Improvements Needed in Nuclear Power Plant Probabilistic Risk Assessments: Lessons Learned from Fukushima

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PRESENTATION OVERVIEW

I. A Brief Look at the Fukushima Daiichi Accident

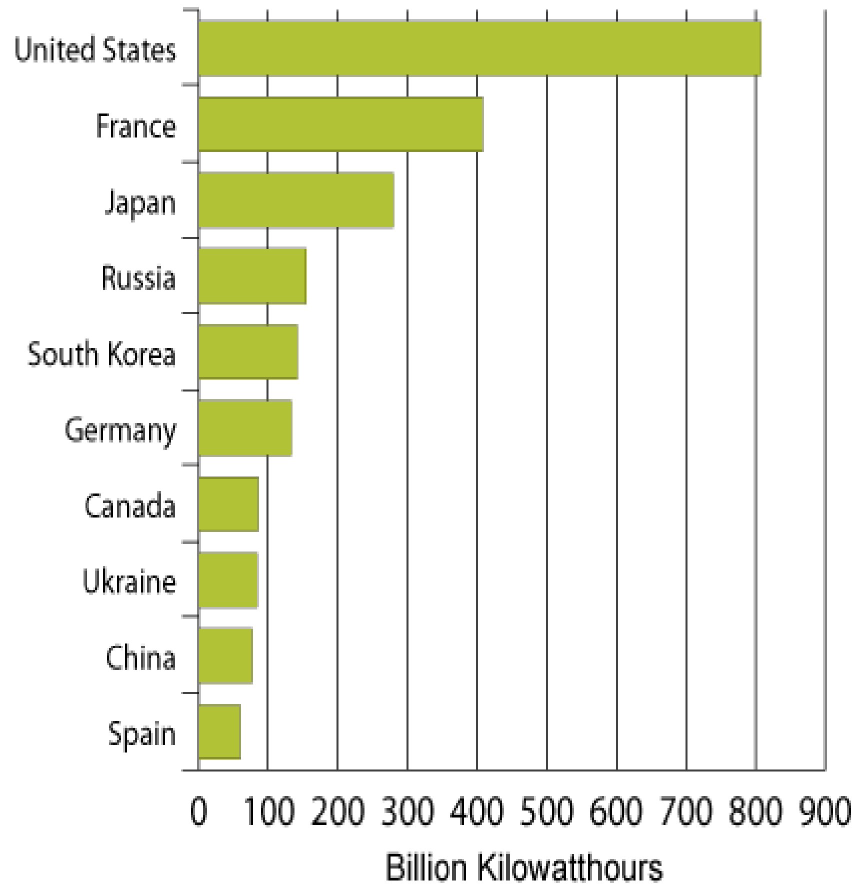
II. PRA Implications considering Fukushima Daiichi

III. Concluding Remarks

Nuclear Energy in the US

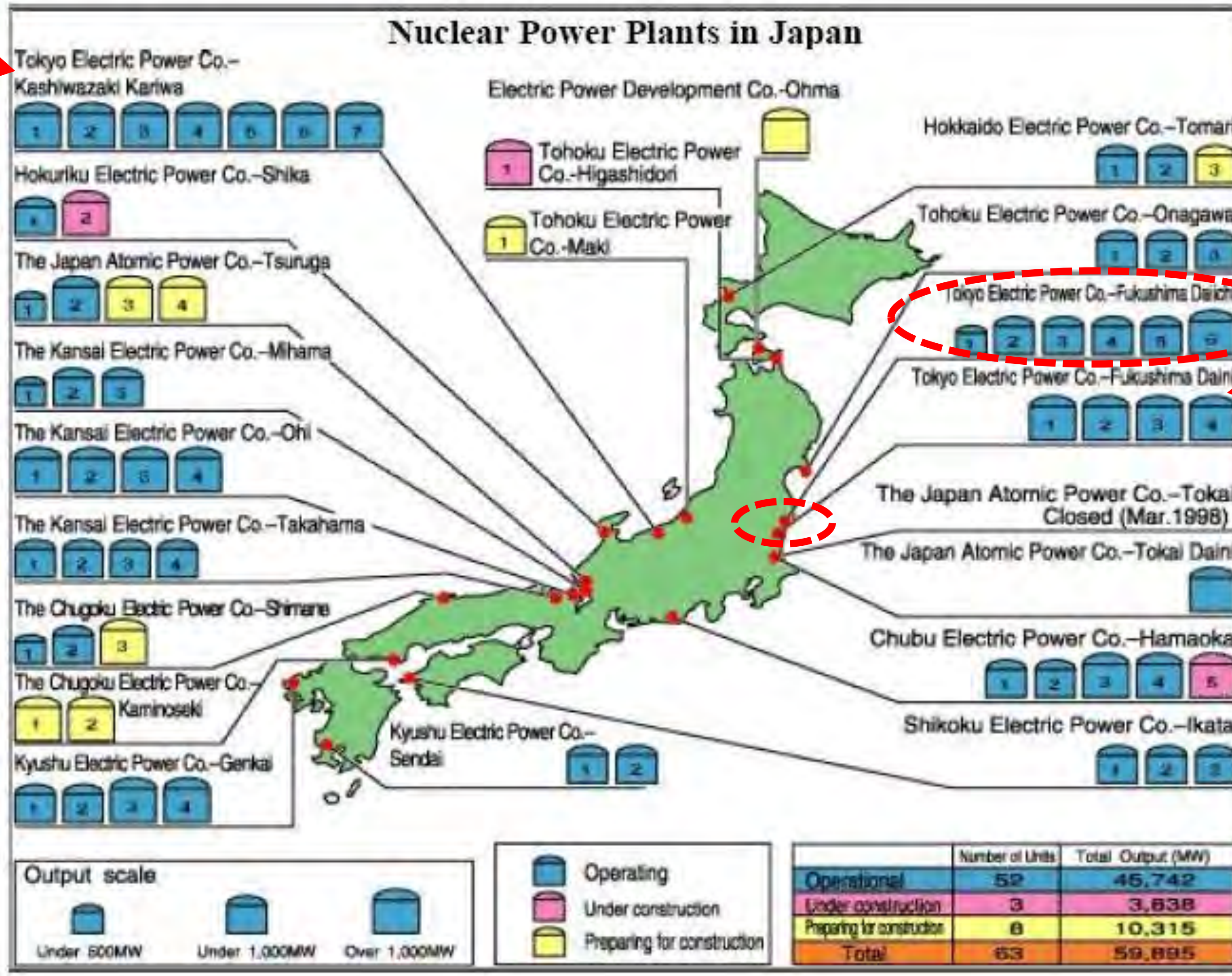
- Currently 104 operable commercial nuclear reactors
- About 20% of the Nation's total electricity supply by nuclear power generation
- Public Opinion Begins To Recover
  - 2009: 64% Favorability
  - April 2011: 46%
  - July 2011: 50% (66% among opinion leaders)
- 81% agree U.S. should learn from Japan and license new plants rather than stopping progress entirely

Source: Luntz Global



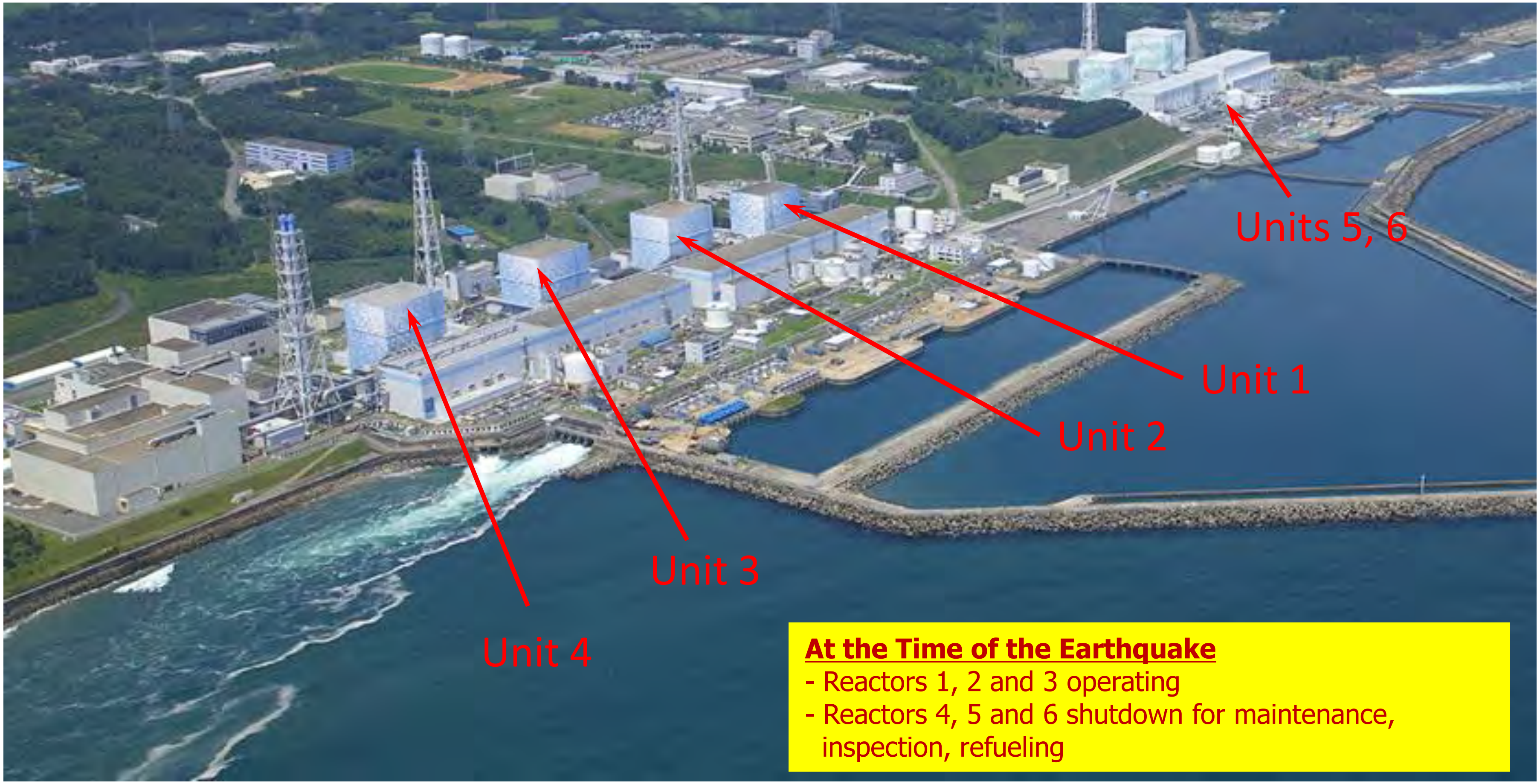
Source: International Atomic Energy Agency, Power Reactor Information System File

Nuclear Power Plants in Japan



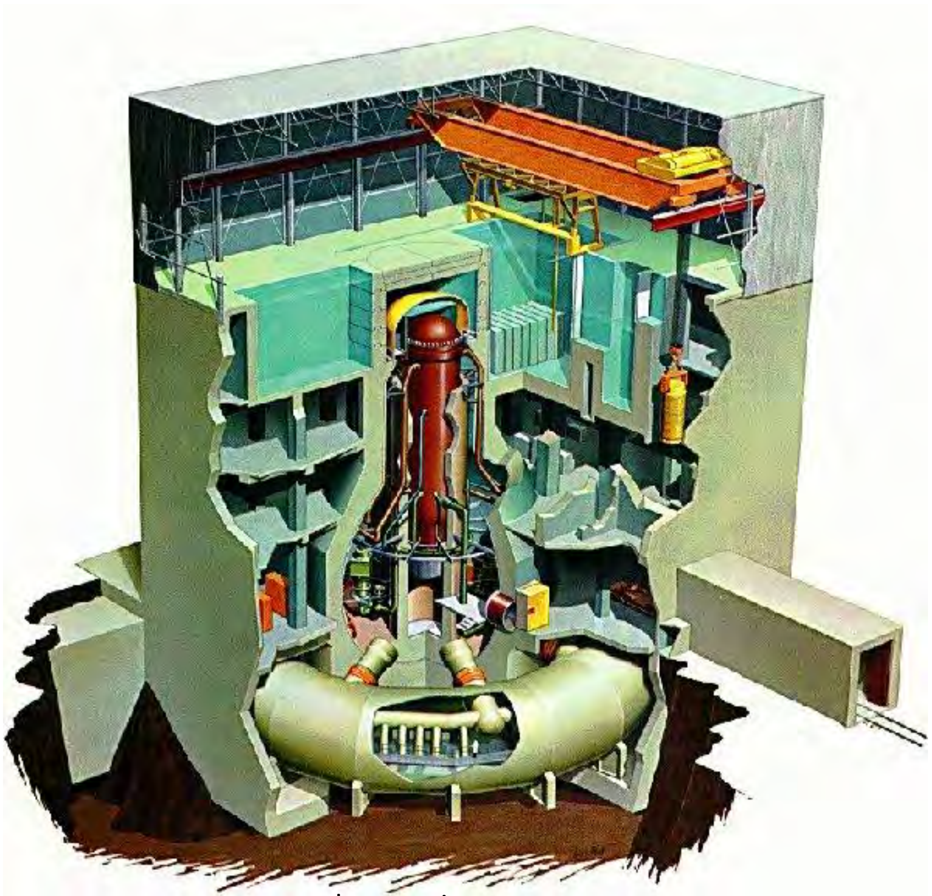
	Number of Units	Total Output (MW)
Operational	52	45,742
Under construction	3	3,838
Preparing for construction	8	10,315
Total	63	59,895

Fukushima Daiichi Nuclear Power Plant



Boiling Water Reactor Plant Design

- Building structure
  - Concrete Building
  - Steel-framed Service Floor
- Containment
  - Pear-shaped Dry-Well
  - Torus-shaped Wet-Well



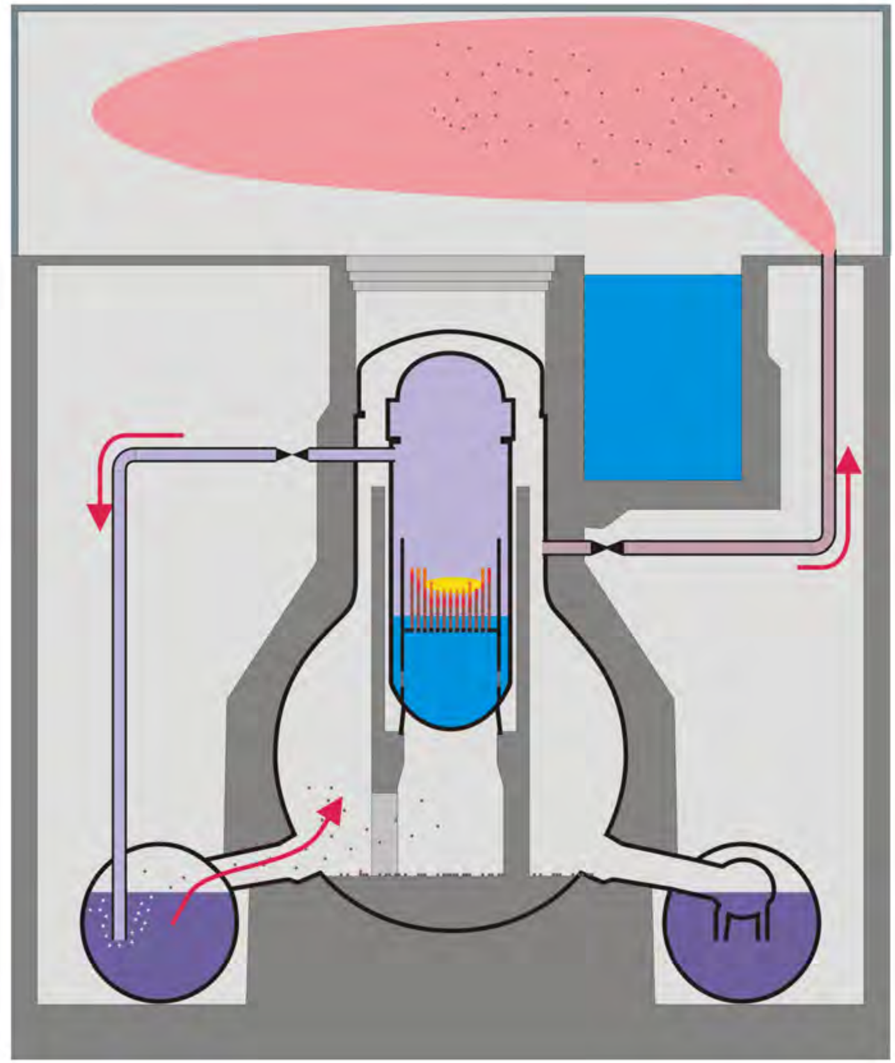
nucleartourist.com

en.wikipedia.org/wiki/Browns_Ferry_Nuclear_Power_Plant

Dr. Matthias Braun, AREVA

Accident Progression

- Positive and negative aspects of depressurizing the containment
  - Removes energy from the reactor building (only way left)
  - Reducing the pressure to ~4 bar
  - Release of small amounts of Aerosols (Iodine, Cesium ~0.1%)
  - Release of all noble gases
  - Release of hydrogen
- Gas was released into the reactor service floor
  - Hydrogen is flammable



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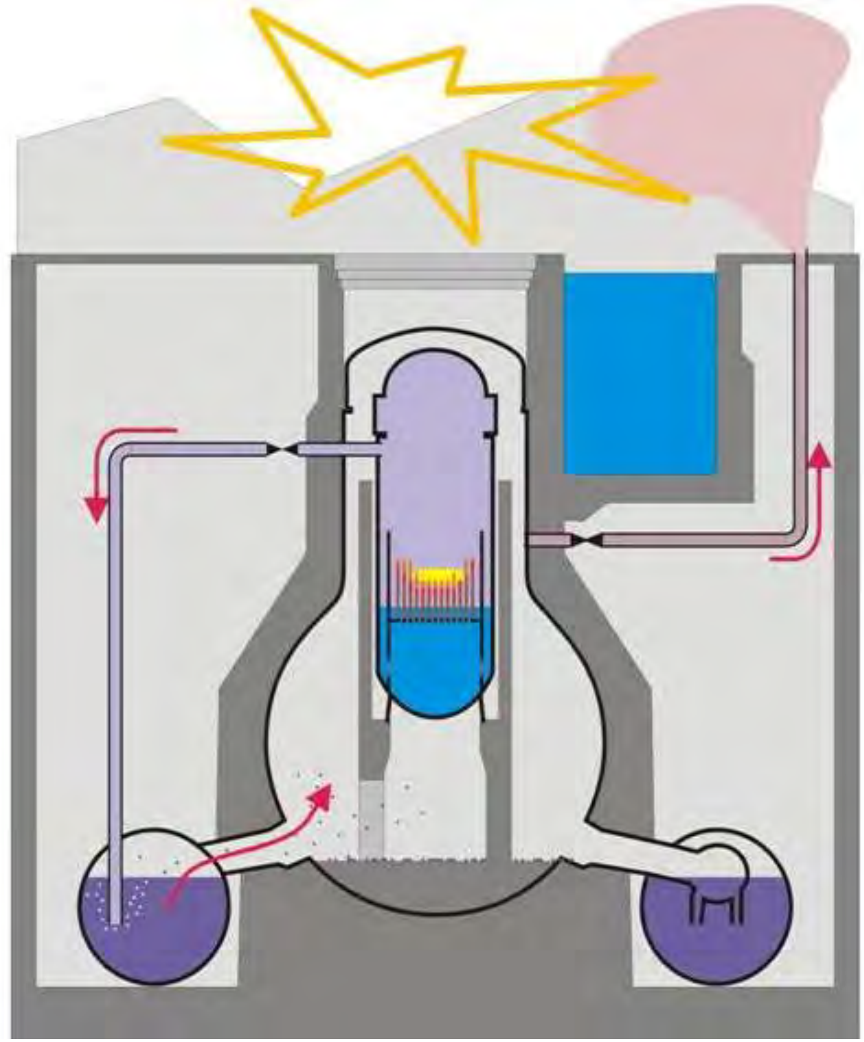
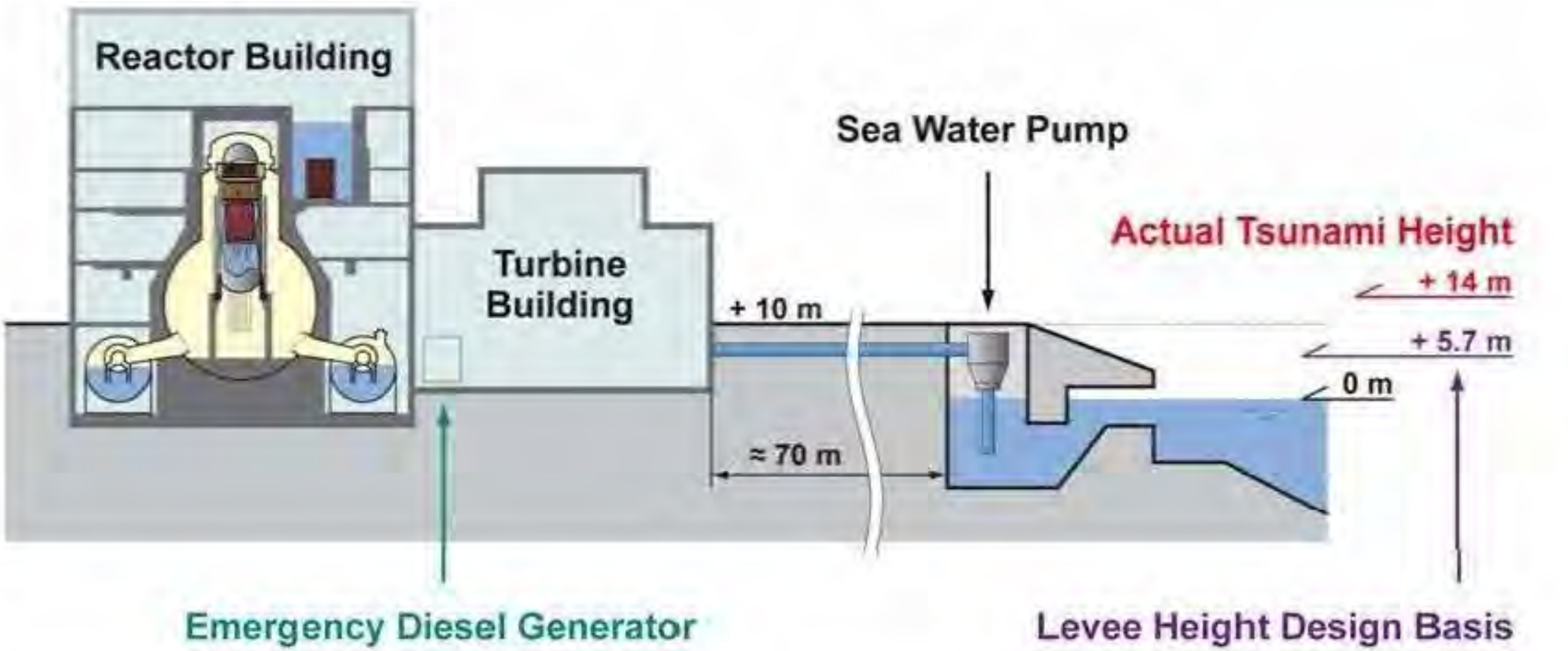
Hydrogen Explosion at Units 3&4

- Unit 1 und 3
  - Hydrogen burn inside the reactor service floor
  - Destruction of the steel-frame roof
  - Reinforced concrete reactor building seems undamaged
  - Spectacular but minor safety relevant



Aerial View of Units 1~4

Design Basis Against Tsunami



- At Fukushima Daiichi, countermeasures for tsunamis had been established with a design basis height of **5.7 m** above the lowest Osaka Bay water level.
- As additional safety margin, the ground level had been set to as + 10 m.

Source: Janti, 2011 All levels are related to the base level of Onahama Bay

Critical Safety Implications of Fukushima Events

- Concurrent Events and Common Cause Failures
  - Great East Japan Earthquake followed by tsunami (50 minutes later)
    - Earthquake 9.0 vs design 8.2
    - Tsunami wave 14 m vs design 5.7 m
      - Maximum tsunami height 38.9 m in Aneyoshi, Miyako
  - Lost offsite power for Units 1-6 due to earthquake
    - Units 1-3 in power operation; Units 4-6 in shutdown
  - All 12 diesel generators in service for Units 1-6 (1 DG for Unit 6 in maintenance) all lost due to tsunami
- Simultaneous Damages to the Multiunit Site
  - Hydrogen explosions at Units 1, 3 and 4
  - Melting of multiple reactor cores (i.e., Units 1, 2 and 3) and spent fuels (i.e., Unit 4)

II. PRA Implications Considering Fukushima

Concept of Accident Sequence in PRA

Plant Condition:
1. **Full Power**
2. **Low Power & Shutdown**

$$IE * HW_1 * \ldots * HW_n * SW * HE * NR$$

Initiating Event:
1. **Internal**
2. **External**

Analysis Level:
1. **Core Damage**
2. **Release**
3. **Dose / Conseq.**

1. Initiating Events Analysis

2. Event Tree Analysis

3. Fault Tree Analysis

4. Basic Events Analysis

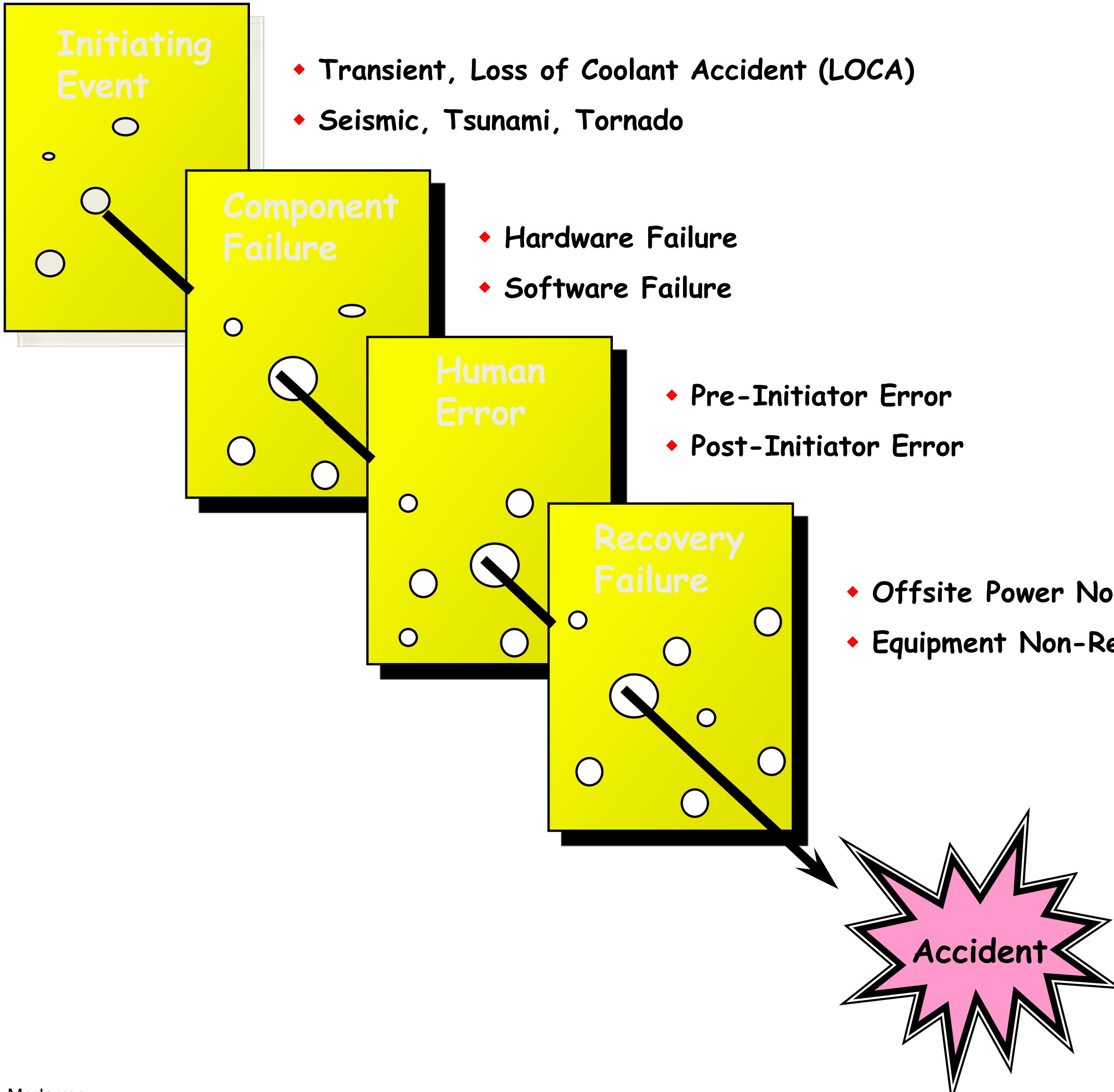
5. Common Cause Failure Analysis

6. Human Reliability Analysis

7. Risk Quantification

IE = Initiating Event; HW = Hardware; SW = Software; HE = Human Error; NR = Non-Recovery;

Accident Causation from a PRA Perspective



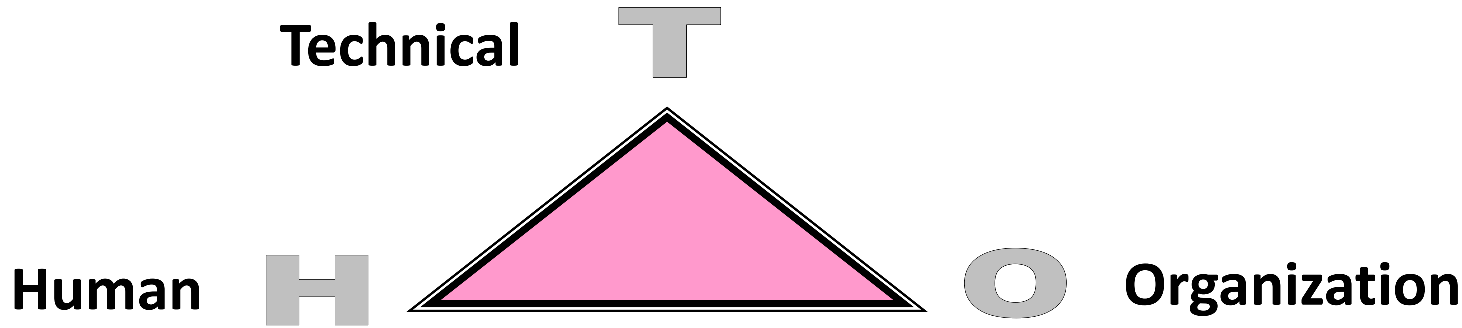
- Transient, Loss of Coolant Accident (LOCA)
- Seismic, Tsunami, Tornado

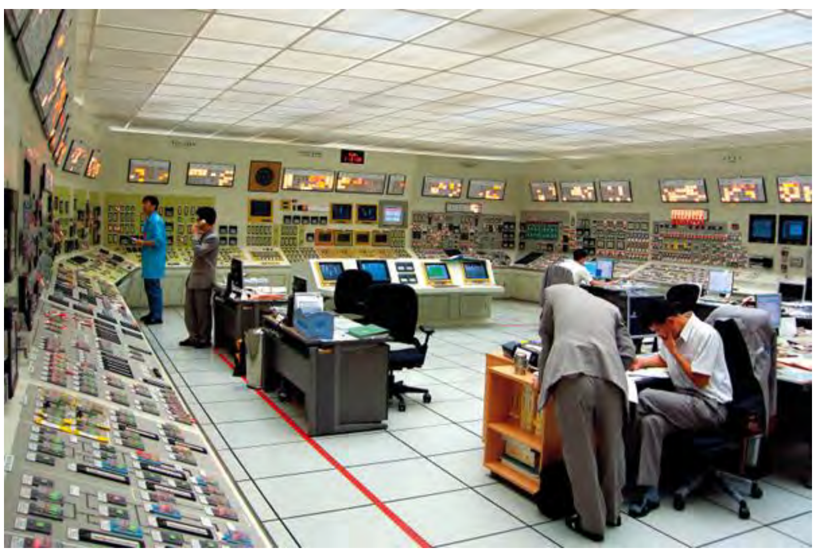
- Hardware Failure
- Software Failure

- Pre-Initiator Error
- Post-Initiator Error

- Offsite Power Non-Recovery
- Equipment Non-Recovery, etc.

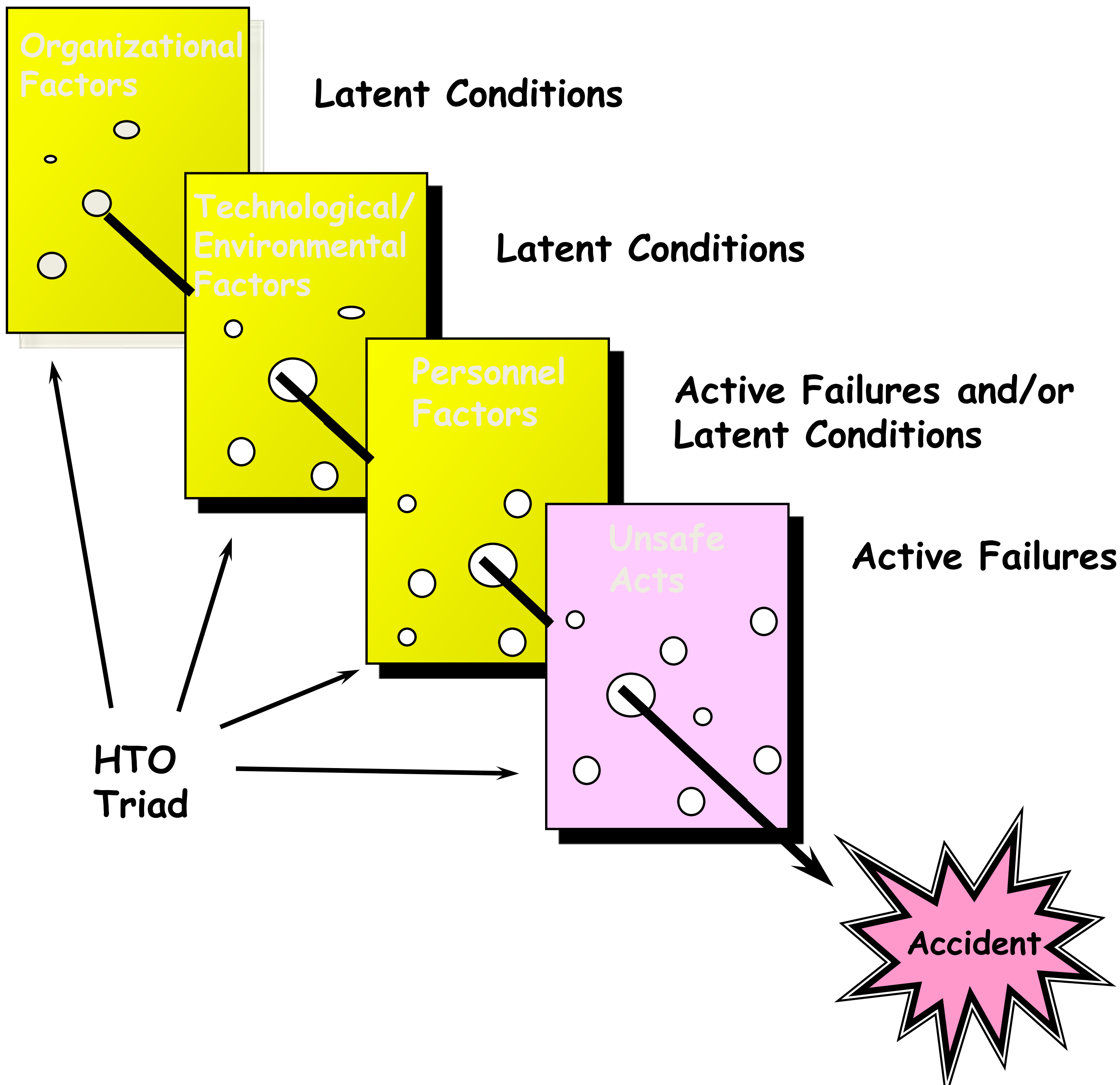
HTO Perspective





Regulation

Accident Causation from an HTO Perspective



Weaknesses in HTO Elements

Element of HTO	Weakness in HTO Elements as Revealed by the Fukushima Accident	Remarks on Global Status
H	o Inappropriate definition of design basis o Improper analysis of plant risk (e.g., underestimation of external events risk, less emphasis on concurrent events and site risk)	Globally was the case prior to the Fukushima accident
T	o Lack of sufficient equipment to cope with extreme events simultaneously affecting the whole site o Lack of plant emergency guidelines for extreme site events (e.g., as caused by natural disasters)	Globally was the case except the US where post 9/11 mitigative measures are already in place (e.g., Extensive Damage Mitigation Guidelines, portable pumps)
O	o Lack of emergency management capability for multiunit events	Globally was the case prior to the Fukushima accident except the US wherethe emergency management capability has been considerably enhanced since the 9/11 terrorist attack

US Response to Fukushima Event

- Carried out Special Inspection of All 104 Reactor Units in May
  - Assessed licensee's capability to mitigate conditions that result from beyond design basis events
  - Testing of active and passive equipment specifically designated for B.5.b (i.e., post-9/11 mitigative measures) or SAMG (Severe Accident Management Guidelines) mitigation such as the portable B.5.b diesel driven pump, B.5.b auxiliary equipment such as adapters and hoses, and the site fire engine
  - Verified that procedures are in place and can be executed (e.g., walkdowns, demonstrations, tests, etc.); adequacy of training and qualifications of operators and support staff
  - Inspection reports for each unit publicly available
- Near-Term (i.e., 90-Day) and Longer-Term NRC Task Forces
  - 34 recommendations; 12 orders, 7 proposed rules, 15 NRC staff and long-term recommendations

PRA Implication: Modeling Issues

– Multi-Module Risk
  - ➢ Hard dependencies
    - ✧ Common initiating events / shared SSCs
    - ✧ Shared instrumentation, control, other cables, electric divisions
    - ✧ Shared systems (e.g., FPS)
    - ✧ Capacity of shared equipment (e.g., batteries)

PRA Implication: Modeling Issues (Cont.)

- Multi-Module Risk (Cont.)

- Soft Dependencies
  - Human/organizational Pre-imitating event dependencies
  - Post accident human actions (operators, fire brigade, etc.
  - Common environments (caused by)
    - Natural events
    - Internal events (e.g., SBO)
    - Internal events external to the system (e.g., Fire)
    - Accident-induced dependencies (for example hydrogen explosion at Unit 3 of Fukushima disabled fire pumps used for seawater injection at Unit 2. Also, fire/explosion at Unit 4 was caused by leakage of hydrogen released from Unit 3 through shared duct-work with Unit 4)

PRA Implication: Modeling Issues (Cont.)

- Severe accident phenomena
  - Relevance of severe accident phenomena
    - H generation / explosions
    - Containment failure modes
    - Integrity of instrumentations
- Long-term cooling
  - Capacity of heat sinks (24 hr, 72 hr, or longer accidents)
  - Conditions necessary to maintain long-term cooling

PRA Implication: Modeling Issues (Cont.)

- HRA
  - Multi-Unit control room crew dynamics
  - Errors of commission
  - Recovery actions / accessibility
- External events
  - Consideration of seismic hazard
  - Fragilities of integrated structures
  - Combined external initiators
- Spent fuel pool considerations
  - Interplay with the operating modules

PRA Implication: Policy / Regulatory Issues

- CDF of site more appropriate
- LERF vs. LRF
- Method for SSC classification
  - RAW/FV measures
  - F-C curves

Concluding Remarks

- Traditional PRA methods should be improved
- More research needed to develop models
- Reliability tests may be necessary to develop fragility data
- New standards, regulatory guidance needed