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

Status: April 15, 2011

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www.vgb.org
Preliminary Note

► Collection of information about the Tohoku-Taiheiyou-Oki earthquake und tsunami in Japan on March 11, 2011.

► Main Idea
  ▪ Provide an impression of the sequence of events.
  ▪ Understand consequences for nuclear power plants.

► All data have principally not yet been verified finally, but have been collected to the best of knowledge.

► The presentation is continuously being updated, as the VGB office gets new information.

Source: Reuters, 2011
Tohoku-Taiheiyou-Oki Earthquake

Epicenter Location
38.3 °N, 142.4 °E

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

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

Source: GRS, 2011  F: Fukushima  JST: Japan Standard Time
Northern Honshu Power Supply System

- Northern Honshu is separated electrically (50 Hz) from the southern part (60 Hz).
- Only three frequency converters with a total capacity of ≈ 1 GW.
- Earthquake-induced shutdown of numerous conventional power plants (hydroelectric, fossil-fired) and all nuclear plants (11 units at 4 sites, automatic safety system) in northeastern part of Honshu.

- Total Load: ≈ 41 GW
- Total Supply: ≈ 31 GW
- Supply Gap: ≈ 10 GW
Tohoku-Taiheiyou-Oki Earthquake

- **Vertical Displacement**
  \[ D \approx 7 \text{ to } 10 \text{ m} \]

- **Peak Displacement**
  \[ D_{\text{max}} \approx 17 \text{ to } 25 \text{ m} \]

- **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**
  \[ Z \approx 8 \text{ km} \]

**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.**

Source: Dr. Hein Meidow, Cologne, 2011  
JST: Japan Standard Time  
UTC: Coordinated Universal Time  
1) in deep underground
Topographic Effects

- Relative horizontal displacement of Japan, based on GPS data:
  \( \approx 5.2 \text{ m (maximum)} \)

- Displacement on rupture surface:
  \( \approx 25 \text{ to } 27 \text{ m} \)

- Rupture length (aftershock):
  \( \approx 400 \text{ km} \)

- Sea bed lifting:
  up to 7 m

Sources: Dr. Hein Meidow, Cologne, GFZ Potsdam, 2011
Tohoku-Taiheiyou-Oki Earthquake Intensity

<table>
<thead>
<tr>
<th>Scale</th>
<th>Japan</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>JMA</td>
<td></td>
<td>EMS</td>
</tr>
<tr>
<td>Kurihara</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Fukushima</td>
<td>6↑</td>
<td>≈ 9 to 10</td>
</tr>
</tbody>
</table>

- Modified Mercalli Scale (USA)
- Seismic Intensity at Coast: VIII

There are different scales to estimate local seismic intensities.

Tohoku-Taiheiyou-Oki Earthquake Magnitude

- **Moment-Magnitude:** $M_W = 9.0$
- **Fukushima Design Basis:** $M_W = 8.2$
  - Earthquake effects on the plant depend on the distance between plant and epicenter.
  - At the same location: Moment-Magnitude is by a factor of $10^{(9.0 – 8.2)} \approx 6.3$ higher.

- **Richter-Scale for Local Magnitude $M_L$:**
  - Upper limit on the highest measurable local magnitude (saturation).
  - All large earthquakes will tend to have a local magnitude of $M_L \approx 7$.
  - Not applicable (reliable) for earthquakes with large magnitudes.

- **Historic Classification:** Rank 1 in Japan, Rank 5 Worldwide.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Intensity JMA</th>
<th>Intensity EMS</th>
<th>Magnitude $M_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tohoku 2011</td>
<td>7</td>
<td>$\approx 11$</td>
<td>9.0</td>
</tr>
<tr>
<td>Basel 1356</td>
<td>$\approx 6^\uparrow$</td>
<td>9</td>
<td>6.9</td>
</tr>
<tr>
<td>Düren 1756</td>
<td>$\approx 6^\downarrow$</td>
<td>8</td>
<td>5.9</td>
</tr>
<tr>
<td>Albstadt 1978</td>
<td>$\approx 5^\uparrow$ to $6^\downarrow$</td>
<td>7.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Roermond 1992</td>
<td>$\approx 5^\uparrow$</td>
<td>7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Source: Dr. Hein Meidow, Cologne, 2011   EMS: European Macroseismic Scale   JMA: Japan Meteorological Agency
# Chu-Etso Earthquake 2007 Accelerations

► **Kashiwasaki-Kariwa Nuclear Power Plant Site**
- Located on the inland sea coast of (northwestern) Honshu,
- 5 BWRs (older units) of similar design, based on GE BWR-5,
- 2 ABWRs (newer units) with gas-tight inner and outer containments.

<table>
<thead>
<tr>
<th>Seismic Motion</th>
<th>Acceleration in cm/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Older Units</strong></td>
<td><strong>Newer Units</strong></td>
</tr>
<tr>
<td>Design Basis, Plant</td>
<td>167 to 194</td>
</tr>
<tr>
<td>Chu-Etso 2007, Plant</td>
<td>384 to 606</td>
</tr>
<tr>
<td>Design Basis, Bedrock</td>
<td>450</td>
</tr>
<tr>
<td>Chu-Etso 2007, Bedrock</td>
<td>1011 to 1478</td>
</tr>
</tbody>
</table>

► Chu-Etso earthquake led to accelerations that exceeded the design basis values by a factor of about 2 to 3 without major safety-relevant damages.

► In 2011 four of seven units are back in service again after retrofit measures.

Source: Dr. Hein Meidow, Cologne, 2011  
ABWR: Advanced Boiling Water Reactor  
BWR: Boiling Water Reactor  
GE: General Electric
Tohoku-Taiheiyou-Oki Earthquake

Peak Accelerations Contour Map

<table>
<thead>
<tr>
<th>Source</th>
<th>Peak Acceleration in cm/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fukushima</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td></td>
<td>N-S</td>
</tr>
<tr>
<td>Daiichi-1</td>
<td>460</td>
</tr>
<tr>
<td>Daiichi-2</td>
<td>348</td>
</tr>
<tr>
<td>Daiichi-3</td>
<td>322</td>
</tr>
<tr>
<td>Daiichi-4</td>
<td>281</td>
</tr>
<tr>
<td>Daiichi-5</td>
<td>311</td>
</tr>
<tr>
<td>Daiichi-6</td>
<td>298</td>
</tr>
<tr>
<td>Design Basis</td>
<td>441</td>
</tr>
<tr>
<td>Daini-1</td>
<td>254</td>
</tr>
<tr>
<td>Daini-2</td>
<td>243</td>
</tr>
<tr>
<td>Daini-3</td>
<td>277</td>
</tr>
<tr>
<td>Daini-4</td>
<td>210</td>
</tr>
<tr>
<td>Design Basis</td>
<td>415</td>
</tr>
<tr>
<td>Shutdown 2)</td>
<td>135 to 150</td>
</tr>
</tbody>
</table>

- Measured accelerations were up to 26 % higher than earthquake design basis values for Fukushima Daiichi (≈ 10 % for Onagawa).

Sources: Nied, Wano Tokyo, Tepco, 2011  
E-W: East-West  
N-S: North-South  
1) maximum response, preliminary data  
2) threshold for reactor scram
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.

Sources: FPL, KIT, 2011  JST: Japan Standard Time
Initial Response to Tsunami

About 55 minutes later

► At least Fukushima Daiichi is struck by the tsunami, with a wave height ($\approx 14 \text{ m}$) 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).

Sources: FPL, AFP, JIJI Press, 2011
Tsunami Impact at Fukushima Daiichi

4 to 5 m inundation height across the ocean side of main structures area (reactor and turbine buildings).

Source: Tepco, 2011
Tsunami Impact at Fukushima Daini

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.

Sources: AFP, GRS, 2011 ¹) calculations and GPS-data ²) according to Janti, related to the base level of Onahama Bay
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.

Source: Janti, 2011   All levels are related to the base level of Onahama Bay
Fukushima Daiichi Aerial View

| Unit | Power   | Status  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>439 MWe</td>
<td>Operating</td>
</tr>
<tr>
<td>2</td>
<td>760 MWe</td>
<td>Operating</td>
</tr>
<tr>
<td>3</td>
<td>760 MWe</td>
<td>Operating</td>
</tr>
<tr>
<td>4</td>
<td>760 MWe</td>
<td>Outage</td>
</tr>
<tr>
<td>5</td>
<td>760 MWe</td>
<td>Outage</td>
</tr>
<tr>
<td>6</td>
<td>1067 MWe</td>
<td>Outage</td>
</tr>
</tbody>
</table>

1) before earthquake

Source: Nuclear Engineering Handbook, 2010
Fukushima Daiichi Site Layout

Environmental management
Solid waste storage
Shared spent fuel pool
Main offices

4 units
2 units

Outlet
Internal emergency diesel systems
Spent fuel dry storage facility
Sea water intake

„Bird‘s Eye Views“

<table>
<thead>
<tr>
<th>Unit</th>
<th>Year</th>
<th>Reactor</th>
<th>Containment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1971</td>
<td>BWR-3</td>
<td>Mark I</td>
</tr>
<tr>
<td>2</td>
<td>1974</td>
<td>BWR-4</td>
<td>Mark I</td>
</tr>
<tr>
<td>3</td>
<td>1976</td>
<td>BWR-4</td>
<td>Mark I</td>
</tr>
<tr>
<td>4</td>
<td>1978</td>
<td>BWR-4</td>
<td>Mark I</td>
</tr>
<tr>
<td>5</td>
<td>1978</td>
<td>BWR-4</td>
<td>Mark I</td>
</tr>
<tr>
<td>6</td>
<td>1979</td>
<td>BWR-5</td>
<td>Mark II</td>
</tr>
</tbody>
</table>

Sources: Florida Power & Light, AFP, Jiji Press, 2011
Tsunami possibly had flooded up to this line?

- Open gate
- Trenches for piping and cabling
- Damaged gate
- Sea water pumps
- Sea water intake

Sources: Janti, Digital Globe, 2011
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.

Sources: IAEA, WNN, 2011
Flooded Trenches for Piping and Cabling

Sea water pumps

Trenches flooded with contaminated water

Sources: Janti, www.cryptome.org, 2011
The Fukushima Daiichi Accident

Question: Is this accident a matter of residual risk of nuclear energy?

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:
\[ f = \frac{16}{513} \approx 0.0312 \text{ a}^{-1} \]
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!

Sources: Dr. Johannis Nöggerath, Swiss Nuclear Society, March 28, 2011, www.tsunami-alarm-system.com  
1) magnitude  
2) maximum amplitude
The Fukushima Daiichi Accident

► Is a Japan-like tsunami reasonable for Europe?

- The Atlantic and Mediterranean coasts of Europe are not safe from tsunamis and therefore must be protected.

- In comparison to the Pacific region only a few devasting tsunamis occur in the Atlantic and Mediterranean regions.

- In the Mediterranean on average one devasting tsunami has to be expected every century. About ten percent of all tsunamis taking place worldwide occur in the Mediterranean. Moreover, Greece and Italy are mostly affected by tsunamis in this region.

- Up to now the largest tsunami on the European Atlantic coast took place at Lisbon, Portugal, on November 1, 1755. This tsunami was induced by an earthquake with a magnitude of about 9.0 and had a maximum amplitude of 12 m.

► Conclusion: There is no specific risk for Central Europe.

Sources: Dr. Johannis Nöggerath, Swiss Nuclear Society, March 28, 2011, www.tsunami-alarm-system.com
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 $\approx 850 \, ^\circ\text{C}$ (exochemical 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).

Source: FPL, 2011  JST: Japan Standard Time
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).

Source: FPL, 2011
Unit 1 and Unit 3 Hydrogen Explosions

Vented gas released into service floor

- Hydrogen explosions in two service floors:
  - Unit 1 on March 12,
  - Unit 3 on March 14.
- Concrete reactor building structures remained intact.
- Reactor building explosion spectacular, but of minor safety importance.

- Estimated Hydrogen Production (Recalculation)
  - Service floor volume: \( \approx 8000 \text{ m}^3 \)
  - Within flammable range: \( \approx 320 \text{ kg H}_2 \)
  - Extent of Core Oxidation: \( \approx 60 \text{ to } 70 \% \)

Source: General Electric, 2011
Aerial Views at Fukushima Daiichi

Before Tsunami

Shared spent fuel pool building

After Tsunami and Detonation in Unit 3

Missing heavy oil tanks

Displaced oil tank?

Source: Wano PC, Barrwood, 2011
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!

Source: WANO PC, Barnwood, 2011
Units 1 to 4 after Hydrogen Explosions

Sources: Areva NP, www.nirs.org
Aerial View after Hydrogen Explosions

Source: www.cryptome.org, 2011
Aerial View after Hydrogen Explosions

- Vent stack
- Containment vent pipe
- Vent pipe break
- Cables, fire hoses

Source: www.cryptome.org, 2011
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

Sources: NRC, General Electric, www.nucleartourist.com
Design of Fukushima Daiichi Unit 6

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

Sources: NRC, General Electric
Service Floor with Primary Containment Head

Source: www.nucleartourist.com
Reactor Pressure Vessel Head

Source: www.zwentendorf.com
Boiling Water Reactor Internals

Fuel Assembly
Control Rod
Fuel Assemblies (4)

Reactor Core

Source: www.nucleartourist.com
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

Source: AREVA NP, March 24, 2011  LOCA: Loss of Coolant Accident
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 $\approx 0.5\%$

Source: AREVA NP, March 24, 2011   JST: Japan Standard Time
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

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
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 ≈ 900 °C.
  ▪ Ballooning and/or bursting of claddings (local damages).
  ▪ Release of volatile fission products (noble gases) from internal gaps between fuel pellets and claddings.

Source: AREVA NP, March 24, 2011
Event Sequence – Accident Progression

Temperature Escalation Phase

► About 75% of the core cooled by steam only.
  - Cladding temperatures exceed ≈ 1200 °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 ≈ 44.2 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.

Source: AREVA NP, March 24, 2011
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
- \( T \): absolut temperature in K
- \( V \): volume

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

Sources: D. W. Akers et al., 1989  
CSA: Core Support Assembly  
TMI-2: Three Mile Island Unit 2, Pressurized Water Reactor, 900 MW
Core Materials Liquefaction Regimes

**Melting Temperatures**

- **UO₂**
  - 2850 °C
- **ZrO₂**
  - 2690 °C
- **B₄C**
  - 2450 °C
- **Zircaloy 4**
  - 1760 °C
- **Stainless Steel**
  - 1450 °C

**Liquefaction Regimes**

- **3000 °C**
  - Melting of the ceramic materials UO₂ and ZrO₂ as well as formation of ceramic (U, Zr, O) melts
- **2000 °C**
  - 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
- **1000 °C**
  - Ballooning and bursting of fuel rod claddings, release of volatile fission products

**Core Damage**

- ▶ Complete
- ▶ Extended
- ▶ Localized
- ▶ Initiation

Source: KIT, GRS, 2011
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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
**Event Sequence – Accident Progression**

► **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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
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.

Source: AREVA NP, March 24, 2011
Fukushima-Daiichi-1

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

Source: Tepco, 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.

Source: AREVA NP, March 24, 2011
Spent Fuel Transfer Pools & Shared Pool

<table>
<thead>
<tr>
<th>Unit</th>
<th>Number of Assemblies</th>
<th>Water m³</th>
<th>Power MW</th>
<th>Fresh Core</th>
<th>Cooling</th>
<th>Fuel Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>292</td>
<td>1020</td>
<td>0.3</td>
<td>No</td>
<td>?</td>
<td>?</td>
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<tr>
<td>2</td>
<td>587</td>
<td>1425</td>
<td>1.0</td>
<td>No</td>
<td>Steam Plume</td>
<td>?</td>
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<tr>
<td>3</td>
<td>514</td>
<td>1425</td>
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<td>Boiling</td>
<td>?</td>
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<tr>
<td>4</td>
<td>1331</td>
<td>1425</td>
<td>3.0</td>
<td>Yes</td>
<td>Pump Car</td>
<td>Major</td>
</tr>
<tr>
<td>5</td>
<td>946</td>
<td>1425</td>
<td>4.5</td>
<td>Probably</td>
<td>Diesel ²)</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>876</td>
<td>1497</td>
<td>1.5</td>
<td>Probably</td>
<td>Diesel</td>
<td>No</td>
</tr>
<tr>
<td>S</td>
<td>6291 ¹)</td>
<td>?</td>
<td>?</td>
<td>No</td>
<td>Working</td>
<td>No</td>
</tr>
</tbody>
</table>

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 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).

S: site shared spent fuel pool ¹) total number on the site in November 2010, overall capacity: 6840 assemblies ²) unit 6
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).

Source: TEPCO, March 22, 2011
Unit 4 Spent Fuel Transfer Pool Cooling

Concrete pump car

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

Source: www.cryptome.org, 2011
Fukushima Daiichi Refueling Cooling System

Reactor pressure vessel and primary containment are open for refueling.

Source: FPL, 2011
Dose Rates at Fukushima Daiichi

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

Source: GRS, March 30, 2011   JST: Japan Standard Time
Dose Rates at Fukushima Daini

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

Source: GRS, March 30, 2011  JST: Japan Standard Time
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.

Source: GRS, March 24, 2011
### Fukushima Daiichi, Status as of March 19, 2011

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core and fuel</td>
<td>Damaged</td>
<td>Damaged</td>
<td>Damaged</td>
<td>No fuel in the reactor</td>
<td>Not Damaged</td>
<td>Not Damaged</td>
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<tr>
<td>integrity</td>
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<tr>
<td>Reactor</td>
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<td>Unknown</td>
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<tr>
<td>Pressure</td>
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<tr>
<td>Vessel Integrity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Containment</td>
<td>Not Damaged</td>
<td>Damage Suspected</td>
<td>Might be not</td>
<td>Not Damaged</td>
<td>Not Damaged</td>
<td>Not Damaged</td>
</tr>
<tr>
<td>Integrity</td>
<td></td>
<td></td>
<td>damaged</td>
<td></td>
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<tr>
<td>Reactor</td>
<td>Severely Damaged</td>
<td>Slightly</td>
<td>Severely</td>
<td>Open a vent</td>
<td>Open a vent</td>
<td>Open a vent</td>
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<td>building</td>
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<td>hole on the</td>
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<td>hole on the</td>
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<tr>
<td>integrity</td>
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<td>rooftop for</td>
<td>rooftop for</td>
<td>rooftop for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>avoiding</td>
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<tr>
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<td></td>
<td>hydrogen</td>
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<td></td>
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<td>explosion</td>
<td>explosion</td>
<td>explosion</td>
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<td>Water injection</td>
<td>Continuing (Seawater)</td>
<td>Continuing (Seawater)</td>
<td>Continuing (Seawater)</td>
<td>Not necessary</td>
<td>Not necessary</td>
<td>Not necessary</td>
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<tr>
<td>to core</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water injection</td>
<td>Continuing (Seawater)</td>
<td>to be decided (Seawater)</td>
<td>Continuing (Seawater)</td>
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<td>Not necessary</td>
<td>Not necessary</td>
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<tr>
<td>to Containment</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vessel</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel integrity</td>
<td>Water injection to</td>
<td>no info</td>
<td>level low -</td>
<td>Pool temperature</td>
<td>Pool temperature</td>
<td>Pool temperature</td>
</tr>
<tr>
<td>in the spent</td>
<td>be considered</td>
<td></td>
<td>water injection</td>
<td>increasing</td>
<td>increasing</td>
<td>increasing</td>
</tr>
<tr>
<td>fuel pool</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Quelle: AREVA NP, March 19, 2011
### Fukushima Daiichi, Status as of April 2, 2011

#### Table: Status of Reactors

<table>
<thead>
<tr>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Type</td>
<td>BWR-3</td>
<td>BWR-4</td>
<td>BWR-4</td>
<td>BWR-4</td>
<td>BWR-4</td>
<td>BWR-G</td>
</tr>
<tr>
<td>Thermal Power ($MW_{th}$)</td>
<td>1380</td>
<td>2381</td>
<td>2381</td>
<td>2381</td>
<td>2381</td>
<td>3293</td>
</tr>
<tr>
<td>Electric Power ($MW_{e}$)</td>
<td>460</td>
<td>784</td>
<td>784</td>
<td>784</td>
<td>784</td>
<td>1100</td>
</tr>
<tr>
<td>Status before earthquake</td>
<td>In service, auto shutdown</td>
<td>In service, auto shutdown</td>
<td>In service, auto shutdown</td>
<td>Outage</td>
<td>Outage</td>
<td>Outage</td>
</tr>
<tr>
<td>Core and fuel integrity</td>
<td>Damaged</td>
<td>Severe Damage</td>
<td>Damaged</td>
<td>No fuel in reactor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor outside temperatures</td>
<td>250 °C, 128 °C</td>
<td>180 °C, 450 °C</td>
<td>90 °C (?), 150 °C</td>
<td>Not applicable due to outage plant status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Containment integrity</td>
<td>Pressure of 2 bar, flooded?</td>
<td>Pressure of 1 bar, damage suspected</td>
<td>Pressure of 1 bar, damage suspected</td>
<td>Cold Shutdown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Power</td>
<td>Yes plus control room light</td>
<td>Yes plus control room light</td>
<td>Yes plus control room light</td>
<td>Yes plus control room light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building</td>
<td>Severe damage</td>
<td>Slight damage</td>
<td>Severe damage</td>
<td>Severe damage</td>
<td></td>
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</tr>
<tr>
<td>Reactor water level</td>
<td>40 % of fuel uncovered</td>
<td>30 % of fuel uncovered</td>
<td>50 % of fuel uncovered</td>
<td>Not applicable due to outage plant status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor pressure</td>
<td>About 5 bar, decreasing</td>
<td>Less than 1 bar (?)</td>
<td>1 bar</td>
<td>Sea water and fresh water by concrete pump car</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Status of spent fuel pool</td>
<td>Fresh water by concrete pump car</td>
<td>58 °C, sea water and fresh water by pool cooling</td>
<td>Sea water and fresh water by concrete pump car</td>
<td>Sea water and fresh water by concrete pump car</td>
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</tr>
</tbody>
</table>

Quelle: IAEA, April 2, 2011  ■ Severe condition  ■ Concern  ■ No immediate concern
### INES-Classification as of April 12, 2011

**Fukushima Daiichi**

<table>
<thead>
<tr>
<th>Unit</th>
<th>INES-Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
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<tr>
<td>2</td>
<td>7</td>
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<tr>
<td>3</td>
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<td>4</td>
<td>3</td>
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<tr>
<td>5</td>
<td>not specified</td>
</tr>
<tr>
<td>6</td>
<td>not specified</td>
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</tbody>
</table>

**Fukushima Daini**

<table>
<thead>
<tr>
<th>Unit</th>
<th>INES-Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>not specified</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Sources: IAEA, GRS, April 12, 2011
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

Sources: DPA, Nisa, IRSN, March 20, 2011 ¹) in case of short-term exposure ²) in Japan, 20 mSv/a in Germany
## Status of Other Plants as of April 4, 2011

<table>
<thead>
<tr>
<th>Plant</th>
<th>Status</th>
<th>Diesels, pumps</th>
<th>Venting</th>
<th>Offsite power</th>
<th>Damages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fukushima Daini</strong></td>
<td>cold shutdown</td>
<td>?</td>
<td>prepared</td>
<td>available</td>
<td>tsunami?</td>
</tr>
<tr>
<td>Units 1 to 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Onagawa</strong></td>
<td>cold shutdown</td>
<td>at least one, one pump</td>
<td>no</td>
<td>available</td>
<td>fire in unit 1, extinguished, no tsunami damage due to the higher ground level</td>
</tr>
<tr>
<td>Units 1 to 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tokai</strong></td>
<td>cold shutdown</td>
<td>one of three, one emergency pump</td>
<td>no</td>
<td>?</td>
<td>safe status</td>
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<tr>
<td>Unit 2</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Rokkasho</strong></td>
<td>none</td>
<td>available</td>
<td>not required</td>
<td>?</td>
<td>not reported</td>
</tr>
<tr>
<td>Reprocessing</td>
<td></td>
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</tbody>
</table>
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 Daini?
- 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)
Casualties

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
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ludger.mohrbach@vgb.org

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Registergericht: Amtsgericht Essen
Registernummer: VR 1788
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