Important Lessons Learned from the Severe Accident at Fukushima Daiichi

Shunsuke Kondo, Dr.

President

Nuclear Waste Management Organization of Japan (NUMO)

On March 11, 2011 the Great East-Japan earthquake and the resulting tsunami attacked the Pacific coast of the northeast district of Japan.

Tsunami waves are hitting TEPCO Fukushima Daiichi NPP.

- **The tsunami attack triggered a major accident at unit 1- 4 of TEPCO Fukushima Daiichi nuclear power station.**

Verdicts of Various Accident Investigation Teams

- After the accident, various accident investigation teams including those organized by the IAEA, the Japanese Government, the Diet of Japan, INPO and various NPOs including AESJ, ANS, ASME etc. published their judgment on the causes of the accident and lessons learned from it in succession.
- Most of them judged that though the accident was triggered by a massive force of nature, it was existing weaknesses regarding defense against natural hazards, regulatory oversight, accident management and emergency response that allowed the accident to unfold as it did.

Message from the Chairman of NAIIC* Dr. Kurokawa

- What must be admitted – very painfully – is that **this was a disaster "Made in Japan."** Its fundamental causes are to be found in the ingrained conventions of Japanese culture: our reflexive obedience, reluctance to question authority, devotion to 'sticking with the program', groupism and insularity.
- The accident was the result of **collusion** between the government, the regulators and TEPCO, and the lack of governance by said parties. Therefore, we conclude that the accident was clearly **"man-made."**
- The nuclear regulators lacked the expertise and the commitment to assure the safety of nuclear power: their independence from the ministries promoting nuclear energy and the operators was a mockery: they were in the state of **regulatory capture**, in which the industry had too great an influence over the regulator

* National Diet of Japan Accident Independent Investigation Commission

The Independence of Regulatory Body

NAIIC report: the regulators lacked the expertise and the commitment to assure the safety of nuclear power, which resulted in the delay of the implementation of relevant regulations. Their independence from the ministries promoting nuclear energy and the operators was a mockery.

Paraphrasing it in a more positive statement, the accident taught us that

- A high degree of independence in the way the regulatory body operates its regulatory decision making must be clearly defined in the appropriate legal instruments.
- An independent regulator, in which organization and staff an effective safety culture pervades, must commit to implement legislation and act to promote plant safety so as to protect individuals, the public and the environment.

To be reliable is necessary but not sufficient to be safe.

A. Reliable: the probability that a hardware system will satisfy its performance requirements for a specified time interval within design basis conditions is sufficiently high.

B. Safe: the likelihood of accidents with serious radiological consequences, i.e. accident risk is extremely small.

C. A highly reliable system designed based on design basis events is not highly safe if it degrades abruptly when experiencing more challenging conditions than those considered in the design basis, i.e. beyond design basis conditions.

D. Nuclear operators should be vigilant to the possibility that beyond design basis conditions would lead to a disproportionate increase in radiological consequences (**cliff-edge**), by conducting and updating a probabilistic risk assessment (PRA).

Design Basis for Station Blackout

- Guideline 27 of NSC requires: the nuclear reactor facilities shall be so designed that safe shutdown and proper cooling of the reactor after shutting down can be ensured in case of a short-term total AC power loss. **The duration for a short-term AC power loss should be 30 minutes**.
- No particular considerations are necessary against a longer-term total AC power loss because the repair of troubled power transmission line or emergency AC power system can be expected in a short time **according to excellent track records** that had been established by the persistent quality circle or Kaizen activities that aimed at realizing reliable and high quality systems.

Lack of Vigilance: Duration of SBO

- After the enactment of this guideline, however, long hour power supply suspension events due to a large scale transmission line failure caused by typhoon occurred in 1991, 2002, 2005 etc.
- No action was taken to revise this guideline as the investigation team for these failures concluded that they were caused by the defect in the quality of pylon construction processes and proposed the check of other pylons.
- Though meteorologist claimed that the effect of global warming had already been actualized, **the team cared about quality only but not risk from global warming**.

Lack of Vigilance to the Cliff-edge

- When TEPCO's expert obtained inundation height of 15.7m in one hypothetical case study, the Chief Nuclear Operator (CNO) was embarrassed and ordered to consult with the tsunami expert group, since
  - It had been previously thought that subduction zone off-Fukushima coast could not generate megaquakes. It was just a few years before the Great East Japan earthquake hit Japan, the seismological community had accepted that all subduction zones of sufficient length could generate megaquakes.
  - No tsunami residue was found around the site.
- The CNO should have been attentive not only to design basis tsunami but also to the cliff-edge as uncertainty is a fact of life.

Lessons Learned

- Remain **vigilant** as new insights and sources of information emerge, casting a wide net for all relevant information and carefully considering that information in the determining design basis (external) events.

- As the occurrence of severe external events is not subject to accurate prediction or control, be attentive to the vulnerability of their system against beyond design basis events*, and deliberate the way to mitigate the result of beyond design basis events, respecting Defense-in-Depth philosophy that is reflected in layers of independent prevention and mitigation capability for preparing ourselves for uncertainties.

  * Be vigilant that a change in severity of design basis external events should not lead to a disproportionate increase in radiological consequences (cliff-edge effect).

IAEA Safety Requirement 20: Design Extension Conditions

- A set of design extension conditions shall be derived for the purpose of further improving the safety of the nuclear power plant by enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures.
- These design extension conditions shall be used to identify the additional accident scenarios to be addressed in the design and to plan practicable provisions for the prevention of such accidents or mitigation of their consequences if they do occur with a view to assuring sufficient margin to the cliff-edge.
- The design enhancement shall be such that design extension conditions that could lead to significant radioactive releases are practically eliminated

Defense-in-Depth: Tsunami

Prevent – Protect – Diversify

a) Seawall designed based on design-basis tsunami
b) Water-tightness of safety-significant buildings
c) Bunkered system for essential safety function

Seawall that protects flooding by tsunami

Watertight door that prevents water intrusion into safety significant buildings

Defense Against Common Mode Failures (CMFs) Is Critical

- At Fukushima Daiichi,
  - ✧ Flooding damaged emergency switchgear and redundant EDGs: CMF
  - ✧ Flooding did not damage air-cooled EDG located at a higher place and DC power at a higher place: diversity prevented CMF.
  - ✧ Loss of both AC and DC power sources made inoperable various engineered safeguards except those depending on steam-driven pumps: diversity prevented CMF.
- NRA: in the design of plant capabilities for withstanding design extension conditions or beyond design basis events, **defense against common mode failures** such as preparing diverse means to respond to events is critically important, considering internal and external threats with widespread damage potential caused by them.

Accident Response at 1F

<Challenging Condition in Main Control Room>

Checked instrumentation in near-complete darkness.

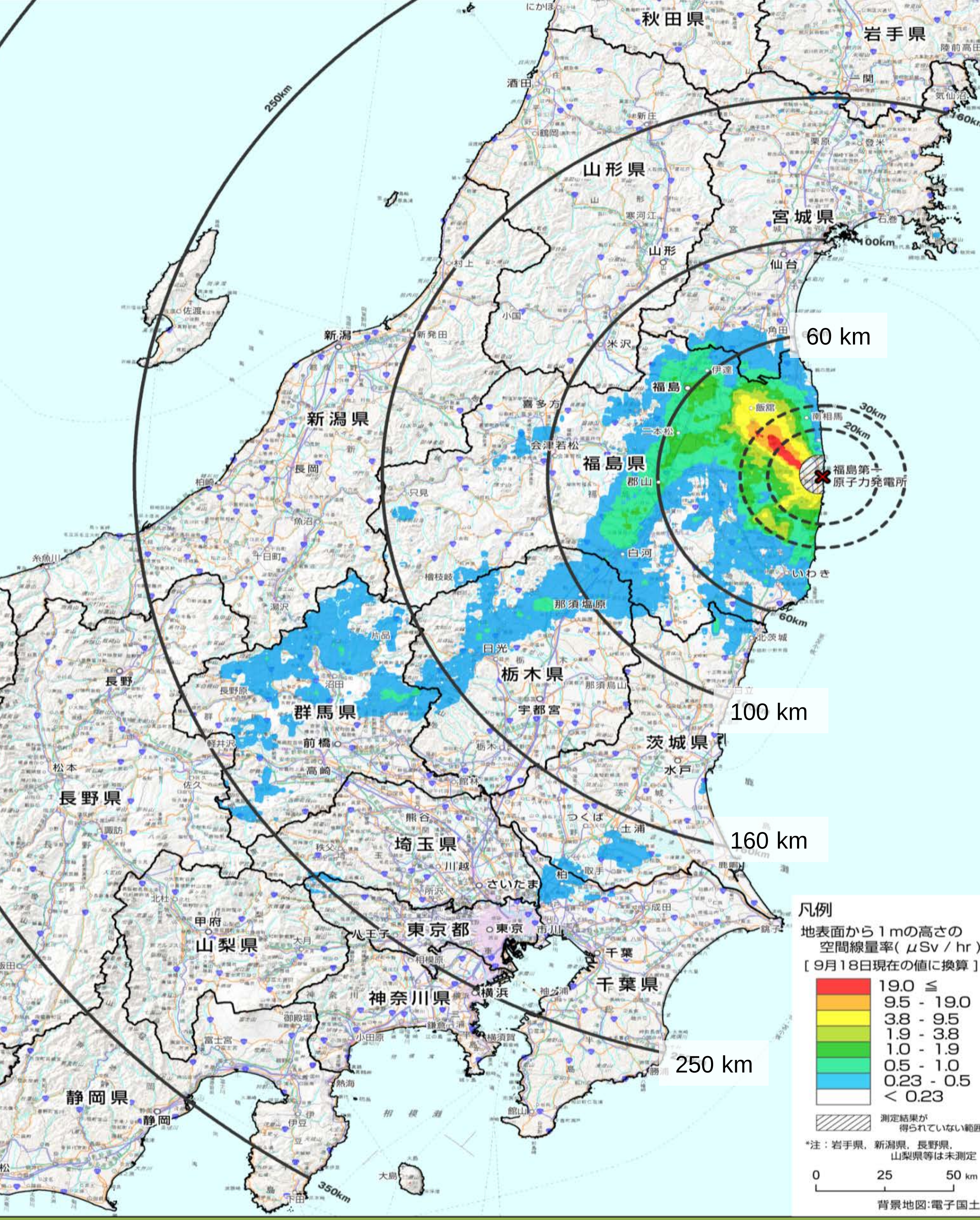
Supervised operation wearing full-face mask.

Brought in heavy batteries to restore instrumentations.

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

Severe Accident Management (SAM) and Emergency Preparedness and Response

- Make SAM and emergency preparedness **resilient** so that it can withstand or even tolerate surprises. The approaches to be considered are to
  - Develop procedures to manage severe accidents caused by EE or IE or their combination at the multi-unit site;
  - Prepare multiple sets of portable, backup safety equipment at different locations in the site that is not easily affected by external initiators including terrorisms;
  - Establish regional off-site response centers that provide flexible and tailored backup in the events of extreme unexpected events; and
  - Prepare robust communication capability between operators and regulators that can be relied even with extensive disruption of infrastructure.



Extent of Land Contamination

Land contamination (dose rate at 1m above ground>1mSv/y) extended over areas within 250 km or so from the NPP, though that corresponded to dose rate at 1m above ground>20mSv/y was within 50 km.

About 80,000 people are still requested to evacuate from their home and about 60,000 people, many of whom are families with children, have left their home, having made up their own mind to do so.

Off–Site Consequences

Fatalities Indirectly Related with the Accident

- The accident has caused 2,911deaths (Dec. 2013) due to the worsening of diseases owing to dislocation, including careless emergency evacuation from hospitals, and/or physical and psychological stress in the life in a shelter after dislocation, being separated from communities and/or families. 90% of who died were over the age of 66.

Probabilistic Risk Assessment (PRA)

- PRA is used to estimate risk by computing real numbers to determine what can go wrong, how likely is it, and what are its consequences. Thus, PRA provides insights into the strengths and weaknesses of the design and operation of a nuclear power plant.
- For the type of nuclear plant currently operating in the world, a PRA can estimate three levels of risk
  - Level 1 PRA estimates the frequency of accidents that cause damage to the nuclear reactor core. This is commonly called core damage frequency (CDF).
  - Level 2 PRA, which starts with the Level 1 core damage accidents, estimates the frequency of accidents that release radioactivity from the nuclear power plant.
  - Level 3 PRA, which starts with the Level 2 radioactivity release accidents, estimates the consequences in terms of injury to the public and damage to the environment.

Consequences Estimation in PRAs

- Nuclear operators should conduct site-level PRAs, multi-unit PRAs in the case of multi-unit site, to confirm the effectiveness of new safety features introduced based on the lessons learned from the TEPCO Fukushima accident from the viewpoint of ALARP decision making about the investment in risk reduction.
- These PRA should take into consideration a comprehensive estimation of consequences of severe accidents that reflect the lesson at Fukushima, i.e. that even large scale land contamination events that do not have extensive radiation-related health consequences could impose grievous damage, including psychological agony of evacuees, socio-political and economic disruptions that inflict enormous cost to society.

Conclusions

- The Fukushima-Daiichi accident challenged us to keep our focus on safety if the nuclear industry is going to be operating for the benefit of our society effectively.
- I hope that Young Generation will concentrate on continuous learning, continued vigilance, and reflection of the best available information on your decisions, keeping in mind the George Santayana’s statement that those who fail to learn from history are doomed to repeat it.

Thank you for your attention!

Karl Weick and Kathleen Sutcliffe: Managing the Unexpected

- A mindful infrastructure is created by continually tracking small failures, resisting over simplification, remaining sensitive to operations, maintaining capabilities for resilience and taking advantage of shifting location of expertise.
- Failure to move toward this type of mindful infrastructure magnifies the damage produced by unexpected events and impairs reliable performance.

Leadership and Responsibility for Safety

TEPCO did not take any action to identify flood vulnerability and deliberate mitigation measures against flooding after a flooding event in Fukushima in 1991. It did not do so even after a flooding event at Le Blayais NPP in 1999 was reported and discussed in international fora in 2000s.

Lesson 4: Every operator should recognize its fundamental responsibility for safety, and should promote a continuous and self-imposed drive for safety excellence from this recognition, including agile investment to address insights arising from operating experience and evolving knowledge of external events and to incorporate advances in safety technology.

Make Response System Resilient

Lesson 7:

As it is difficult to precisely predict the characteristics of severe natural hazards and terrorisms, make your system resilient so that it can withstand or even tolerate surprises by way of

- Preparing multiple sets of portable, backup safety equipment, facilities, services, and information technology systems for emergency response at different locations in the site which are not easily affected by external initiators including terrorisms.
- Establishing regional off-site response centers that make technical resources that are already positioned at nuclear facilities for emergency response readily available so as to provide flexible and tailored backup in the events of extreme unexpected events.

Robust Communication Capability and Emergency Plan Exercise

Regulators and the Government could not have good information about the progress in the accident because of failure in the data transmission system between operators and regulators caused by the earthquake. As a result, they could not responsibly oversight the accident management activities at the site.

Lesson 8:

It is essential to prepare robust communication capability between operators and regulators that can be relied even with extensive disruption of infrastructure.

It is important to hold emergency plan exercises. Planning for emergencies cannot be considered reliable until it is exercised and has proved to be workable and staff involved has developed sufficient competencies in carrying out their roles in the plans. Live exercises are particularly useful for testing logistics, communications and physical capabilities.

Management of Accident at Multi-unit Sites Caused by Multiple Hazards

At Fukushima Daiichi countermeasures were complicated by the fact that several units were impacted by multiple hazards at the same time. In the execution of emergency operation, operators suffered from lack of staff and equipment and spread of contamination due to the accident progression, as well as lack of procedure to cope with such situation.

Lesson 6: It is important to assess the safety of multi-unit sites for multiple hazards in parallel with the development of procedures to manage severe accidents caused by EE or by IE or their combination at the multi-unit site. The currently available guidance material for managing and assessing the safety of multi-unit sites in relation to external events is not comprehensive.

Design Basis for Severe Accident Management

A beyond design basis external event caused severe accident. But the severe accident management (SAM) measures prepared were unpractical, as situation caused by the beyond design basis external event such as long lasting loss of power supply, loss of ultimate heat sink, damages of infrastructure, hostile environment, loss of communication and a long lasting isolation from off-site features useful for management had not been taken into consideration when the measures, including instrumentation and the power sources essential to their practice were designed.

Lesson 5: When you design and evaluate SAM measures, you should take the wide spectrum of situation caused by internal and external initiators of severe accidents, including beyond design basis external events, into consideration.

Quality First Culture Distorted the Perception of Safety

- Promotion of QC circle activities, i.e. Kaizen activities in nuclear industry in 80's resulted highly reliable nuclear power plants in Japan:
  - The Lowest scram frequency in the world;
  - Very Low fail to start probability of EDGs;
  - Extremely low defective fuel element rates.
- The success gave rise to nuclear safety myth: highly reliable nuclear power station designed based on design-basis events (DBEs) is safe.

Lack of Vigilance

- Hanshin-Awaji Earthquake in 1995
  - The validity of design basis earthquakes for nuclear power plants became a critical issue in public domain and therefore a major regulatory concern and the request for conducting external PRAs was put aside:
- 9/11 terrorist attack:
  - Quickly deliberated measures for preventing such unlawful acts: increase in security, increase in the severity of its punishment etc.
  - The discussion of vulnerability and mitigation measure was not done, being afraid that such action would cut through the psychological and political fogs that surround this disgusting issue for the nation: reflexive obedience?

SAM and Emergency Preparedness and Response

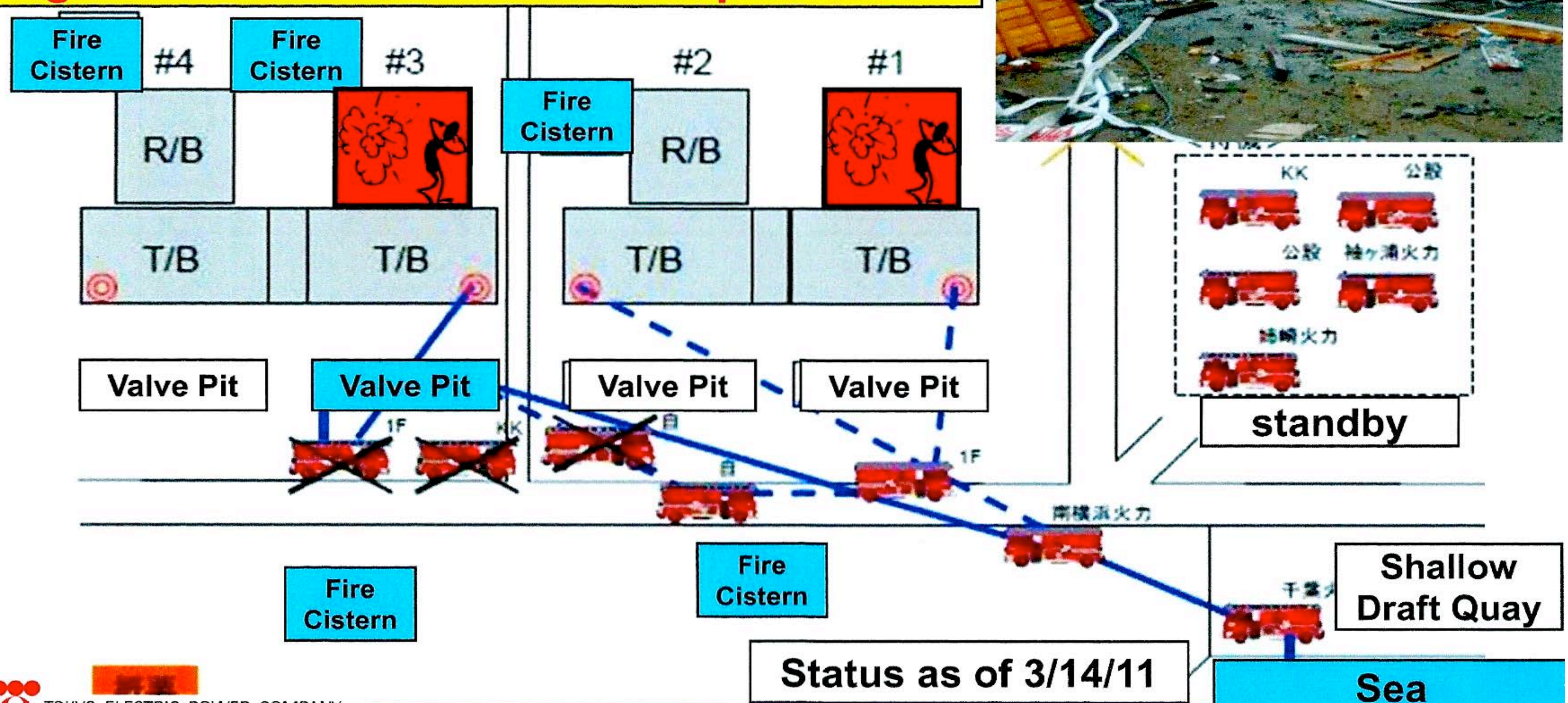
- Ensure flexibility and resilience in emergency preparedness and response against logistical, organizational and human challenges resulting from unexpected harsh situations
  - Staffing levels for extended multi-units events
  - Emergency response center and its organization that can provide responders with flexible response options
- Assistance from off-site in a timely manner, under the disastrous conditions on-site and off-site.
  - Make available last recourse equipment at regional off-site response centers, with a view to providing flexible backup in the events of extreme unexpected events.

Consequences of Severe Accidents

- Despite the fact that significant detectable long-term radiation-related health effects have not arisen and are not expected, the accident has caused significant off-site economic, psychological and sociological impacts as a result of the evacuations, the extensive land contamination and the disruption of the economy due to the bad reputation as well as the restriction of production.
- In addition Japan is confronting a severe challenge to its entire energy system in the aftermath of the accident: as a consequence of the loss of public confidence, all of Japan's NPPs, which had provided about 30% of Japan's electrical power, are not in operation.

Emergency Response at Fukushima Daiichi

- Fire trucks played critical role in injecting water into reactors and spent fuel pools.
- 24 fire trucks deployed.
- Fire brigade operated fire trucks amidst high radiation and successive explosions.



Regulatory Capture

- Regulatory capture, that is, special interest influence in the regulatory process, varies in both degree and kind, across regulations and agencies. Furthermore capture is neither absolute nor uni-dimensional.
- Strategies for preventing capture are
  - Dividing Power: competition among regulators could reduce the likelihood of collusion between individual regulators and a regulated industry
  - Administrative Procedure: administrative review of agency inaction as well as action, review of regulations based on cost-benefit analysis.
  - Cultivation of diverse and independent experts, involvement of subnational officials in federal notice and comment
  - Media Coverage and Journalistic Scrutiny and Consumer Empowerment
  - Exposing the rulemaking process to diverse viewpoints and interests
  - Judicial review of regulatory decisions.

* “Preventing Regulatory Capture: Special Interest Influence and How to Limit It” Edited by Daniel Carpenter (Harvard University) and David Moss (Harvard Business School), Cambridge University Press, 2013