Fukushima
Lessons to be learned
Fukushima – Lessons to be learned

11.03.2011

Tōhoku Earthquake  
14.46 JST  
Magnitude 9 (MW)

Tsunami  
14 m Height

Station 1,2,3,4  
Black-out

Disabled Reactor Cooling  
Nuclear Radiation Leaks  
30 km Evacuation Zone
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Pacific Plate

Main Shock 9 $M_W$

9 cm/a

Fore- and Aftershocks
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- All operating units were automatically shut down
- Emergency D/Gs have worked properly until Tsunami attack

Earthquake: Loss of Offsite Power

Tsunami more than 10 m height (estimated)

Tsunami: 14 m
Design: 5,7 m
Protection: 6,5 m

Station Black Out

All motor-operated Pumps became inoperable
“Three of the reactors at Fukushima I overheated, causing meltdown that eventually led to explosions, which released large amounts of radioactive material into the air”
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The events have been rated at Level 7 on the International Nuclear Event Scale INES

(major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures)
We feel deep sympathy with the Japanese People

We
the international nuclear community,
the engineers, authorities, owners, and media
are concerned and take the responsibility

We
have to learn the lessons from Fukushima
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- Reactor Service Floor (Steel Construction)
- Concrete Reactor Building (secondary Containment)
- Reactor Core
- Reactor Pressure Vessel
- Containment (Dry well)
- Containment (Wet Well) / Condensation Chamber

Energies 2011, 4, 818-825
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Course of Events

Heat generation: (due to decay of fission products)
After SCRAM ~6%       After 1 Day ~1%

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
Course of Events

Fukushima I Unit 1

(1) Isolation Condenser
- Steam enters heat exchanger
- Condensate drains back to reactor pressure vessel
- Secondary steam released from plant

Need pumps for water supply

Fukushima I Unit 2 and 3

(2) Reactor Core Isolation Pump
- Steam from reactor drives turbine
- Turbine drives a pump, pumping water from the wet-well in the reactor
- Steam gets condensed in wet-well

Necessary:
- Battery power
- Wet-well temperature < 100°C

No heat sink from the buildings
Course of Events

Loss of Coolant Accident LOCA

- **11.3. 16:36 in Unit 1**
  - Isolation condenser stops

- **13.3. 5:30 in Unit 3**
  - Reactor Isolation pump stops

- **14.3. 13:25 in Unit 2**
  - Reactor Isolation pump stops

- Reactors of Units 1-3 are cut off from any kind of heat removal
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Course of Events

- ~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
  - Ballooning / Breaking of the cladding
  - Release of fission products from the fuel rod gaps
Course of Events

~3/4 of the core exposed

- Cladding exceeds ~1200°C
- Zirconium water reaction starts under steam atmosphere
  \[ \text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2 \]
- Exothermal reaction heats the core additionally
- Generation of hydrogen
  - Unit 1: 300-600kg
  - Unit 2/3: 300-1000kg
- Hydrogen gets pushed via the wet-well, the wet-well vacuum breakers into the dry-well
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Course of Events

- at ~1800°C [Unit 1,2,3]
  - Melting of the cladding
  - Melting of the steel structure

- at ~2500°C [Unit 1,2]
  - Breaking of the fuel rods
  - debris bed inside the core

- at ~2700°C [Unit 1]
  - Melting of Uranium-Zirconium eutectics

- Supply of seawater to the reactor pressure vessel stops the core melt 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)
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Venting

Containment (MARK I)
- Last barrier between fission products and environment
- Wall thickness ~30 mm
- Design pressure 4-5 bar

Pressure reached up to 8 bars
- Normal inert gas filling (Nitrogen)
- Hydrogen from core oxidation
- Boiling in the condensation chamber
- Possible leakages at containment head seal

Depressurization of the containment
- Unit 1: 12.3. 4:00
- Unit 2: 13.3 00:00
- Unit 3: 13.3. 8:41
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Course of Events

▸ Unit 1 and 3

Hydrogen explosion inside the reactor service floor
  ◆ Destruction of the steel-frame construction
  ◆ Reinforced concrete reactor building seems undamaged
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Mark of Respect

We pay full respect for the accident management to
the technicians, engineers, and management, for their
reasonable, professional, and eventually successful commitment
under the concurrence of extremely severe circumstances
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Accident Mangement

- Sea water stopped accident progression
  - No further core degradation
  - RPV temperatures decline
  - No further releases from fuel

- Further cooling of the reactors via
  - Unit 1: Isolation Condenser
  - Unit 2 & 3: Containment Venting
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**Accident Management**

- **Short-term recovery steps**
  - Trap fission products on ground with dust binders (Epoxy)
  - Install closed cooling cycles
  - Decrease the water inventory in the Reactor buildings
  - Build storm-prove shelters around the reactors (especially a roof)

- **Long-term recovery steps**
  - Build a water cleansing facility to decontaminate the stored water
  - Remove Salt from Reactors
  - Empty the spend fuel pools
  - Wait 10 Years that radioactivity declines [see TMI2]
  - Remove Core inventory
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Accident Management

Happy Moments:
Recovery of Main Control Room Light
Unit 3: March 22    Unit 2: March 26
Unit 1: March 24    Unit 4: March 29
# Fukushima – Lessons to be learned

## Accidental Damage

<table>
<thead>
<tr>
<th>Earthquake &amp; TSUNAMI</th>
<th>FUKUSHIMA</th>
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<tbody>
<tr>
<td>a natural disaster of historic magnitude</td>
<td>a man-made disaster of cat. 7 on INES</td>
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- **Death Count:** 25,000 People
- **Economic Loss:** $ 250 billion

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<tr>
<th>Radiation Fatality: No</th>
<th>Decommissioning: $ 2.53 billion (TEPCO Allocation)</th>
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<tr>
<td>Exposure &gt; 250 mSv: 6</td>
<td>Release ~ 10% Chernobyl</td>
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Lessons learned

- Design Rules
- Aging Systems
- Knowledge

- Codes and Regulations
- Licensing
- Controlling

Key Focus: Nuclear Safety

Engineers

- Public Media
- Risk Acceptance
- Framing & Agenda Setting

Authorities

- Responsibility
- Business & Safety Culture

Society

Owner

Q NET Consulting - Prof. M. Kröning
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Engineering Lessons

NUCLEAR SAFETY ENGINEERING

DEFENSE IN DEPTH with PROBABILITY RISK ANALYSIS

INHERENT SAFETY DESIGN with HIGHEST BASIC REQUIREMENTS

Broad Claim on System Safety Engineering Resilient Structures that Mitigate & Recover from Catastrophic Failures
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Engineering Lessons

NUCLEAR SAFETY SYSTEMS (as defined by the NRC)

- Shut down and maintain in shut down condition
- Prevent the release of radioactive material

Defense in Depth

Safety

Systems

Layers

Redundant

Multiple

Critical Single Failure

Independent
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Engineering Lessons

PROBABILISTIC RISK EVALUATION for COMPLEX SYSTEMS
(SYSTEM SAFETY ANALYSIS)

MAGNITUDE (SEVERITY) of CONSEQUENCES

X

LIKELIHOOD (PROBABILITY) of OCCURRENCE
INHERENT SAFETY DESIGN of CONTROL SYSTEMS + PASSIVE SAFETY DESIGN of SAFETY SYSTEMS

“An ‘inherently safer’ approach tries to:

- Avoid or eliminate hazards
- Reduce their magnitude and severity and likelihood of occurrence by careful attention to the fundamental design and layout”
Engineering Lessons

WEAKNESS:

Probabilistic Risk Assessment does not account for UNEXPECTED FAILURE MODES

Difficult Modeling of “COMMON-CAUSE” FAILURES

SYSTEM SAFETY RESEARCH (MIT):

“Any complex system, no matter how well it is designed and engineered, cannot be deemed failure-proof”
Engineering Lessons

CATASTROPHIC NUCLEAR ACCIDENTS ARE INEVITABLE

Safety Indicator: Frequency $f$ of Core Melt Accidents

NRC (Mandated): $f < 1$ in 10,000 years
Modern design: $f < 1$ in 100,000 years

“First and most elementally, nuclear accidents happen…we can never have confidence that we will succeed absolutely.”
(John Ritch, Director General, WNA)

NON-COMPLIANCE WITH SYSTEM SAFETY DESIGN PRINCIPLES

After lessons we know better:

06-11: IAEA Ministerial Conference

- External Hazards
- Accident Management
- Emergency Preparedness

Report of Japanese Government

IAEA Ministerial Conference on Nuclear Safety, Vienna, 21 June 2011
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Engineering Lessons

NO OVERCONFIDENCE - SEVERE ACCIDENTS MAY HAPPEN

GLOBAL COOPERATION IN SAFETY ENGINEERING

APPROPRIATE EVALUATION AND PROTECTION AGAINST EXTERNAL HAZARDS

CONTROLLED SYSTEM SAFETY DESIGN RULES (INSAG) - DEFENCE IN DEPTH & INHERENT/PASSIVE SAFETY - ACCORDING TO THE LATEST STATE-OF-THE-ART
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SAFETY CULTURE

DEFENSE IN DEPTH
with
PROBABILISTIC RISK ANALYSIS

INHERENT SAFETY DESIGN
with
HIGHEST BASIC REQUIREMENTS

Report of Japanese Government to the IAEA Ministerial Conference

External Hazard / Common Mode Failure
Flooding
Black-Out
Loss of Heat Sink
H₂ in the Service Floor
Loss of Spent Fuel Pool Cooling

NPS and Component Design
TSUNAMI Height: 14 – 15 m
Seawater Pump
Switchboard
Diesel Generators
Battery Life
MARK I Containment
Safety Culture

Report of Japanese Government to the IAEA Ministerial Conference
Japan will Establish a Safety Culture …
Pursuing Defense-in-Depth by Constantly Learning Professional Knowledge on Safety

THOROUGHLY INSTIL A SAFETY CULTURE

A Safety Culture that Governs the Attitude and Behavior in Relation to Safety of all Organizations and Individuals Concerned must be Integrated in the Management System
(IAEA: Fundamental Safety Principles, SGF-1, 3.13)
INTERNATIONAL CONVENTION ON NUCLEAR SAFETY:

NATIONAL OPERATIONAL TRANSPARENCY
- INDEPENDENT, EFFECTIVE NUCLEAR REGULATION
RE-VISITATION of THREATS of EXTERNAL HAZARDS
BINDING INTERNATIONAL SAFETY STANDARDS

Yukiya Amano, IAEA (June 21):
- Safety Checks on a regular basis by IAEA Inspectors -
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Public Opinion

Respect for the negative Stance on Nuclear Power

We all feel the task of mastering the future

Maintaining Consensus
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Public Opinion

We were right after all

REFRAMING OF AGENDA SETTING
MEDIA
POLITICS

HAZARD

BENEFITS

57 \downarrow 49
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Public Opinion

DEVIL’S BARGAIN
THE BEST LESSON
LET US WORK TOGETHER FOR ONE WORLD

ANYBODY OF MORE THAN 9 BILLION PEOPLE WILL GET A FAIR CHANCE FOR A SAFE AND GOOD LIFE, EVERYWHERE IN THE WORLD.
THANK YOU VERY MUCH FOR YOUR ATTENTION ENJOY THE CONFERENCE AND THE CHARM OF VALENCIA
Fukushima – Lessons to be learned

The Best Lesson: Let Us Work Together for One World

ANYBODY OF MORE THAN 9 BILLION PEOPLE WILL GET A FAIR CHANCE FOR A SAFE AND GOOD LIFE, EVERYWHERE IN THE WORLD