SFR Safety Consideration in Light of Fukushima Dai-ichi Accident

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Safety Functions and Accident

• Essential safety functions
  – Reactivity and power control
  – Heat removal and transfer to ultimate heat sinks
  – Containment of hazardous materials and no release of them to off-site

• Possible Accident scenarios
  – Unprotected (without scram)
    • Anticipated transient without scram (ATWS)
  – Protected (with scram) scenarios
    • Loss of heat sink (LOHS)
    • Loss of reactor level (LORL)
Lessons-Learned
Technical and Engineering Viewpoints

• Two reports identified the lessons-learned from the Fukushima Dai-ichi accident
  – The Japanese government report to the IAEA in June 2011
  – The Japanese regulatory body (NISA) report, March 2012
• We must understand the lessons thoroughly and reflect them on enhancement of SFR safety
• The lessons-learned in Dai-ichi NPS event are to be investigated through the perspective of the specific features of SFR to extract SFR safety considerations
# Threat of Earthquake and Tsunami

<table>
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<tr>
<th></th>
<th>Fukushima #1 Unit 1-4</th>
<th>Fukushima #1 Unit 5-6</th>
<th>Fukushima #2</th>
<th>Onagawa (EQ)</th>
<th>Tokai #2</th>
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<td>Plant status at EQ occurrence</td>
<td>Full power Full power Full power Shutdown</td>
<td>Shutdown Shutdown</td>
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<td>Full power Start-up Full power</td>
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<td>Emergency DG</td>
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<td>Heat Sink</td>
<td>LOHS by Tsunami</td>
<td>LOHS by Tsunami</td>
<td>LOHS by Tsunami Unit 3 OK</td>
<td>LOHS by Tsunami Unit 2 OK</td>
<td>Partial LOHS by Tsunami</td>
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</tbody>
</table>
Summary of Fukushima Dai-ichi Accident

• Combined LORL and LOHS type initiated from SBO
• High pressure water-steam cooling system
  – Depressurization
  – Ultimate heat sink
  – Continuous water injection
• Finally severe accident management worked
  – RPV failure resulted in depressurization
  – Heat sink to atmosphere
  – Mobile power supply
  – Seawater injection with fire engines
• Containment performance and accessibility
  – Containment - High temperature and pressure for long period (organic seal material)
  – Explosives - Hydrogen explosion deteriorated accessibility
SFR Characteristics

- Low pressure system
- High temperature system
- Large boiling margin of sodium
- Small freezing margin of sodium
- Single phase system
- Large temperature difference of sodium and heat sink
- Positive void reactivity and passive reactivity feedback
- Chemical reactions of sodium-water-air
SFR Considerations: Fukushima Dai-ichi Accident

- Combined LORL and LOHS type initiated from SBO
- High pressure water-steam cooling system
  - Depressurization - Not needed
  - Ultimate heat sink - Robust (NC to atmosphere)
  - Continuous injection - Not needed (large sensible heat capacity)
- Severe accident management
  - RPV failure resulted in depressurization - Elevated temperature
  - Heat sink to atmosphere - Freeing risk, sodium fire risk
  - Mobile power supply - External resource may not be needed
  - Seawater injection with fire engines - Sodium injection not needed
- Containment performance and accessibility
  - Containment - Large containment volume and low pressure system
  - Explosives - Sodium fire and hydrogen explosion
More Lessons and Key Issues

• Passive reactivity and power control
  – Engineered features (SASS, FAIDUS, Sodium plenum)
  – Core deformation, Doppler, etc.

• Passive decay heat removal
  – Grace time for recovery actions is long (10 hours or more)
  – Controllability (Temperature and NC driving force)
  – Manageability (sodium leakage and fire)

• Maintenance of sodium inventory
  – Vessel failure risk
  – Multiple boundary failure risk
  – Direct vessel cooling

• Cliff edge of SFR
Practical Accident Management

- Accessibility (sodium fire, HVACS unavailable, etc)
- Visibility of plant situations and I&C reliability
- Possibilities of I&C malfunction
- Mission time of DC power for plant control
- Physical separation of safety systems and AM equipment
- Adverse interaction and influence on safety
- Necessary alternative (backup) safety function
  - mobile equipment
  - emergency procedures
28 Lessons in 5 Categories

• Defence in Depth
  – Severe accident prevention (Category 1)
  – Severe accident mitigation (Category 2)
  – Emergency preparedness and responses (Category 3)

• Accident management was not successful enough. Confusions in off-site emergency responses for resident evacuation and food and water control.

• General Issues
  – Safety infrastructure (Category 4)
  – Safety culture (Category 5)
PRA and Safety Margin Study

The 2nd Defence SA mitigation

- Known unknown
  - Urgent Provisions

- Known known
  - Design Basis

The 1st Defence SA Prevention

The 3rd Defence

Emergency response

- PRA
- Residual Risk
- Stress test

Recognition level

Knowledge level
Procedure for External Hazard and Risk Assessment

- Comprehensive survey of external hazard
- Risk potential of external hazard
- Risk-significance of external event
- Available quantitative evaluation methodology
- Protection and management against external hazard

1. Identify external hazard
   - Natural event / Man-made event
   - Single event / Multiple event

2. Categorize external hazard
   - Frequency
   - Distance
   - Grace period
   - Influence

3. Select risk assessment approach
   - Screening
   - Bounding analysis
   - Margin analysis
   - DSA
   - PRA
Identification of Possible Natural Hazard

- **Japanese Diet Report**
  - Natural disaster for 416-1995
  - Secondary disaster included

- **ASME/ANS standard**
  - Natural event
  - Man-made event

- **IAEA NS-R-3**
  - Natural event
  - Man-made event
<table>
<thead>
<tr>
<th>External hazard</th>
<th>Phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake and tsunami disaster</td>
<td>Earthquake / Subsidence / Ground uplift / Ground crack / Soil discharge / Liquefaction / Landslide / Debris flow / Mountain slide / Cliff failure / Flooding / Tsunami / Fire</td>
</tr>
<tr>
<td>Volcano disaster</td>
<td>Volcanic bomb / Volcanic lapillus / Pyroclastic flow / Lava flow / Debris flow / pyroclastic surge / Blast wave / Ash fall / Flooding / Tsunami / Forest fire / Volcanic gas stagnation / Cold weather by volcanic gas / Boiling water / Earthquake / Mountain collapse</td>
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<tr>
<td>Meteorological calamity</td>
<td>Storm(wind / fire / avalanche / sandblasting) / Wind wave/Tidal wave / Abnormal elevation of sea level / Intense rainfall (immersion / flooding / Debris flow / flash flood / mountain slide / landslide / cliff failure / High tide water / Seiche / Wind wave / Fog and mist / Heavy snow (dead weight / avalanche) / Snowstorm / Heavy snow (flooding) / Snowmelt (mountain slide / landslide) / Lighting strike (current / fire) / Hail / Frost / Tornado / River blockage by ocean water / Water level declination in lake and river / Drought / High temperature / Low temperature (freeze) / Abnormal change in ocean current</td>
</tr>
<tr>
<td>Others</td>
<td>Forest fire / Coastal erosion / Biological event / Meteor / High tide / Toxic gas / River channel change</td>
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<tr>
<td>Man-made event</td>
<td>Airplane crash / Artificial satellite / Transport accident / Ship impingement / Turbine missile / Industrial or military facility accident / Pipeline accident / Abnormal gas eruption cased by boring / Oil spill / Chemical substance release from onsite storage facilities / Flooding and wave by failure of flood control structure</td>
</tr>
</tbody>
</table>

Underlined hazards typed in red are from ASME/ANS Standard, IAEA NS-R-3
PRA and safety margins study

• To prepare for two types of unexpected events
  – Exceedance of design requirement level
  – Occurrence of out-of-consideration or unlikely events

• To identify the cliff edge if any and pragmatic accident management procedures to prepare for the unknowns
  – Safety margin study
  – Probabilistic Risk Assessment

• PRAs and margin studies for SFRs are limited
  – Plant-specific assessment is necessary
Sharing Knowledge and Resources

- SFR operational experience and number of specialists are not abundant at present
- Severe accident management and emergency response
  - knowledge, expert judgment, accident delineation capabilities, and external support are indispensable
- The safety design guideline should be based on common safety criteria
- External support is effective in extreme conditions to mitigate the severe accident consequence
- Most practical and effective way is well-organized international collaboration
Conclusions

• Passive safety features ensure reliability and robustness of SFR safety
• Resilience in SA mitigation is to be realistically investigated
  – Loss of sodium inventory, Containment vessel
  – Accessibility, visibility and I&C performance
• Cliff edge scenario is to be identified and studied
  – PRA and stress test
• International sharing of knowledge and resources
Thank you for your attention -
Maintenance of Reactor Level and Ex-Vessel Phenomena

• Only if the reactor core is submerged under sodium, severe core damage is prevented
  – Maintenance of sodium inventory is required because the difficulty in pouring sodium in the primary system.

• Loss of coolant situation may be caused by multiple failure of primary coolant boundaries although a multiple primary structure failure is very rare

• Scenario is to be studied and possible SAM procedures such as ex-vessel long term cooling

• prevent the containment failure and significant radioactive material release.
SFR Consideration

• Early Sequence Management
  – Emergency Coolant Injection
  – Anticipated Transient Without Scram

• Flexibility in Late Sequence Management
  – Mobile Equipment
  – Knowledge-Base
  – External Assistance

• Resilience against uncontrollable scenarios
Summary of Fukushima Dai-ichi Accident

• Low pressure sodium system
  – Depressurization is not needed
  – Natural circulation and large boiling margins ensure decay heat removal to ultimate heat sink
  – Continuous coolant injection is not needed (latent heat)

• Severe accident management
  – High temperature structure may result in sodium leakage
  – External resource may not be needed for long term cooling

• Containment performance and accessibility
  – Containment volume is large
  – Explosives - Hydrogen explosion deteriorated accessibility
Effective Accident Management

• Prompt operations are not necessary and the power supply is less important
• Accessibility to the safety systems and visibility of plant situations are inferior to LWR
• Reliability and mission time of DC power and I&C systems should be investigated.
• Possibilities and limitation of the I&C system malfunction are to be investigated to ensure the AM operations.
• As to the AM operations, physical separation of safety systems and AM equipment is very important to prevent common cause/mode failures. Possibility of adverse interactions of facilities should be identified and avoided.
• According to the characteristics of the SFR, alternative safety function, mobile equipment and emergency procedures are to be prepared for, which may be different from those for LWRs.
Containment function

- Low pressure system
- Latent heat – No
- Current design generally has large volume
- Pressure and temperature control
  - Sodium fire
  - Hydrogen burning and explosion
- In severe accidents, a certain mechanical energy release can cause the sodium ejection in air atmosphere on the operational floor. The ejection of the sodium is a threat on the containment integrity. The trade-off of the containment cooling capability and the thermal-hydraulic respond and load on the containment should be considered to define the containment requirement.
On March 11, 2011 two massive tsunamis struck the Dai-ichi NPS, the first at 15:27 (41 minutes after the earthquake struck) and the second at 15:35. The design basis tsunami water level is 3.1 m. According to an assessment (2002) based on “Tsunami Assessment Methods for Nuclear Power Plants” by the Japan Society of Civil Engineers, the revised tsunami water level was 5.7 m. However, the tsunami height on March 11 reached 14 to 15.5 m high.
The Tsunami Caused Station Blackout (SBO) and Loss of Ultimate Heat Sink

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  – Black Swan and White Raven....White Snake
• PRA Standard Development
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• Conclusions
SFR Consideration

- Depressurization
  - Not needed
- Ultimate heat sink
  - Natural circulation deliver decay heat to atmosphere
  - Large boiling margins ensure natural circulation (heat source is localized)
- Continuous coolant injection
  - Closed loop (large sensible heat capacity)
- Long term cooling
  - External resource (coolant, power supply, fuel, etc) may not be needed
  - High temperature structure may result in sodium leakage
  - High freezing temperature
- Containment performance and accessibility
  - Containment volume is large
  - Small possibilities of elevated temperature and pressure
  - Explosives and chemical reaction
Automatic reactor shutdown due to the earthquake, loss of off-site power supply

- Dependency on emergency power was inevitable.
- Emergency diesel generators started up and power supply was secured.
- Reactors were cooled by core cooling system.

Start-up / Shutdown operations for IC-RCIC were going on.

Most of electric systems including emergency diesel generators and switchboards were unavailable due to the tsunami.

Cooling sea water pumps installed along the coast were also unavailable. (Loss of ultimate heat sink)

Station Blackout

(On March 13, Unit 5 received power supply from Unit 6 on emergency basis.)

Soaking / depletion of battery, depletion of compressed air, etc.

- Many on-site works were necessary due to difficulty of measurement / control / communication.

Shutdown of the core cooling system

Unit 1 has lost its function at an early phase. Due to this reason, there was only a short period of time to address the situation.

Fuels were exposed and melted while cooling was not conducted.

Serious degradation of containment led to the release of radioactive materials into the environment.

Water injection from fire protection system (Alternative water injection)

The exposure time of fuels is considered to be prolonged due to insufficient reactor depressurization (reactor depressurization operation for containment, reactor containment depressurization (vent) to the pressure lower than the fire extinguishing pump head.

Hydrogen generated through zirconium–water reaction. Explosions that seemed to be hydrogen explosion occurred in the reactor buildings of Units 1, 3 and 4. (Pressure in the pressure suppression chamber in Unit 2 dropped simultaneously with the Unit 4 explosion.)

- The explosions deteriorated work performance in the surrounding areas.
- Water leakage from containments / buildings were observed.

(Only one of emergency air cooling DGS in Unit 6 maintained its function)
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Summary of Fukushima Dai-ichi Accident

- Radiation Exposure of Fukushima Residents (for 4 months after the accident)
  - 99 out of 25,520 exceed 10mSv (public), maximum 25.1mSv
  - 48 out of 147 exceed 10mSv (workers in nuclear facilities)
- Confusion in evacuation, food and water control
- Contamination of land is significant

- If emergency preparedness works, they should have been mitigated
  - Exposure limitation in emergency situation
  - Radioactivity control in food and drinks
  - Mitigation measure of significant radioactive release
Crossroad in Fukushima Dai-ichi Accident

- Earthquake - Practically no damage on safety functions at 14:46, March 11
- Tsunami - Loss of multi-functions (not only safety but logistics) at 15:42
  - Station blackout (SBO)
  - Loss of ultimate heat sink (LUHS)
  - Loss of instrumentation and control
  - Loss of communication and information (lighting, computer, mobile phone, paging)
  - Loss of off-site external assistance
  - Fear on aftershock and another tsunami
- Hydrogen Explosion on Unit 1 at 15:36, March 12
  - Loss of accident management
  - Loss of accessibility
  - Loss of habitability
  - Fear on the next explosion
Recovery from Disaster

• The staff always considered priority; to select the best action on the worst unit

• Knowledge-base management
  – Mobile equipment
  – Car batteries

• Information is helpful for good decision making
  – Helicopter flight confirmed water in the spent fuel pool on March 16

• External support started (Self-Defense Force, Fire Management Agency, etc)
  – Core cooling using fire engines
  – Spent fuel pool cooling using concrete pump vehicles
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Lessons Learned

• We can manage things, even in very serious situations
• Flexibility, knowledge-base and imagination really work in beyond design basis event
• Agreement with society is important to make preparation for emergency practicable
• Justification of nuclear and acceptance of risk are inseparable
• Risk is uncertainty—PRA deals with uncertainty
Lessons from Japanese Government Report

• The most important basic principle in securing nuclear safety is “defense in depth”
  – Strengthen preventive measures against a severe accident (8)
  – Enhancement of response measures against severe accident (7)
  – Enhancement of nuclear emergency responses (7)
  – Reinforcement of safety infrastructure (5)
  – Thoroughly instill a safety culture (1)

Recommendations for Enhancing Reactor Safety in the 21st Century

• Clarifying the Regulatory Framework (1)
• Ensuring Protection (2)
• Enhancing Mitigation (5)
• Strengthening Emergency Preparedness (3)
• Improving the Efficiency of NRC Programs (1)

The Near-Term Task Force Review of Insight from the Fukushima Dai-ichi Accident, JULY 12, 2011
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How to Ensure Safety...

Risk Model - in Mathematical Form

- To ensure safety, suppress the risk to low level
  - Reduce Frequency
  - Mitigate Consequence
- It works only if we know the frequency precisely and we control the consequence

\[
\text{Risk} = \text{Frequency} \times \text{Consequence}
\]
Frequency and Consequence; Which Is More Important?

Large risk means large uncertainty
Low Frequency: What Does It Mean?

Low frequency means less information (ignorance).

Low level of knowledge / recognition.

Low Frequency

Large Risk

Small Risk

Low Consequence

Likelihood

Frequency

Consequence
Approach to Ensure Safety – Limit the Risk

• Risk is not “frequency” times “consequence”
  – Risk comes from uncertainty which we cannot be free from
  – We must be prepared for uncertainty and overcome ignorance

• Approach to prepare for uncertainty and to limit the risk is: Defense-in-Depth

• What causes the risk?
  – Source term or radioactive material: fission product causes the risk

• Who sustains the risk?
  – Public health and safety and environment sustain the risk
Goal: What Is Hazard? Who Should be Protected?

• Identify Hazard Source
  – Radioactive materials

• Define Safety Objective
  – Health and property of public and environment

• Keep Hazard and Public Separate
3rd Defense: Objective Is the Goal

- To protect public is most important
- Emergency response is scenario-less
  - Scenario is unpredictable
  - 1st defense depends on scenario
- Flexibility and knowledge-base action works
  - Management system
  - Drill and education
  - Safety culture
2nd Defense Is Flexible and Broad

1st Defence
Prevention

2nd Defence
Mitigation

3rd Defence
Emergency
preparedness

- Hazard (Fission Product)
- No Severe Accident
- Contain Fission Product
- Respond to Emergency Barrier / Distance / Time

Management

Purpose of the 2nd defense is ambiguous
Boundaries are overlapped
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“Absolutely Unlikely” Is Impossible

- Black Swan / White Raven

Black Swan (N. Taleb, 2007)  White Ravens (Hempel's Ravens)
Four Categories of Undesirable Event

- Known known
- Known unknown
- Unknown known
- Unknown unknown

Two Beyond-Design-Basis Type: Unlikely Event and Rare Event
Precursor is Messenger of Safety

- White Snake (Iwakuni City, Yamaguchi, Japan)

- Appearance of unknowns is messenger of safety

*We know white raven / black swan, then, be prepared for them*
Known Unknown Becomes Reality

Earthquake and tsunami in the Indian Ocean off Sumatra: Kalpakkam NPP

Flooding: Le Blayais NPP, France

Fort Calhoun NPP: Missouri River Flooding in 2011, USA
To Prepare for Unknown High Consequence Event

• Low Frequency High Consequence Event (Rare Event)
  – We recognize the event but it is rare. We do not collect knowledge
  – Although frequency is very low, we should have at least knowledge on:
    • Cliff edge, weak link, safety margins, practical preparedness
  – Stress test (comprehensive safety evaluation)

• Low Likelihood High Consequence Event (Unlikely Event)
  – Event is unlikely and we do not understand the importance
  – We should imagine unknown scenario and investigate every possibility
    • Accident sequence precursors (Empirical / Factual)
    • Probabilistic Risk Assessment (Deductive / Eliciting)
**Identification and Preparation for Unknowns**

- “Known Known” is already considered
  - Design basis
- “Unknown Unknown” becomes “Knowns”
  - PRA find out sequences (Unknown Known)
    - BWR containment vessel failure (SBO scenario): hardened vent
  - Unexpected event becomes reality (Known Unknown)
    - Small LOCA and human error (TMI)
    - SBO+LUHS (Fukushima Daiichi) by tsunami
- “Unknown known” is investigated in detail (stress test)
- “Known unknown” is protected (provisions)
Do We Accept Residual Risk?

IAEA Fundamental Safety Principles
Facilities and activities that give rise to radiation risks must yield an overall benefit.

Justification is the action of declaring or making righteous in the sight of God (Oxford Dictionary of English)

Be ready to accept risk under justification
But continue to reduce / optimize risk

正義の女神、ユースティティア（Justitia）
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Lessons Learned #27

Effective Use of PSA in Risk Management

• PSA has not always been effectively utilized in the overall reviewing processes or in risk reduction efforts at nuclear power plants. While a quantitative evaluation of risks of quite rare events such as a large-scale tsunami is difficult and may be associated with large uncertainty, Japan has not made sufficient efforts to improve the reliability of the assessments by explicitly identifying the uncertainty of these risks.

• Considering knowledge and experiences regarding uncertainties, the Japanese Government will further actively and swiftly utilize PSA in developing improvements to safety measures including effective accident management measures based on PSA.

## Atomic Energy Society of Japan

### PRA Standard Line-up

<table>
<thead>
<tr>
<th>Standard</th>
<th>Issuance</th>
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<tbody>
<tr>
<td>Level 1 PRA</td>
<td>March 2009 (under revision)</td>
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<tr>
<td>Level 2 PRA</td>
<td>March 2009</td>
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<tr>
<td>Level 3 PRA</td>
<td>March 2009</td>
</tr>
<tr>
<td>Shutdown Level 1 PRA</td>
<td>February 2002 (revised in November 2011)</td>
</tr>
<tr>
<td>Seismic PRA</td>
<td>September 2007 (under revision)</td>
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<tr>
<td>PRA Parameter Estimation</td>
<td>June 2010</td>
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<tr>
<td>Use of Risk Information</td>
<td>October 2010</td>
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<tr>
<td>Tsunami PRA</td>
<td>December 2011</td>
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<tr>
<td>Internal Flood PRA</td>
<td>November 2012</td>
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<tr>
<td>Tsunami PRA Usage Example</td>
<td>To be published</td>
</tr>
<tr>
<td>Terms and Definitions Used in PRA</td>
<td>January 2012</td>
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</tbody>
</table>
Earthquake Experience and NPPs Affected

- Hyogo-Ken Nambu Earthquake
  - (January 17, 1995, Magnitude 7.3)
- Miyagi-Oki Earthquake
  - Onagawa NPP
  - (August 16, 2005, Magnitude 7.2)
- Noto Peninsula Earthquake
  - Shika NPP
  - (March 25, 2007, Magnitude 6.9)
- Niigata-ken Tyuetsu-Oki Earthquake
  - K-K NPP
  - (July 16, 2007, Magnitude 6.8)
- Suruga-Bay Oki Earthquake
  - Hamaoka NPP
  - (August 11, 2009, Magnitude 6.5)

- We have overcome the earthquake threat, but....may be unbalanced consideration on external events
PRA Standard Updates

• Japanese regulatory authority required utilities to implement emergency safety measures for currently operating NPPs on March 30, 2011
• Additional vital power and alternative equipment for cooling have been equipped
• Risk reduction effect is to be quantified of the measures
• Emergency measures have to be taken into account not only in tsunami PRA, but internal level 1 PRA and seismic PRA

• Tsunami PRA development (completed)
• Level 1 PRA standard and seismic PRA standard update so that the up-to-date safety level are appropriately evaluated (in progress)
Premises in Tsunami PRA

- Initiator is a tsunami caused by earthquakes
- NPP is in power operation when the earthquake occurs
  - No direct effect by earthquakes
    - Supported by Kashiwazaki (2007) and Fukushima, Onagawa and Tokai (2011)
    - Sensitivity analysis on off-site power
  - According to earthquake and/or tsunami alarms, the reactor is in safe shutdown
  - Earthquake does not influence safety function of NPP. Safety-related SSCs for the reactivity control, core cooling, and containment of the fission products are all intact
Earthquake and Tsunami Coupling

• Earthquake 3-7km/s while Tsunami 50-100km/hour (time lag)

• Coupling of earthquake and tsunami
  – Supporting systems and equipment which may fail at relatively low intensity earthquake
  – Added equipment and structures to enhance the water-tightness
  – Emergency measures (equipment and procedures) for may not be seismically qualified
External Event Coupling Effect

• Seismic experience of secondary failure
  – In Onagawa NPP a fire was induced by the earthquake in a transformer in 2011 earthquake off the Pacific coast of Tohoku
  – In Kashiwazaki-Kariwa NPP, the Tyuetsu Offshore Earthquake triggered a fire of a station service transformer of in 2007
  – Spent fuel pool sloshing
• Seismic-induced fire and seismic-induced internal flooding of especially non-safety grade equipment are probable
• Several external events are mutually interactive
  – Internal flooding PRA standard mentions earthquake-induced flooding is out of scope
• Some external events may induce multiple failures and/or another external event
Other Unresolved Issues
Level 2 PRA and Level 3 PRA

- Tsunami PRA standard deals with level 1 PRA for reactors in power operation
- AESJ has developed level 2 PRA standard and level 3 PRA standard for internal events
  - They can be applied to external event as well
  - Necessity to develop standards for level 2 PRA and level 3 PRA for external events
  - Consideration if an external event has specific features in terms of the fission product release, containment performance and the emergency responses
Other Unresolved Issues
Shutdown PRA

• In Fukushima Dai-ichi Accident:
  – Units 4, 5 and 6 are in shutdown for refueling.
  – In unit 4, all the fuel assemblies are unloaded and transferred to the spent fuel pool to replace the reactor vessel shroud

• In shutdown condition
  – Some safety systems may be out of service
  – Water-tight doors and openings may not be closed

• Practical and efficient tsunami protections is to keep the safety-related SSCs away from the tsunami water
  – Dry site concept, water-tight structure, water-resist and water-proof SSCs
  – During shutdown situations, they may not work

• Is shutdown PRA for external events necessary? Yes, probably.
Other Unresolved Issues

Risk Assessment of Spent Fuel Pool

- Spent fuel pool risk is a safety concern
- Inventory of the fuel and fission products may be larger than in the reactor core
- Decay heat in the spent fuel pool is quite small and the maintenance of water level is enough for cooling
- Do we need to estimate the spent fuel pool risk in the framework of the PRA?
- In the Fukushima Dai-ichi accident
  - Difficulty in spent fuel pool cooling comes from hydrogen explosion
  - Accessibility were extremely deteriorated
  - Spent fuel pool risk may be well controlled by management
- Technological requirement, quantification methodology, and data are not enough to complete spent fuel pool PRA but the risk is controllable
Contents

• Fukushima Dai-ichi Accident
• Lessons-Learned
• How to Ensure Safety
• Unknowns
  – Black Swan and White Raven....White Snake
• PRA Standard Development
• Comprehensive Risk Assessment
• Conclusions
Other Unresolved Issues

Comprehensive External Event PRA

• External event PRA
  – Necessary if occurrence frequency and/or consequence significant
  – Internal flooding PRA and fire PRA standards are under development
  – Other external events?

• Concurrency of multiple external events
  – Priority on combined PRA of earthquake and tsunami
    • Seismic failure of anti-tsunami SSC, loss of function or deterioration of infrastructure such as power supply system and communication system
    • Deterioration of the accessibility for the operators and workers is to be considered in case that the human recovery actions are taken into account.
  – Combinations of earthquake and internal flooding and fire
  – Other combinations?
Comprehensive External Event PRA Impact Based Approach

• Nuclear power plant should be designed safe for postulated events, that are “likely” and “influential”

• All possible “influential” events are considered in PRA regardless of the likelihood
  – We cannot tell an event is likely or unlikely precisely

• Provisions for influential but unpostulated events have varieties according to event characteristics

• Selection of influential unpostulated event is based on impact and tolerability
  – Frequency of event, capacity of plant, isolation capability
  – Practical and effective metrics is “Risk”
Selection Criteria of External Event

Yes / No / Uncertain

• C-1: Current PRAs practice cover the external event?
• C-2: Licensing evaluations cover the event and show it is not influential and dominant
• C-3: Occurrence frequency definitely small
• C-4: Distance of hazard and NPP is kept large enough
• C-5: Hazard progression (time scale) is slow enough
• C-6: Influence on NPP is small enough

• If one or more of C-2 to C-6 is yes, PRA is not required
• If one or more of C-2 to C-6 is uncertain, select appropriate risk assessment method
• If all of C-2 to C-6 is no, PRA is required
## Hazard – Criteria (EQ, Tsunami, Volcano)

<table>
<thead>
<tr>
<th>Natural Disaster Type</th>
<th>Natural Hazard</th>
<th>Criteria</th>
<th>Reason</th>
<th>Impact</th>
<th>Probability</th>
<th>Severity</th>
<th>Total Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Tremors</td>
<td>✔ (Ground PRA)</td>
<td>△</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>B (only if the uncertainty is large, risk assessment must be done) → Ground PRA</td>
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<tr>
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</tbody>
</table>

### Notes:
- Ground PRA: Ground Proof Risk Assessment
- △: The risk is not assessed.
- ×: The risk is small.
- ✔: The risk is large.
- B: The risk is high.
- C: The risk is moderate.
- D: The risk is low.
- E: The risk is very low.

### Additional Information:
- B (only if the uncertainty is large, risk assessment must be done) → Ground PRA
- C: The risk is moderate.
- D: The risk is low.
- E: The risk is very low.
## Hazard – Criteria (Natural Phenomena)

<table>
<thead>
<tr>
<th>Natural Hazards</th>
<th>Hazard Criteria</th>
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<tbody>
<tr>
<td></td>
<td><strong>Natural Phenomena</strong></td>
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<tr>
<td></td>
<td><strong>Frequency</strong></td>
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<tr>
<td></td>
<td><strong>A</strong></td>
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</tbody>
</table>

### Natural Phenomena
- Earthquakes
- Floods
- Volcanoes
- Earthquakes
- Landslides
- Storms
- Lightning
- Tornadoes
- Hailstorms
- Thunderstorms
- Heat waves
- Cold waves
- Droughts
- Wildfires
- Infectious diseases
-Biological hazards
- Chemical hazards
- Nuclear disasters

### Hazard Evaluation Factors
- Frequency
- Severity
- Risk
- Mitigation
- Precaution

### Hazard Level
- A: High
- B: Moderate
- C: Low
- D: Very Low
- E: Negligible
<table>
<thead>
<tr>
<th>Hazard – Criteria (Natural Phenomena and man-made event)</th>
</tr>
</thead>
</table>

<table>
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<th>Man-Made Disasters</th>
<th>Criteria</th>
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<td>Tsunami</td>
<td>Tsunami</td>
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<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

**References:**

A: 定量的リスク評価不要、基準4の不確定さが大きいため、定量的リスク評価が必要。→ 基準PRA
B: (ただし、基準4の不確定さが大きいため、定量的リスク評価が必要) → 基準PRA
C: 定量的リスク評価不要、基準4の不確定さが小さいため。→ 基準PRA
D: 不確定さ確認のための分布を求める。基準4の不確定さが小さいため。→ 基準PRA
Concept of Event Selection

Safety evaluation by PRA or Design

**Frequency**

- **Criterion 1**: Occurrence of natural hazard
- **Criterion 2**: Safety evaluation by PRA or Design

**Separation**

- **Criterion 3**: Physical Distance
  - Volcano
- **Criterion 4**: Large grace time
  - Geological change
  - Drought

**Consequence**

- **Criterion 5**: Little impact
  - Fog
  - Frost

Hazard

Separation Barrier

Impact
Conclusions

• Good management and knowledge lead us to the right way at crossroads

• Preparation for Uncertainty (Unpostulated scenarios)
  – Defense-in Depth
  – Unlikely Event and Rare Event

• Being prepared for three types of Unknowns
  – Stress test covers rare event: Unknown known
  – Appropriate back-fit prepares for: Known unknown
  – PRA deal with unlikely event: Unknown unknown

• External PRA Standard Development at AESJ