Fukushima Nuclear Accident
~A TEPCO Nuclear Engineer’s Perspective~

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Kenji Tateiwa
Manager, Nuclear Power Programs
Tokyo Electric Power Company, Washington Office
tateiwa.kenji@tepco.co.jp
My Background

- ’90~’96: Kyoto University
  BS/MS in Nuclear Engineering

- ’96~: TEPCO
  ’96~’00: Fukushima Daini NPS
  ’00~’02: Nuclear Engineering Dept., Tokyo-H/Q (severe accident analysis)
  ’02~’04: MBA, Stanford Graduate School of Business
  ’04~’05: Nuclear Engineering Dept.
  ’05~’11: International Affairs Dept.
  Sept. ’11~: Washington DC Office

TEPCO class of ‘96 in Naraha-town, Fukushima (Jan. 2000)

Pursued “Nuclear Renaissance” in Texas (June 2010)
’90~’96: Kyoto University
BS/MS in Nuclear Engineering

’96~: TEPCO
’96~’00: Fukushima Daini NPS
’00~’02: Nuclear Engineering Dept., Tokyo-H/Q (severe accident analysis)
’02~’04: MBA, Stanford Graduate School of Business
’04~’05: Nuclear Engineering Dept.
’05~’11: International Affairs Dept.

Sept. ’11~: Washington DC Office

Great East Japan Earthquake (March 11, 2011)
My Post-Accident Activities

IAEA Preliminary Mission
(4/6/2011@Fukushima Daiichi NPS)
My Post-Accident Activities (cont’d)

Preparation for IAEA Fact-Finding Mission (5/21/2011@Fukushima Daiichi “Bedroom”)
“Nothing has been more important in my career than supporting TEPCO”

U.S. INPO-Led Industry Support Team (8/19/2011@Fukushima Daini)
Damage Due to Great East Japan Earthquake (GEJE)

- **Largest earthquake (M9.0) and tsunami (M9.1) in recorded history of Japan**
- 20+ m tsunami run-up in coast line spanning 200 km
- 560 km² flooded (10x Manhattan)
- 19,000 dead/missing
Operation *Tomodachi* ("Friends") by U.S. Armed Forces

U.S. Armed Forces’ disaster relief efforts were highly appreciated by the Japanese people
Comparison of Seismic Energy (Magnitude)

M9.0
Great East Japan Earthquake (2011)

M8.6
Keicho-Sanriku (1611)

M8.4
Jogan (869)

M8.3
Meiji Sanriku (1896)

M5.8
Hanshin Awaji (1995) 6,400 casualties

Virginia, USA (2011)

63,000x

Impact of GEJE to TEPCO Facilities

Shutdown:
- Nuclear power: 7 units
- Thermal power: 12 units
- Hydro power: 25 units
- Substations: 8

Power outage:
- 4 million households
- Rolling blackout for 10 days

Massive interruption of infrastructure:
- Public transportation
- Telecommunication
- Food/water supply

>99% of power restored by day 4
TEPCO’s Nuclear Power Stations (17 BWR Units)

Kashiwazaki-Kariwa (KK)
- U-5, 6, 7
- U-4, U-3, U-2, U-1

Fukushima Daiichi (1F)
- U-5, U-6
- U-4, U-3, U-2, U-1

Fukushima Daini (2F)
- U-1, U-2, U-3, U-4

(source) JAIF

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Tsunami Observed at 1F

- Tank (height: 5.5m)
- Ground Level (10m above sea)
- Tank Fully Submerged
- Car Stuck in the Building
Impact of Earthquake/Tsunami at 1F

- **After the Earthquake** (near design-basis):
  - Loss of all off-site power
  - Plant responded as designed (automatic shutdown of operating units/startup of EDGs)

- **After the Tsunami** (beyond design-basis):
  - Tsunami height (13.1 m): 4x historical-high and 2x design-basis
  - Station Black Out (SBO) for 5 out of 6 units
  - Loss of almost all safety system, instrumentation, lighting, etc.
Amplification of Multiple Tsunami Waves Due to Large-scale Earthquake

Postulated Tsunami Model

Sea Floor Displacements

Max. slip: 56.7 m

Water depth [m]

Peaks coinciding → Tsunami height: High

Peaks not coinciding → Tsunami height: Low

No expert/institution predicted large-scale tsunami source of this magnitude

Time T

Max. tsunami height [m]

Fukushima Daiichi

Fukushima Daini

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No Historical Evidence of Huge Tsunamis Near Fukushima NPSs

Commonly misquoted "Tsunami Warning Stone" and "Once-in-400-year recurrence of 7-m tsunami" both refer to locations in Iwate Prefecture, 300 km north of Fukushima NPS.

(source) http://blog.miyakomall.jp/2012/04/
Iwate has deep-indented coastline that tends to magnify tsunami height.

Fukushima has flat coastline and historically experienced significantly lower tsunami height compared to Iwate.

However, we should have been prepared for the unexpected.
Reactor automatically shutdown after earthquake

Loss of all AC/DC power + core cooling capability due to tsunami

Core melt and Zr-water reaction led to H2 explosion in R/B

Stabilization by sea water injection via fire trucks
Turbine-driven RCIC continued to cool core for about 3 days
Plant Status After Tsunami (1F Unit 3 : BWR-4/Mk-I)

Turbine-driven RCIC and HPCI continued to cool the core for about 1.5 days.
Accident Response at 1F: In the Field

- Roads blocked by tsunami debris
- Roads damaged by earthquake
- Continual aftershocks, tsunami alerts, open manholes, etc. exacerbated the situation
Accident Response at 1F: In the Main Control Room

Checked instrumentation in near-complete darkness

Supervised operation wearing full-face mask

Brought in heavy batteries to restore instrumentations

- Lack of: instrumentation, communication means, lighting, food, water, sleep, ...
- Increase in: radiation level, fatigue, fear, despair, ...

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Six men formed 3 “last-resort teams” to manually open 2 valves in highly-radioactive area

Core damage already progressing by this time (3/12 9:04-9:30)

Remote operation unavailable due to SBO.
Accident Response at 1F: Water Injection by Fire Trucks

- Fire trucks played critical role in injecting water into reactors
- Fire brigade operated fire trucks amidst high radiation/successive explosions

Status as of 3/14/2011

Fire Trucks

Fire Cistern

Valve Pit

R/B

T/B

Sea

Shallow Draft Quay

standby
Accident Response at 1F: Protecting Units 5&6

- Ultimate heat sink restored: 3/19
- Cold shutdown achieved: 3/20
- Determination to save Units-5/6
Impact of Earthquake/Tsunami at 2F

- **After the Earthquake** (smaller than design-basis):
  - Loss of all but one line of off-site power
  - Plant responded as designed

- **After the Tsunami** (beyond design-basis):
  - Loss of Ultimate Heat Sink for 3 out of 4 units
Accident Response at 2F: Recovery from Tsunami

- Restored ultimate heat sink by:
  - Laying 9 km of heavy power cables by hand
  - Rapidly procuring and replacing motors
- Executed “FLEX On-The-Fly”
## Overview of the 10-Unit Simultaneous Accidents

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<tr>
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<tr>
<td>3/11</td>
<td>3/11 15:27 1st Tsunami, 15:35 2nd Tsunami</td>
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<tr>
<td>3/12</td>
<td>3/12 15:36 Unit 1 Explosion</td>
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<tr>
<td>3/13</td>
<td>3/14 11:01 Unit 3 Explosion</td>
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<td>3/14</td>
<td>3/15 6:00-6:10 Unit 4 Explosion</td>
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<tr>
<td>3/15-19</td>
<td>3/20 15:46 P/C-2C</td>
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<td>3/20</td>
<td>3/22 10:36 P/C-4D</td>
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### 2F

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### Key Events

- **Station Blackout**
- **Loss of Ultimate Heat Sink**
- **Cold Shutdown**

### Actions

- **Water Injection:** NO
- **Heat Removal:** NO
- **Water Injection:** YES
- **Heat Removal:** YES

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Hundreds of Aftershocks Greater than M 5.0

On March 11th alone
179 times > M 5.0
38 times > M 6.0
3 times > M 7.0

cf. Earthquake in Virginia on Aug. 23, 2011: M 5.8

Visualization of earthquakes in 2011
http://www.youtube.com/watch?v=eKp5cA2sM28
“In an attempt to check the status of Unit 4 D/G, I was trapped inside the security gate compartment. Soon the tsunami came and I was minutes away from being drowned, when my colleague smash opened the window and saved my life.”

“In total darkness, I could hear the unearthly sound of SRV dumping steam into the torus. I stepped on the torus to open the S/C spray valve, and my rubber boot melted.”

“Unit 3 could explode anytime soon, but it was my turn to go to the main control room. I called my dad and asked him to take good care of my wife and kids should I die.”
“At that time, I was conjuring up faces of fellow colleagues who would die with me.”
(Masao Yoshida, Site Superintendent)

“I was determined to stay behind to my death; however I was resolved to send my men back home alive.”
(Ikou Izawa, Shift Manager)

“The Man Who Saw The Brink of Death”
“Book reveals human drama in Fukushima No. 1 crisis”
The Japan Times 12/11/2012

“At that time, I was conjuring up faces of fellow colleagues who would die with me.”
(Masao Yoshida, Site Superintendent)

“I was determined to stay behind to my death; however I was resolved to send my men back home alive.”
(Ikou Izawa, Shift Manager)

“Let me go and vent the containment. I know where the valve is and I can run fast. Let me protect the unit that I love.”
(Kazuhiro Yoshida, Deputy Shift Manager)
“Tangible” Countermeasures

- Flood Protection
- High-pressure Injection System
- Depressurization System
- Low-pressure Injection System
- Heat Removal/Cooling System
- Power Supply for Instrumentation
- Post-Core Damage Mitigation
- Common Items
- Mid-to-Long Term Items

“Intangible” Countermeasures

- Operational Measures in Relation to Tangible Modifications
- Emergency Preparedness
- Info. Dissemination and Sharing
- Roles and Responsibilities
- Information Disclosure
- Transportation of Resources
- Access Control
- Radiological Protection
- Plant Status Recognition
- Suggestions to the Government

Major Lessons Learned:

- Recognize large uncertainty in external events
- Prepare for the unexpected
Follow-up Study on 1F Accident Unresolved Issues

- 1st Progress Report Issued on Dec. 13, 2013
- 10 out of 52 Issues Resolved

Rapid depressurization of Unit 3 RPV caused by inadvertent ADS actuation; not by RPV breach
Tsunami-induced Accident Prevention Measures

- Sea wall (1.5 km long)
- Tidal walls
- Water-tight doors (~60 places)
- Tidal boards
- Start up Transformer
- Emergency D/G, Power supply panel
- Cable tray
- Piping
- Waterproof treatment (~300 places)

15 m above sea
Safety Enhancement Measures at KK NPS (cont’d)

Core Damage Prevention Measures

High Pressure Alternate Cooling System

Gas Turbine Generators: 2

D/G trucks: 23

Fresh Water Reservoir: 20k ton

Emergency power supply

DC power

Alternative heat exchangers: 7

Fire engines: 8

gas cylinders

Emergency power supply
Post Core Damage Mitigation Measures

- Passive auto-catalytic recombiner
- Reactor well
- Top head flange cooling
- Fire engine
- R/B top vent
- Hydrogen detector
- Filtered vent
Current Status of Fukushima Daiichi (1F) NPS

Live Camera View (as of 1/12/2014)

Progress Made at 1F Unit 1

Reactor building cover to be dismantled to enable rubble removal work to be conducted on refueling floor
Progress Made at 1F Unit 2

Steam Coming Out From Blow-out Panel (4/10/2011)

Gamma Camera Image of Refueling Floor (2/21/2013)

Inside Containment (8/12/2013)

Blow-out Panel Closed (3/11/2013)

Attempt to investigate inside reactor pressure vessel by bore scope via TIP guide tube

TIP: Traversing In-core Probe
Progress Made at 1F Unit 3

Crippled Reactor Building (3/15/2011)

Large Rubble Removed (10/11/2013)

Torus Room (7/11/2012)

Spent Fuel Pool (Feb. 2013)

Preparation work underway to install fuel removal structure
Progress Made at 1F Unit 4

Water Injection by Concrete Pumper (3/22/2011)

Fuel Removal Structure (Nov. 2013)

Concrete wall

Steel Pillars

SFP Structure Reinforced (7/30/2011)

Fuel Removal from SFP (11/18/2013)

264/1,533 fuel bundles transferred to common pool

Circulating-Water Core Cooling System at 1F

- Groundwater Inflow: +400 m³/day
- Contaminated Water
- 3 km-long Closed Loop
- Chloride Removal (RO)
- Treated Water Tanks
- Cesium Removal (Kurion/SARRY)
- Core Injection: 360 m³/day
- Partially-treated Water Tanks (330,000 m³)
  (cf. Olympic-size pool: 2,500 m³)
- Multi-nuclides Removal (ALPS)

- All reactor cores stably cooled
- Increasing water inventory posing challenge
Contaminated Water Issues at 1F

Contamination detected in groundwater near sea bank; Suspected leakage of contamination into sea; Immediate and fundamental measures taken to:

- Prevent groundwater from being contaminated
- Prevent contaminated groundwater from flowing into sea
- Reduce groundwater inflow into buildings
Decommissioning Roadmap for 1F

**Cold Shutdown Condition Achieved (Dec., 2011)**

- **Phase-1**
  - Begin removal of fuels from spent fuel pools

- **Phase-2**
  - Begin retrieval of fuel debris
  - **Unit 4: Nov. 2013**

- **Phase-3**
  - Complete decommissioning

**Within 2 years**

- Endeavor to push schedule forward

**Within 10 years**

**30 to 40 years**

**Global collaboration vitally important to tackle this unprecedented undertaking**
Feasibility Study Agreement with U.S. Nat’l Labs to identify their expertise applicable to decommissioning at 1F (Sept. 2012-March 2013)

Pursuing further collaboration in following areas:

- Groundwater contamination
- Reactor bldg. waterproofing
- Radioactive waste disposal
- Fuel debris recovery/storage
- Contaminated water treatment
Global Collaboration: through IRID

Council for Decommissioning 1F (chaired by METI minister)

Utility Companies Reactor Vendors

Integrated Management of Decommissioning Technologies

Advices from Domestic and Int’l Organizations

Joint Studies/R&D with Research Organizations

International Research Institute for Nuclear Decommissioning (IRID) established in Aug. 2013

Soliciting information for technologies in:
Contaminated water issues; Fuel debris retrieval
Other Activities

- Compensation for afflicted people:
  ¥3.3 trillion (approx. $32 bil.)
  (paid out as of Jan. 2014)

- Cooperation with gov’t in off-site radiation survey,
  decontamination work, etc.

- Assistance in temporary return of evacuees to homes, cleaning homes, etc.
TEPCO’s Post-Accident Activities in the U.S.

Nuclear Industry
- INPO
- EPRI
- Electric Power Research Institute
- PWRG
- Nuclear Industry Owners’ Group
- Exelon
- FirstEnergy
- Bechtel
- Hitachi
- Westinghouse
- A
- AREVA
- MPR
- GE
- Pillsbury
- Global Organizations

Gov’t Agencies
- U.S. NRC
- U.S. Department of Energy
- SRNL
- Congressional Research Service
- Pacific Northwest National Laboratory
- Lawrence Livermore National Laboratory

Academia
- MIT
- Harvard University
- NYU Stern
- Johns Hopkins University

Professional Organizations, Think Tanks, NPOs, Media
- IAEA.org
- International Atomic Energy Agency
- WANO
- IEEE
- ASME
- CSIS
- Brookings
- CARNEGIE ENDOWMENT

Committed to disseminating lessons learned globally and working together to make nuclear power plants safer

→ Weekly update teleconference on Fukushima status
References

[Japan]
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➢ Nuclear Reform Monitoring Committee of TEPCO
   http://www.nrmc.jp/en/index-e.html
➢ Ministry of Economy, Trade and Industry (METI)
   http://www.meti.go.jp/english/earthquake/
➢ Nuclear Regulation Authority (NRA)
   http://www.nsr.go.jp/english/
➢ Japan Atomic Industrial Forum (JAIF)
   http://www.jaif.or.jp/english/
➢ Japan Nuclear Safety Institute (JANSI)

[USA]
➢ Institute of Nuclear Power Operations (INPO)
➢ Electric Power Research Institute (EPRI)
   http://www.epri.com/Our-Work/Pages/Nuclear.aspx
➢ Nuclear Energy Institute (NEI)
   http://safetyfirst.nei.org/japan/
➢ National Academy of Science—Fukushima Lessons Learned Committee

[International]
➢ International Atomic Energy Agency (IAEA)
   http://www.iaea.org/
➢ World Association of Nuclear Operators (WANO)
   http://www.wano.info/
➢ World Health Organization (WHO)