Overview of the Accident in Fukushima Daiichi Nuclear Power Plants

May 26, 2011

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Vice Dean, School of Engineering, The University of Tokyo
Associate Member of Science Council of Japan
Contents

1. Earthquake and Tsunami on March 11, 2011
2. Fukushima Daiichi and other NPPs
3. Accident in Fukushima Daiichi Units
   • Unit 1 : Core Status, AM Code Simulation
   • Unit 2 : PCV Damage, Contaminated Water
   • Unit 3 : H₂ explosion
   • Unit 4 : Spent Fuel Pool, H₂ explosion ?
4. Release of Radioactive Materials and INES
5. Summary and Future

The information is preliminary and needs to be confirmed later.
2011.3.11 Earthquake and Tsunami

1) Earthquake
   Moment Magnitude 9.0

2) Tidal wave “Tsunami”
   Max. Height 38 m

3) Casualty Count (May 22)
   15,179 dead and 8,803 missing

4) Collapsed Buildings
   300,157

Photo by Prof. S. Sato, Department of Civil Engineering
The University of Tokyo
震災の科学技術に対するインパクト
Impact of the Disaster upon Science and Technology

1) 原子力発電所の事故
   Accident of nuclear power plant
   4基同時, レベル7
   4 plants, Level 7

2) 電力供給不足
   Shortage of electric power supply
   3950 × 10⁴ kWe/h, 計画停電
   Rolling blackouts

3) 工業生産の低下
   Diminishing industrial production
   サプライチェーンの断壊
   Supply-chain disruption

4) 通信網の断壊
   Disruption of communication network
   1週間
   1 week

科学技術への信頼低下
Loss of credibility of science and technology？
工学者・学生の自信喪失
Loss of confidence in engineering scholars and students？

Prof. T. Kitamori, Dean of School of Engineering, The University of Tokyo
The Main Shock and Aftershock of the Earthquake on 2011.3.11

Earthquake Research Institute, The University of Tokyo
Tsunami after the Earthquake on 2011.3.11

Compiled by 80 members from 33 organization including The University of Tokyo
http://www.coastal.jp/ttjt/
Automatic Shut-down of Nuclear Reactors by the Earthquake on 2011. 3. 11

11 reactors were automatically shut-down
- Onagawa Unit 1,2,3
- Fukushima Daiichi Unit 1,2,3
- Fukushima-Daini Unit 1,2,3,4
- Tokai-2

3 reactors were under periodic inspection
- Fukushima Daiichi Unit 4,5,6

After the automatic shut-down, the Units 1-3 at Onagawa Nuclear Power Station, the Unit 3 at Fukushima Daini Nuclear Power Station, and the Tokai-2 Nuclear Power Station have been cold shut down safely.

As for the unit 1,2,4 at Fukushima Daini Nuclear Power Station, the operator of the station reported NISA nuclear emergency situation because the temperature of the suppression pools became more than 100 ℃, but afterward the three units have been cold shut down.
Nuclear Power Plants in Eastern Coast of Japan

- Onagawa (Tohoku)
- Fukushima Daiichi *(TEPCO)*
- Fukushima Daini *(TEPCO)*
- Tokai-2 *(JAPCO)*

* Fukushima Daiichi locates approximately 230 km north of Tokyo*
Fukushima Daiichi Nuclear Power Plants operated by TEPCO
Overview of Mark-I Type BWR (Units 1,2,3,4 and 5)
# Summary of Fukushima Daiichi NPP

<table>
<thead>
<tr>
<th></th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PCV Model</strong></td>
<td>BWR-3</td>
<td>BWR-4</td>
<td>BWR-4</td>
<td>BWR-4</td>
<td>BWR-4</td>
<td>BWR-5</td>
</tr>
<tr>
<td><strong>Electric Output</strong></td>
<td>460MWe</td>
<td>784MWe</td>
<td>784MWe</td>
<td>784MWe</td>
<td>784MWe</td>
<td>1100MWe</td>
</tr>
<tr>
<td><strong>RPV Operation Pressure</strong></td>
<td>6.89MPa</td>
<td>6.93MPa</td>
<td>6.93MPa</td>
<td>6.93MPa</td>
<td>6.93MPa</td>
<td>6.93MPa</td>
</tr>
<tr>
<td><strong>RPV Max. Design Pressure</strong></td>
<td>8.24MPa</td>
<td>8.24MPa</td>
<td>8.24MPa</td>
<td>8.24MPa</td>
<td>8.62MPa</td>
<td>8.62MPa</td>
</tr>
<tr>
<td><strong>RPV Max. Operation Temp.</strong></td>
<td>300℃</td>
<td>300℃</td>
<td>300℃</td>
<td>300℃</td>
<td>302℃</td>
<td>302℃</td>
</tr>
<tr>
<td><strong>PCV Max. Design Pressure</strong></td>
<td>384kPa</td>
<td>384kPa</td>
<td>384kPa</td>
<td>384kPa</td>
<td>384kPa</td>
<td>279kPa</td>
</tr>
<tr>
<td>**PCV Max. Pressure ***</td>
<td>427kPa</td>
<td>427kPa</td>
<td>427kPa</td>
<td>427kPa</td>
<td>427kPa</td>
<td>310kPa</td>
</tr>
<tr>
<td><strong>PCV Max. Temp</strong></td>
<td>140℃</td>
<td>140℃</td>
<td>140℃</td>
<td>140℃</td>
<td>138℃</td>
<td>171℃:D/W, 105℃:S/C</td>
</tr>
<tr>
<td><strong>Emergency DG</strong></td>
<td>2</td>
<td>2 **</td>
<td>2</td>
<td>2 **</td>
<td>2</td>
<td>3 **</td>
</tr>
<tr>
<td><strong>Electric Grid</strong></td>
<td>275kV × 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>500kV × 2</td>
</tr>
<tr>
<td><strong>Plant Status on Mar. 11</strong></td>
<td>In Operation</td>
<td>In Operation</td>
<td>In Operation</td>
<td>Long Outage for Shroud Replacement</td>
<td>Refueling Outage</td>
<td>Refueling Outage</td>
</tr>
</tbody>
</table>

* Typical operating pressure of PCV is about 5 kPa. ** One Emergency DG is Air-Cooled
Nuclear Power Plants in Japan

1F : Fukushima Daiichi
2F : Fukushima Daini

- BWR : 30 units
- PWR : 24 units
- CGR, ATR

Start of Operation

Electrical Output (MWe)

### Recorded Intensity of Ground Motion and Basic Earthquake Ground Motion

<table>
<thead>
<tr>
<th></th>
<th>Observed Maximum Response Acceleration * (Gal)</th>
<th>Max Response Acceleration against Basic Earthquake Ground Motion (Gal), Ss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal (N-S)</td>
<td>Horizontal (E-W)</td>
</tr>
<tr>
<td><strong>Fukushima Daiichi</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 1</td>
<td>460</td>
<td>447</td>
</tr>
<tr>
<td>Unit 2</td>
<td>348</td>
<td>550</td>
</tr>
<tr>
<td>Unit 3</td>
<td>322</td>
<td>507</td>
</tr>
<tr>
<td>Unit 4</td>
<td>281</td>
<td>319</td>
</tr>
<tr>
<td>Unit 5</td>
<td>311</td>
<td>548</td>
</tr>
<tr>
<td>Unit 6</td>
<td>298</td>
<td>444</td>
</tr>
<tr>
<td><strong>Fukushima Daini</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 1</td>
<td>254</td>
<td>230</td>
</tr>
<tr>
<td>Unit 2</td>
<td>243</td>
<td>196</td>
</tr>
<tr>
<td>Unit 3</td>
<td>277</td>
<td>216</td>
</tr>
<tr>
<td>Unit 4</td>
<td>210</td>
<td>205</td>
</tr>
</tbody>
</table>

* At the lowest basement of reactor building
Tsunami

Fukushima Daiichi

Assumed highest tsunami level +5.7m*

Inundation height +14-15m

Turbine Building

Reactor Building

Base level O.P. 0m

+4m

Water intake

+10m

* Site level on Units 5 and 6 is O.P. +13m

Ocean-side area

Main building area

O.P. +6.5-7m

Assumed highest tsunami water level O.P.+5.2m *

Safety measures has taken against 5.7m Tsunami height

Site level +4m

Heat exchanger building

Water intake

+12m

Ocean-side area

Inundation height apx. O.P. +14-15m

Reactor Building

Turbine Building

Water intake

+10m

* Based on 2002 guidelines for NPPs issued by the Nuclear Civil Engineering Committee of JSCE

Fukushima Daini

O.P.: Onahama bay construction base level
Inundated Area at Fukushima Daiichi

Source: TEPCO
Tsunami, March 11, 2011

Tsunami height in Fukushima Daiichi was about 15 m.

Source: TEPCO
Tsunami, March 11, 2011

Fukushima Daiichi

Heavy Oil Tanks

Sea Water Pumps

Large Crane (45t)

Light Oil Tanks

Unit 1 T/B

Unit 2 T/B

Unit 3 T/B

Unit 4 T/B
Station Black-Out in Units 1-4
- Loss of Off-Site Power Supply and EDG -

**Station Black-Out**

1. Loss of Off-Site Power due to the Earthquake and Tsunami
2. Emergency DG Inoperable due to Tsunami Flood

All the motor operated pumps including ECCS pumps became inoperable.

- **Tsunami** (estimated more than 14 m)
- **Seawater level**
- **Seawater Pump**

10 m

**Note:**
- **Immediate Scram**
  - All the operating units were shut-down by automatic insertion of control rods.
- **Emergency DGs have worked** properly until the Tsunami attack.
Loss of Off-site Power Supply and EDG in Units 1-4

Loss of the external power supply
Okuma 1L, 2L: Breakers were broken due to the earthquake
Okuma 3L: Under modification
Okuma 4L: The failure cause is being investigated

Functions of all the EDG were lost either by
1) Damage at Metal-Clad Switchgear
2) Damage in Generator
3) Loss of Sea-Water Cooling System

(EDG: Emergency Diesel Generator)

Recovery of Off-site Power Supply
Unit 2 on March 20, Unit 1, 3, 4 on March 22
One Air-Cooled DG (DG6B) survived in Units 5 & 6

Pylons damage by the earthquake caused loss of off-site power supply

Damage in sea-Water cooled EDGs by the tsunami

Recovery of Off-site Power Supply on March 20-21
After the Tsunami,

– No lighting available

– What they can get are flashlights, batteries (some are removed from automobiles), fire trucks and some compressors

– Very difficult to measure the major safety parameters like water level, reactor pressure, CV pressure

Source: TEPCO
Summary: Differences of Units 1-4, Fukushima Dai-ichi

➢ **Fukushima Daiichi Units 5 & 6**
  - Elevation of the ground is 13 m. (Units 1 - 4: 10m)
  - One air cooled EDG of Unit 6 which is located on the ground level was survived.
  - Metal Clad Switchgears were not lost.
  - Temporary sea water pump installed after the earthquake was operable, making use of power from survived EDG.

➢ **Fukushima Daini NPPs**
  - External power was not lost.
  - RHR function of Unit 3 was survived.
  - Motors of sea water pumps for Unit 1, 2 and 4 were replaced by March 14, followed by re-activation of core cooling function.

➢ **Onagawa NPPs**
  - Elevation of the plants was 14.8m which is higher than Tsunami height.

➢ **Tokai-2**
  - Although off-site power was lost until May 13, 2 out of 3 EDGs were not lost thanks to the recently installed barrage to one of 2 seawater pump area to protect pumps from tsunami.
Radioactive Materials and Decay Power in Units 1, 2 and 3

**Source Term just after the Shutdown**

**Unit 1 Fuel**
- I-131 : $1.9 \times 10^{18}$ Bq
- Cs-137 : $2.0 \times 10^{17}$ Bq

**Unit 2**
- I-131 : $2.7 \times 10^{18}$ Bq
- Cs-137 : $2.4 \times 10^{17}$ Bq

**Unit 3**
- I-131 : $2.7 \times 10^{18}$ Bq
- Cs-137 : $2.4 \times 10^{17}$ Bq
Short-term Actions for Termination of Accident and Emergency

• Stable Cooling to Cold Shut-down
  – Flooding (?) the containment to a certain level & installation of heat exchanger to remove heat
  – SFP cooling system

• Minimize Airborne and Liquid Effluent
  – Recycling of water, storage of contaminated water, …
  – Cover for reactor building, site soil, ground water, …

• Dose and Contamination Maps
Isolation Condenser (IC) for passive core cooling was operated just after the emergency stop due to the earthquake.
Unit 1: Loss of Cooling

Decrease in reactor water level due to loss of cooling capability of Isolation condenser, followed by uncovering the core

- Decrease in reactor water level
- Uncovering the Core
- Hydrogen Generation due to Zirconium-Water reaction
- Fuel Rod damage and melting

Source: Nuclear and Industrial Safety Agency
Unit 1: PCV Venting and Cooling by Sea Water Injection

- **S/C Venting to depressurize the PCV**
- **Sea water injection using fire water pump**

Sea water injection to the RPV from the existing makeup water system using fire-extinguishing pump.

S/C Venting to depressurize the PCV

Source: Nuclear and Industrial Safety Agency
Hydrogen Explosion in the Operation Floor in Unit 1
- March 12, 15:36 -
**Water Level in RPV, Pressure in RPV and PCV (D/W & S/C)**

*From March 11 to 16 in Unit 1*

Source: Side event material on the “Fukushima Daiichi Accident and Initial Safety Measures Worldwide” in IAEA.
Unit 1: Cooling

Switched to fresh water injection on March 25th

Source: Nuclear and Industrial Safety Agency
Calibration of the reactor water level gauge of Unit 1 was completed in the Reactor Building by May 15.
The actual water level in the RPV has been far lower than its indication reported for these 2 months!
**Reactor Water Level and Core Temperature in Unit 1**

- Simulation Trial by the MAAP code -

*Assuming that IC lost its function by the Tsunami*

- Reactor Water Level (m)
- Maximum Core Temperature(℃)

![Graph showing reactor water level and core temperature over time.]  

- Reached top of active fuel in 3 hours (around 18:00) after the scram
- Reached bottom of active fuel in 4 and a half hours (around 19:30) after the scram

The core temperature started increasing when the reactor water level became lower than top of active fuel, then reached the core melting temperature.

Source: TEPCO
Transition of Core Status in Unit 1
- Simulation Trial Results by the MAAP code -

- Melting starts from the central part of the core.
- In 16 hours after scram, most part of the core fell down to the RPV bottom.
- Although RPV is damaged in this provisional analysis, the actual damage of RPV is considered to be limited according to the temperatures presently measured around the RPV.

Comparison of simulation results and their sensitivity on input parameters from other severe accident analysis codes like MELCOR and THALES should also be made.
System outline of water reuse as reactor coolant by processing accumulated water

Reactor Building

Turbine Building

Closed Cycle

Tank

Purifier

Filtering

Source: TEPCO

Reactor Building Cover for Unit 1
Hydrogen explosion at Unit 3 on March 14

Explosion sound at Unit 2 on March 15

Source: TEPCO
Highly Radioactive Debris near Unit 3

> 1000 mSv/hr

Source: TEPCO
### Unit 3

**Water Level in RPV, Pressure in RPV and PCV**

*From March 11 to 17*

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**Graph Details:**
- **x-axis:** Time (from March 11 0:00 to March 17 0:00)
- **y-axis:**
  - Reactor Pressure (kPa)
  - Reactor Water Level (mm)
  - Drywell Pressure

**Events:**
- **3/11 14:46:** Reactor Shut Down
- **3/11 15:42:** Station Black out
- **3/11 14:46:** Reactor Shut Down

**Legend:**
- **RCIC**
- **Water Injection**
- **HPCI was lost**
- **RCIC inoperable**
- **Sea water injection**
- **Core cooling by RCIC & HPCI**
- **S/C Venting**
- **Hydrogen explosion**
- **S/C Venting**

**Source:** Side event material on the “Fukushima Daiichi Accident and Initial Safety Measures Worldwide” in IAEA.
Unit 2

Water Level in RPV, Pressure in RPV and PCV (D/W & S/C)

From March 16 to April 22

Source: NISA & TEPCO’s press release.
Unit 2  Water Level in RPV, Pressure in RPV and PCV (D/W & S/C)
From March 11 to 17

Source: Side event material on the “Fukushima Daiichi Accident and Initial Safety Measures Worldwide” in IAEA.
On-site Radiation Monitoring in Fukushima Daiichi Site
From March 11 to 18

11.93 mSv/h on March 15
Measures against Water Puddles at Fukushima Daiichi

Source: TEPCO
Leakage of Highly Radioactive Water from Unit 2

Leakage of radioactive water to the ocean between Apr. 1 to 6 from the pit of Unit 2

Amount of Released Water: 520 m³

Concentration of Radioactive Materials
- I-131: $5.4 \times 10^4$ Bq/cm³
- Cs-134: $1.8 \times 10^4$ Bq/cm³
- Cs-137: $1.8 \times 10^4$ Bq/cm³

Total Released Radioactivity
- I-131: $2.8 \times 10^{15}$ Bq
- Cs-134: $9.4 \times 10^{14}$ Bq
- Cs-137: $9.4 \times 10^{14}$ Bq

Countermeasures
- Drilled a hole into the pit and injected water glass (sodium silicate) into the pit.
- By April 6, the outflow was confirmed to stop.

Source: TEPCO
Countermeasure to Seal the Damaged Location in the PCV of the Unit 2

- Water Injection
- Ventilation
- Water Outflow
- Fill Grout Material
- Excavate the 1st floor of R/B and fill grout in the torus

Source: TEPCO
# Fuel Assemblies in Core and Spent Fuel Pool

<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><strong>Number of Fuel Assembly in the Core</strong></td>
<td>400</td>
<td>548</td>
<td>548*</td>
<td>-</td>
<td>548</td>
<td>764</td>
</tr>
<tr>
<td><strong>Number of Spent Fuel Assembly in the SFP</strong></td>
<td>292</td>
<td>587</td>
<td>514</td>
<td>1,331</td>
<td>946</td>
<td>876</td>
</tr>
<tr>
<td><strong>Number of New Fuel Assembly in the SFP</strong></td>
<td>100</td>
<td>28</td>
<td>52</td>
<td>204</td>
<td>48</td>
<td>64</td>
</tr>
<tr>
<td><strong>Water Volume (m$^3$)</strong></td>
<td>1,020</td>
<td>1,425</td>
<td>1,425</td>
<td>1,425</td>
<td>1,425</td>
<td>1,497</td>
</tr>
<tr>
<td><strong>Heat Generation in Spent Fuel Pool (MW)</strong></td>
<td>0.07</td>
<td>0.47</td>
<td>0.23</td>
<td>2.3</td>
<td>0.08</td>
<td>0.07</td>
</tr>
</tbody>
</table>

* including 32 MOX Fuel Assembly
Temperature History of Spent Fuel Pools

Pool Water Temperature (°C)

Source: NISA & TEPCO’s press release
Unit 3: Spent Fuel Pool Cooling

【1st Stage】Sea water injection

Discharge of Sea water
-Self-Defense Force

Water Spray
by
-Self-Defense Force
-Fire Department
-Police

Fuel Pool Cooling Line

SFP

Fire Engine Pump

Fresh water in Fire engine

Sea water

【2nd Stage】Fresh water injection

Dam

Pump

Reservoir tank

Filtrate Tank

Water spray using concrete pump truck

Source: Nuclear and Industrial Safety Agency
**Unit 4: Spent Fuel Pool Cooling**

【1st Stage】Sea water injection

- **Water Spray from the ground by Self Defense Force and Fire Department**

【2nd Stage】Fresh water injection

- **Water spray using concrete pump truck**

- Reactor building damage on March 15

Source: Nuclear and Industrial Safety Agency
Hydrogen Explosion in Unit 4?

Possible mechanisms: (1) Zr-H$_2$O reaction in the SFP, (2) H$_2$ from Unit 3, (3) Decomposition of H$_2$O into H$_2$ and O$_2$ under radiation.
Unit 4: Spent Fuel Pool

- No significant damage was identified by underwater camera inspection
- Water sampling on April 12 also shows relatively low radioactivity in SFP water

Analysis result of water in the SFP of Unit 4
(Date of Collection 4/12)

<table>
<thead>
<tr>
<th>Detected Nuclides</th>
<th>Half life</th>
<th>Density (Bq/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cesium 134</td>
<td>Approx. 2 Years</td>
<td>88</td>
</tr>
<tr>
<td>Cesium 137</td>
<td>Approx. 30 Years</td>
<td>93</td>
</tr>
<tr>
<td>Iodine 131</td>
<td>Approx. 8 Days</td>
<td>220</td>
</tr>
</tbody>
</table>

Source: TEPCO

Zr-H₂O reaction in the SFP at high temperature

Source: TEPCO
Stand-by Gas Treatment Systems for Units 3 and 4

Pipes of stand-by gas treatment systems for Units 3 and 4 are connected.

Source: TEPCO
Possible Mechanism of Hydrogen Explosion in Unit 4

East and west walls on the 4th floor in addition to the 5th floor were heavily damaged.

Source: TEPCO
Experiments on High Concentration of Hydrogen Gas under Radiation at Boiling Temperature

<table>
<thead>
<tr>
<th>G-values</th>
<th>-H₂O</th>
<th>e⁻_aq</th>
<th>OH</th>
<th>H</th>
<th>H₂O₂</th>
<th>H₂</th>
<th>HO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma-ray</td>
<td>4.1</td>
<td>2.7</td>
<td>2.8</td>
<td>0.56</td>
<td>0.68</td>
<td>0.45</td>
<td>~0.01</td>
</tr>
<tr>
<td>Alpha-ray</td>
<td>2.65</td>
<td>0.06</td>
<td>0.24</td>
<td>0.21</td>
<td>0.985</td>
<td>1.3</td>
<td>0.22</td>
</tr>
</tbody>
</table>

New Finding by H₂ production under irradiation:
- Effective transfer of H₂ into gas phase at 100°C
- High concentration of H₂ through condensation of H₂O at lower temperature region

Typical BWR condition simulation of radiation chemistry reactions considering the reaction between H₂ and OH, resulting in steady state concentration of H₂.

May 16, 2011
Prof. Katsumura Group
The University of Tokyo and JAEA

6.8 kGy/h for 1 hr at 80, 97 and 100°C

Experimental Set-up at JAEA Takasaki
INSS (International Nuclear Event Scale) Evaluation

- NISA issued provisional INES ratings, based on “What is known” at the time.
- At first, following units were rated as Level 3 based on “Defense in Depth” criteria about 10 hours later from the earthquake.
  - Fukushima Daiichi Units 1, 2 and 3, Fukushima Daini Units 1, 2 and 4
- In the evening on March 12, the rating of Fukushima Daiichi Unit 1 was re-evaluated to Level 4 based on the “Radiological Barriers and Control” criteria.
- On March 18, Fukushima Daiichi Units 1, 2 and 3 were re-rated to Level 5 based on “Radiological Barriers and Control” criteria because the fuel damage was highly possible. Fukushima Daiichi Unit 4 was evaluated to Level 3 based on the “Defense in Depth” criteria.
- On April 12, Fukushima Daiichi NPPs was revised Level 7 based on the “People and Environment” criteria, as a result of discharged estimation.
- Official rating will be done after cause and countermeasures are identified.
On April 12, Nuclear and Industrial Safety Agency (NISA) released:
- Tentatively assigned Level 7 on INES for the accident at Fukushima Daiichi Nuclear Power Station.
- The amount of released radioactive material is one-tenth as much as the accident at Chernobyl.

### Estimated release from Fukushima Daiichi

<table>
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<tr>
<th></th>
<th>Estimated release from Fukushima Daiichi</th>
<th>(Reference) Release from Chernobyl</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>by NISA</td>
<td>by Nuclear Safety Commission</td>
</tr>
<tr>
<td>Iodine 131 (a)</td>
<td>130 thousands T Bq (1.3X10^{17} Bq)</td>
<td>150 thousands T Bq (1.5X10^{17} Bq)</td>
</tr>
<tr>
<td>Cesium 137</td>
<td>6 thousands T Bq (6.0X10^{15} Bq)</td>
<td>12 thousands T Bq (1.2X10^{16} Bq)</td>
</tr>
<tr>
<td>Iodine value conversion (b)</td>
<td>240 thousands T Bq (2.4X10^{17} Bq)</td>
<td>480 thousands T Bq (4.8X10^{17} Bq)</td>
</tr>
<tr>
<td>(a) + (b)</td>
<td>370 thousands T Bq (3.7X10^{17} Bq)</td>
<td>630 thousands T Bq (6.3X10^{17} Bq)</td>
</tr>
</tbody>
</table>

**INES level 7 equivalent**: over 10 thousands Tera Becquerel (T Bq) (over 10^{16} Bq)

Source: Nuclear and Industrial Safety Agency
Monitoring Posts in the Fukushima Daiichi Nuclear Power Plants Site
On-site Radiation Monitoring in Fukushima Daiichi Site
From March 11 to 18

11.93 mSv/h on March 15

0.0001 0.001 0.1 1 10 100
Measured Dose Rate (mSv/hr)

5:44 10km Evacuation
15:36 #1 H₂ explosion
11:01 #3 H₂ explosion
6:10 #2 CV damage
9:38 #4 Fire
5:45 #4 Fire
8:34 #3 White Smoke
11:06 20-30km Sheltering in House

20:50 2km Evacuation (Fukushima Pref.)
21:23 3km Evacuation & 3-10 km Sheltering in House
On-site Radiation Monitoring in Fukushima Daiichi Site
From March 11 to April 10

Source: NISA & TEPCO’s press release
Survey Map in Fukushima Daiichi Site March 23, 2011

Measured on 3/20
15:00～18:00

Measured on 3/22
11:00～14:00

Measured on 3/23
11:30～12:30

Source: TEPCO
On-Site Monitoring of Radioactive Materials

Radioactive materials in the air measured by TEPCO

Source: TEPCO
Integrated Dose of External Exposure

SPEEDI code

Adult

from March 12 to April 24, 2011

Effective Dose in mSv

1 = 100
2 = 50
3 = 10
4 = 5
5 = 1
Monitoring Radiation Dose in Fukushima Prefecture

Source: MEXT press release
Radiation Monitoring at The University of Tokyo
From March 15 to 31

Measured Dose Rate in Tokyo and Tokai (μSv/h)

Tokai Campus in Ibaraki
Tokai Campus in Ibaraki
Tokyo, Hongo Campus, E-M roof
Tokyo, Hongo Campus, in-door

Distance from Fukushima Daiichi NPPs
Ibaraki, Tokai Campus : 110 km
Tokyo, Hongo Campus : 230 km
Radiation Monitoring at The University of Tokyo
From March 15 to May 24

Measured Dose Rate in Tokyo and Tokai ($\mu$Sv/h)

Tokai, MP-1
Tokai, MP-2
Tokai, MP-2
Monitoring of Radioactive Materials in Near-by Sea of Fukushima Daiichi NPPs
Monitoring of Radioactive Materials in Near-by Sea of Fukushima Daiichi NPPs
Measures to prevent the spread of radioactive water

Intentional discharge of radioactive water (as of April 4)
(from sub-drain of Unit 5&6)
I-131 20 Bq/cm³
Cs-134 4.7 Bq/cm³
Cs-137 4.9 Bq/cm³
※ analysis result of Unit 6 water

Leakage of Highly radioactive water (as of April 12)
I-131 5.4 × 10⁶ Bq/cm³
Cs-134 1.8 × 10⁶ Bq/cm³
Cs-137 1.8 × 10⁶ Bq/cm³

Intentional discharge of radioactive water (as of March 28)
(from radiation Waste treatment building)
I-131 6.3 Bq/cm³
Cs-134 4.4 Bq/cm³
Cs-137 4.4 Bq/cm³

Large-sized Sandbags (finished on Apr. 17)
Silt fence (Finished on Apr. 14)
Steel plate insulation (Finished on Apr. 15)
Sandbags containing Zeolite (in operation)
Sheet Pile (under planning)
Sliding timber weir (under planning)
Sampling Results of Marine Fish Products

Source: Fisheries Agency

So far, radioactive iodine and cesium beyond provisional standards (intake limits) were detected in Sand Lances (sand eels) only. The government told Fukushima Prefecture to suspend shipments of Sand Lances.

All fisheries activities are voluntarily refrained in Fukushima Prefecture.

Fisheries activities for Sand Lances are voluntarily refrained in Ibaraki Prefecture.

: beyond standards (intake limits)
: below standards

as of May 5 (Thu)
Emergency Dose and Goals to Terminate the Accident

Nuclear Safety Commission on April, 12

Avoidance
- Sheltering: 10 mSv
- Evacuation: 50 mSv

Emergency
- 20-100 mSv/year

Post accident
- 1-20 mSv/year

Goal
- 1 mSv/year
Evacuation of Residents

Fukushima Daiichi locates approximately
- 230 km from Tokyo
- 580 km from Osaka
- 600 km from Sapporo
Evacuation of Residents

The government took measures such as taking shelters or evacuation as follows based on the reports from Fukushima Daiichi & Daini.

Fri, 11 March
14:46 The Earthquake
19:03 Emergency Declaration by the Gov’t (Daiichi)
21:23 3 km radius evacuation (Daiichi)
10 km radius taking shelter (Daiichi)

Sat, 12 March
5:44 10 km radius evacuation (Daiichi)
7:45 3 km radius evacuation (Daini)
10 km radius taking shelter (Daini)
17:39 10 km radius evacuation (Daini)
18:25 20 km radius evacuation (Daiichi)

Tue, 15 March
11:00 20-30 km radius taking shelter (Daiichi)

Thu, 21 April
11:00 20 km radius is designated as “Restricted Area” (Daiichi)

Fri, 22 April
9:44 20-30 km radius taking shelter has been lifted (Daiichi)
Establishment of “Planned Evacuation Area” and “Emergency Preparation Area”

Source: NISA website
## TEPCO’s Roadmap on April 17

<table>
<thead>
<tr>
<th></th>
<th>Step 1 (About 3 months)</th>
<th>Step 2 (Minimum about 6 to 9 Months)</th>
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<tbody>
<tr>
<td><strong>Target</strong></td>
<td>Steady Reduction of Radiation Dose</td>
<td>Controlling Radiation Release and Significant Reduction of Radiation Dose</td>
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<tr>
<td><strong>Reactors</strong></td>
<td>Stable Cooling (Water Filling over the Fuel)</td>
<td>Achieving the State of Cold Shutdown</td>
</tr>
<tr>
<td><strong>Spent Fuel Pools</strong></td>
<td>Stable Cooling</td>
<td>Keeping the Sufficient Water Level for More Stable Cooling (Remote Operation)</td>
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<tr>
<td><strong>Radioactive Contaminated Water</strong></td>
<td>Prevention of Outflow to the out of the Site</td>
<td>Processing and Decreasing the Contaminated Water</td>
</tr>
<tr>
<td><strong>Radioactive Contaminated Atmosphere/Soil</strong></td>
<td>Prevention of Spread</td>
<td>Covering Up the Entire Reactor Building</td>
</tr>
</tbody>
</table>
## TEPCO’s Roadmap on April 17

<table>
<thead>
<tr>
<th>Current Status</th>
<th>STEP1 (3 month)</th>
<th>STEP2 (6~9 month)</th>
<th>Mid-term Issues</th>
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<tbody>
<tr>
<td><strong>I. Cooling</strong></td>
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<tr>
<td>Reactors</td>
<td>Injecting fresh water</td>
<td>Nitrogen gas injection</td>
<td>Stable cooling</td>
</tr>
<tr>
<td>Fuel Pools</td>
<td>Injecting fresh water</td>
<td>Extraction and implementation of heat exchange function, etc</td>
<td>Stable cooling</td>
</tr>
<tr>
<td><strong>II. Mitigation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accumulated Water</td>
<td>Storing water with radiation, etc</td>
<td>Restore coolant circulation system, etc</td>
<td>Secure storage</td>
</tr>
<tr>
<td>Atmosphere/Solid Waste</td>
<td>Installation of storage / processing facilities, etc</td>
<td>Installation of storage / processing facilities, etc</td>
<td></td>
</tr>
<tr>
<td><strong>III. Monitoring</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement/Reduction</td>
<td>Dispersion of inhibitor, Installing reactor building cover, etc</td>
<td>Expand/enhance monitoring, etc</td>
<td>Sufficiently reduce radiation dose in evacuation area</td>
</tr>
</tbody>
</table>

- **Prevention of breakage of structural materials, etc.**
- **Removal of fuels**
- **Installation of full-fledged water treatment facilities**
- **Solidification of contaminated soil, etc.**
The Government will request TEPCO to ensure the implementation of this roadmap steadily and as early as possible. To this end, the Nuclear and Industrial Safety Agency and others will make regular follow-up, monitoring of the progress of the works and necessary safety checks.

The Government will request TEPCO to ensure the mobilization and deployment of workers, the procurement and preparation of equipment and materials, and the arrangement of accommodation and other facilities, which are necessary to ensure implementation of the roadmap.

At the end of Step2, the release of radioactive materials will be under control. At this stage, the government will review the Evacuation Area and the Evacuation Prepared Area. Up until that time, we will consider the details of review criteria, and will decontaminate the widest possible area.

Source: Nuclear and Industrial Safety Agency
Major Countermeasures in the Power Station as of May 17

- **Main Countermeasures**
  - Reactor building cover (5, 50, 54, 55)
  - Begin detailed design of full-fledged container (56)
  - Lower the amount of steam generated (4)
  - Maintain and enhance countermeasures in Step 1 if needed (17)
  - Installation of heat exchangers (13)
  - Nitrogen gas injection (2, 11, 15)
  - Flooding up to top of active fuel (3, 9)
  - PCV venting (with filtration) (10)
  - Injection of fresh water with pumps (1)
  - Processing of sub-drainage water after being pumped up (36)
  - Prevent contamination of groundwater (66, 67); consideration of shielding groundwater (68)
  - Improvement of life/work environment of workers (74, 75); improvement of site environment (76)
  - Prevent contamination of groundwater (66, 67); consideration of shielding groundwater (68)
  - Installation of supporting structure under the bottom of spent fuel pool (26)
  - Install interconnecting lines of offsite power (8)
  - Seismic assessment (20), Continued monitoring (21), (Unit 4) Installation of supporting structure under the bottom of spent fuel pool (26)
  - Enhance/Enforce monitoring (55–62), Consideration of necessary measures to reduce radiation dose (63)
  - Preventive measures against leakage of high radiation-level water (29)
  - Prevent contamination in the ocean (64)
  - Isolation of high-level radioactive water (65)

- **Water Processing Facilities**
  - Processing of high radiation-level water (31, 34, 38, 41, 43, 44)
  - Processing of sub-drainage water after being pumped up (36)
  - Sealing the leakage location (6, 16)
  - Sampling of steam/pool water and measurement of radioactive materials (19)
  - Circulation cooling of spent fuel pool (23, 24, 25, 27)
  - Cooling at minimum water injection rate (7, 12, 14)
  - Reuse of processed water (45) (Establish circulation cooling system)
  - Cooling of spent fuel pool by external water injection (18, 22, 28)
  - Sampling of steam/pool water and measurement of radioactive materials (19)
  - Circulation cooling of spent fuel pool (23, 24, 25, 27)
  - Processing high radiation-level water (31, 34, 38, 41, 43, 44)

- **Additional Countermeasures**
  - Dispersion of inhibitor (47, 48, 52)
  - Removal of debris (49, 53)
  - Consideration of countermeasures for contaminated soil (51)
  - Preventive measures against leakage of high radiation-level water (29)
  - Prevention of ground water contamination (66, 67); consideration of shielding groundwater (68)
  - Improvement of life/work environment of workers (74, 75); improvement of site environment (76)
  - Install interconnecting lines of offsite power (8)
  - Enhance/Enforce monitoring (55–62), Consideration of necessary measures to reduce radiation dose (63)
  - Preventive measures against leakage of high radiation-level water (29)
  - Prevent contamination in the ocean (64)
  - Isolation of high-level radioactive water (65)

- **Additional Images**
  - **Storage/Process of Low Radiation-Level Water**
  - **Storage/Process of High Radiation-Level Water**
  - **Processing of Sub-Drainage Water**
  - **Processing of High Radiation-Level Water**
  - **Centralized Waste Processing Building**
  - **Additional Countermeasures**
  - **Seismic Assessment**
  - **Continued Monitoring**
  - **Installation of Supporting Structure Under the Bottom of Spent Fuel Pool**
  - **Various Countermeasures of Radiation Shielding**
  - **Enhancement/Enforcement of Monitoring**
  - **Installation of Interconnecting Lines of Offsite Power**

- **Diagram Notes**
  - Red: added to the previous version
  - Green: new countermeasures
  - Blue: improvements to existing countermeasures
Wall to shield water

Installing Supporting Structure for SFP in Unit 4

Install of Reactor Building Cover for Unit 1

Measure to shield groundwater

Source: TEPCO
The importance of Defense in Depth has been recognized with this accident

(1) Appropriate DBAs

Appropriate consideration for natural hazards by design
- Design basis tsunami height 5.7m against 15m of actual tsunami height

(2) Robustness and diversity in responding to beyond DBAs such as station black-out for long-duration, loss of ultimate heat sink

① Appropriate design philosophy to sustain safety function against common cause failures brought by natural hazards
- All the emergency DGs, except 1 air-cooled DG, were water-cooled and all were located in the basement of T/Bs
- All the sea-water pumps were located slightly above the design tsunami height and they were with no protection against water.

② Appropriate AM measures for both prevention and mitigation of SAs
- No AMs for SFP cooling and Hydrogen gas control in the R/Bs
- No AMs training under severe conditions for multi-units under continuous aftershocks
Conclusion: Preliminary Lessons Learned

(3) Difficult situations for post severe accident recovery
   - **Warning for aftershocks and subsequent Tsunami**
   - **High radiation in the working area**
   - **Massive radioactive debris within the site**

(4) Emergency Preparedness and responses
   - **Evacuation zones**
   - **Function of off-site center**
   - **Communication**
   - **Radiation monitoring**
Prof. T. Kitamori, Dean of School of Engineering, The University of Tokyo