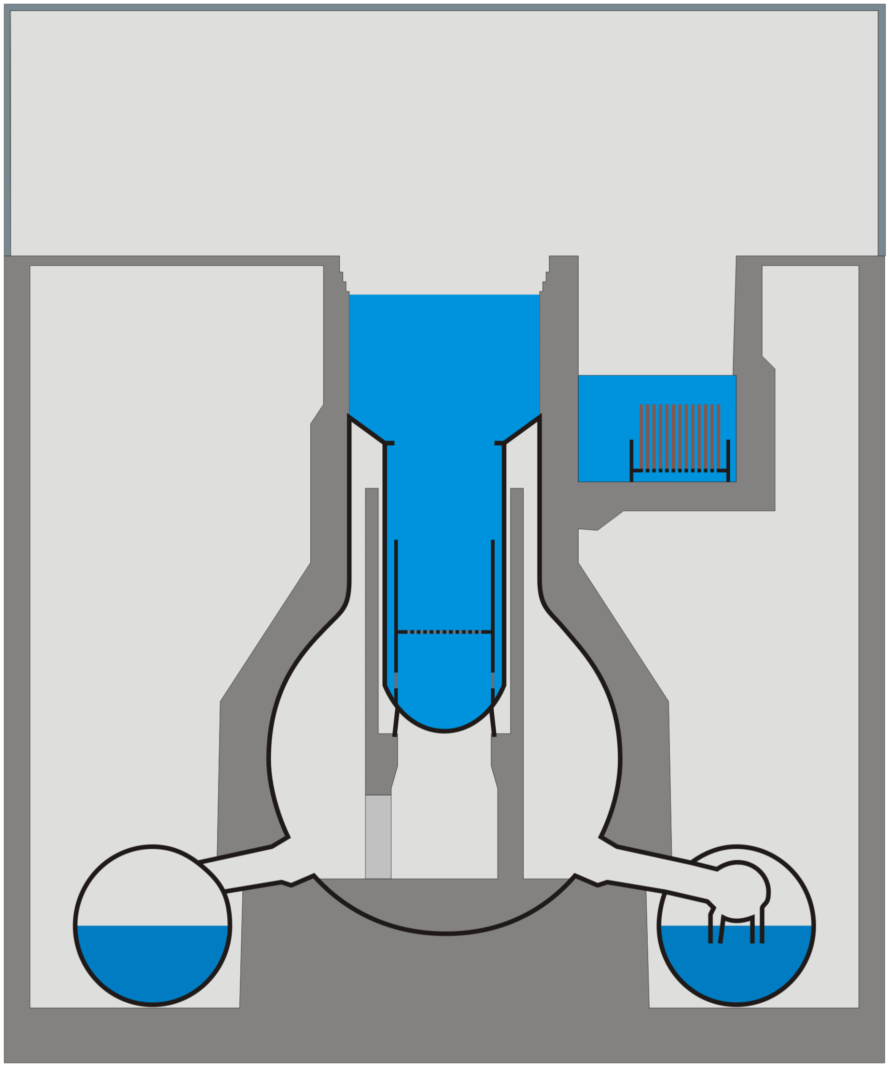

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The Fukushima Daiichi Incident
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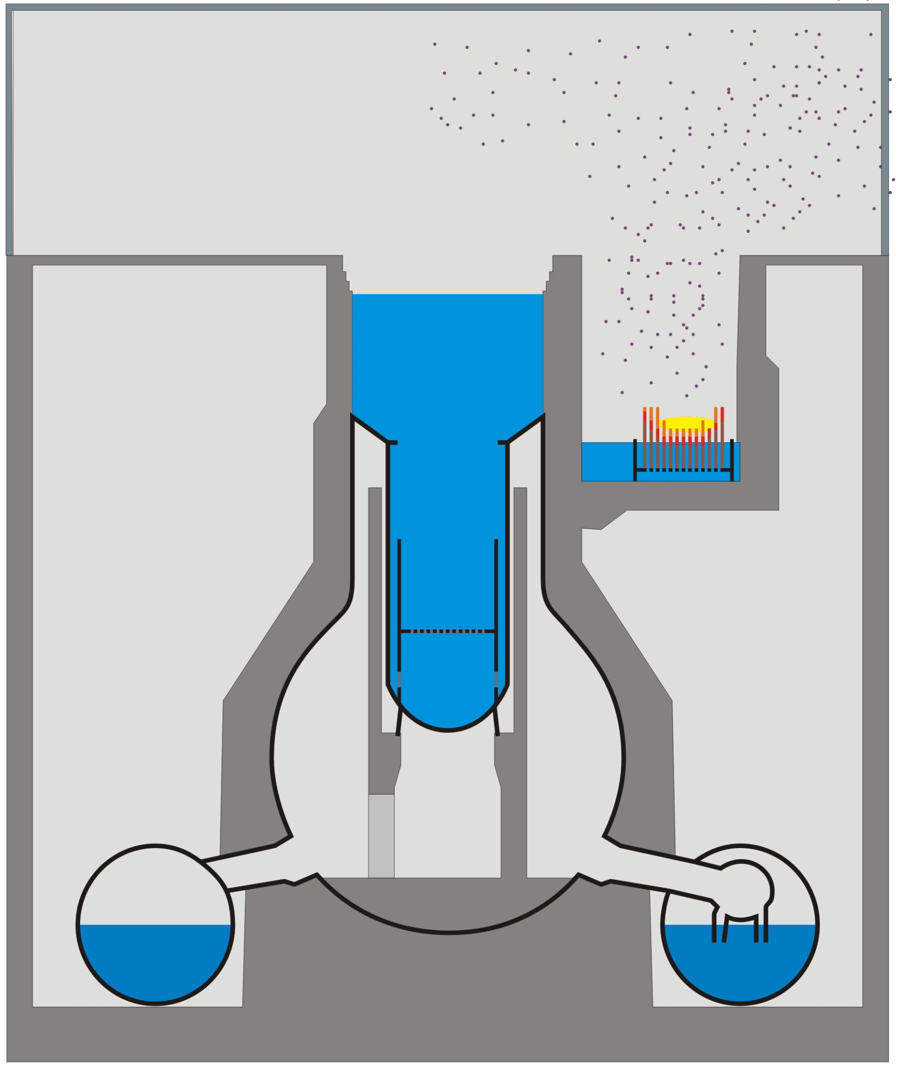

- Consequences
  - Core melt „on fresh air “
  - Nearly no retention of fission products
  - Large release

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

- 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