An overview of what happened at Fukushima NPPs

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2011 PEER Annual Meeting
Hotel Shattuck Berkeley

October 1, 2011

Millstone Unit 1, March 28, 2011

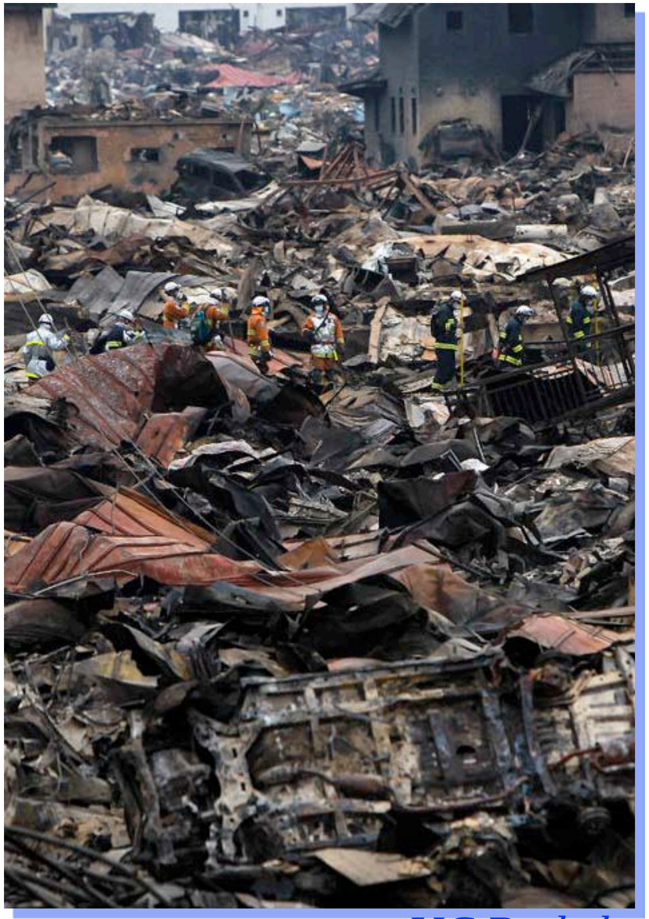
Overview: Lessons from the Fukushima Accident

- **Fukushima—what happened?**
- **Lessons for nuclear safety regulation**
  - **U.S. NRC 90-day Task Force Report (12 recommendations)**
  - **Additional Report of the Japanese Government to the IAEA (28 lessons)**
  - **Defense in depth**
    - » **Station blackout and coping time**
    - » **Extensive damage mitigation guidelines (EDMGs)**
    - » **Severe accident management guidelines (SAMGs)**
  - **Delegation of responsibility and authority for decision making during reactor accidents**
- **What will happen for future reactors? (separate talk)**

The accident at Fukushima Daiichi

The Fukushima: What Happened?

- **Previous major reactor accidents have resulted from combinations of equipment failures and human error**
  - **TMI and Chernobyl**
  - **Improvement in human and equipment reliability have greatly reduced the risk of internally initiated accidents**
- **Fukushima is the first major reactor accident to be caused by a severe external event**
  - **Beyond design basis (BDB) event (although should have been in the design basis)**
    - **NRC 90-day report recommends that U.S. reactors update natural hazard assessments every 10 years**
  - **Defense in depth measures are key to mitigating consequences**



March 11, 2011 Sendai Earthquake and Tsunami

- **2:46 pm magnitude 9.0 earthquake**
  - **Offsite power lost, diesel generators start, plant shuts down safely**
  - **One worker severely injured, subsequently died**
- **3:41 pm 15.0-m (49 ft) tsunami reaches Fukushima nuclear plant**
  - **Disables diesel generators, sea water intake structures, fresh water supplies, inundates electrical equipment inside plant, and severely damages external electrical switchgear**
  - **Two workers die in turbine building from injuries due to tsunami**
- **Additional impacts from earthquake and tsunami**
  - **Over 25,000 people dead or missing (but Japanese tsunami warning system saved a much larger number of lives)**
  - **Total damages estimated to exceed $300 billion**

Additional Report of the Japanese Government to the IAEA (Second Report)

- **"There is a high probability that the recent earthquake was an earthquake of M9 in terms of long-period ground motions, yet had the same time characteristics of an earthquake of M8 in terms of short-period ground motions.**
- **"It is likely that those factors that had a great impact on the tsunami water level include the large slip noted above and the overlap effects of the tsunami water level due to a delay in rupture start time associated with consecutive rupturing of multiple seismic source areas."**
- **"[I]t can be estimated that the major facilities and equipment that had key functions with regard to safety were, at the time of the earthquake and immediately afterwards, at a status at which safety functions could be maintained."**
- **"[T]he inundation pathway leading to the main buildings was mainly the opening on the ground on the sea side of the turbine building and the opening connecting the trench duct to the ground."**

http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html

Loss of backup cooling systems occurred in Units 1-3

- **Unit 1**
  - March 11, 16:36, batteries exhausted (no longer able to make up water to isolation condenser)
  - March 12, 04:00, initial venting of containment
  - March 12, 15:36, hydrogen explosion
  - March 12, 20:20, begin injection of seawater into reactor vessel using fire truck (27 hours without cooling)
- **Unit 2**
  - March 14, 13:25, steam turbine driven injection pump fails
  - March 14, 20:33, begin injection of seawater into reactor using fire truck (7 hours without cooling)
  - March 14, 20:35, further venting of containment (first venting March 13)
  - March 15, 06:20, hydrogen explosion low in the reactor building
- **Unit 3**
  - March 13, 02:44, batteries exhausted, turbine driven pump valves close
  - March 13, 09:38, begin injection of seawater into reactor using fire truck (7 hours without cooling)
  - March 13, 08:41, initial venting of containment
  - March 14, 11:00, hydrogen explosion

Unit 4 spent fuel pool and building also sustained damage

Fukushima Dai-ichi Nuclear Power Plant

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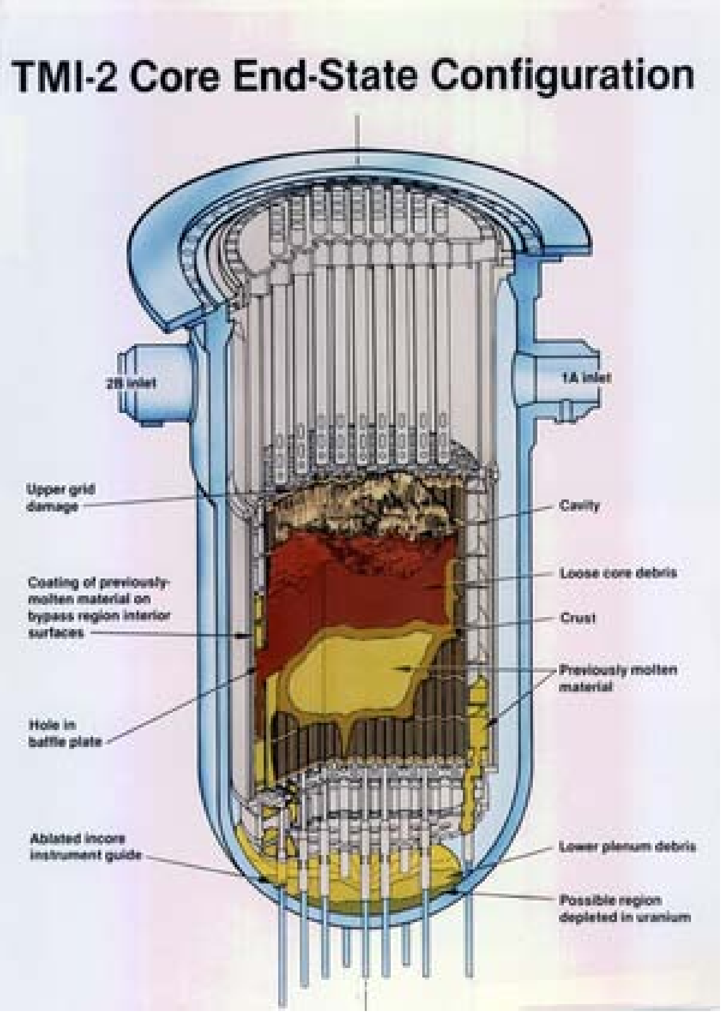
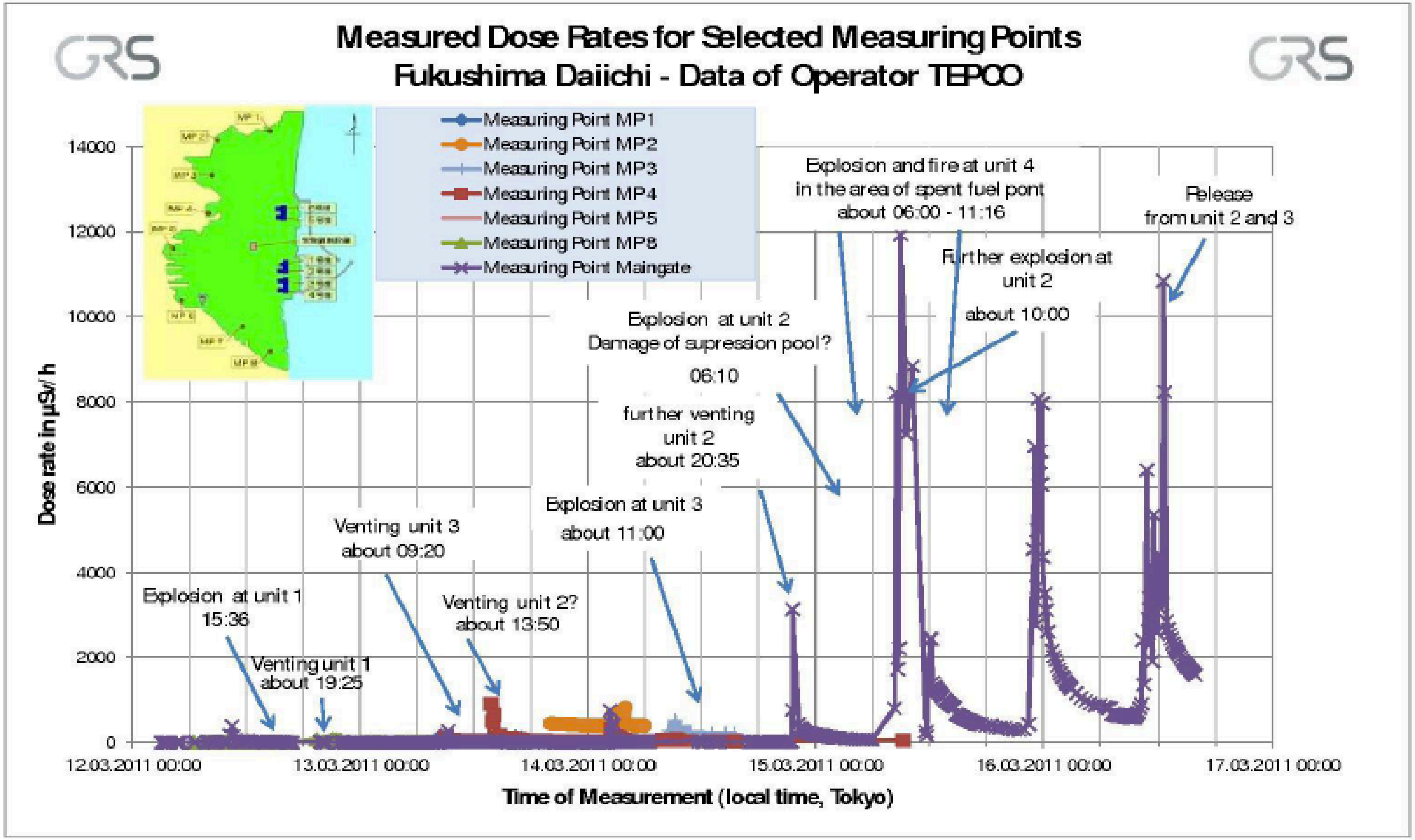
Source: OECD Nuclear Energy Agency

LWR fuel releases hydrogen and fission products when overheated

- **Zirconium cladding reaction with steam to produce hydrogen becomes substantial at temperatures above 1000°C**
- **Volatile fission products released as noble gases (e.g. Kr) or aerosols (e.g. I, Cs)**
- **Fuel pellets melt at 2600°C**



Radiation release chronology – Fukushima Dai-ichi



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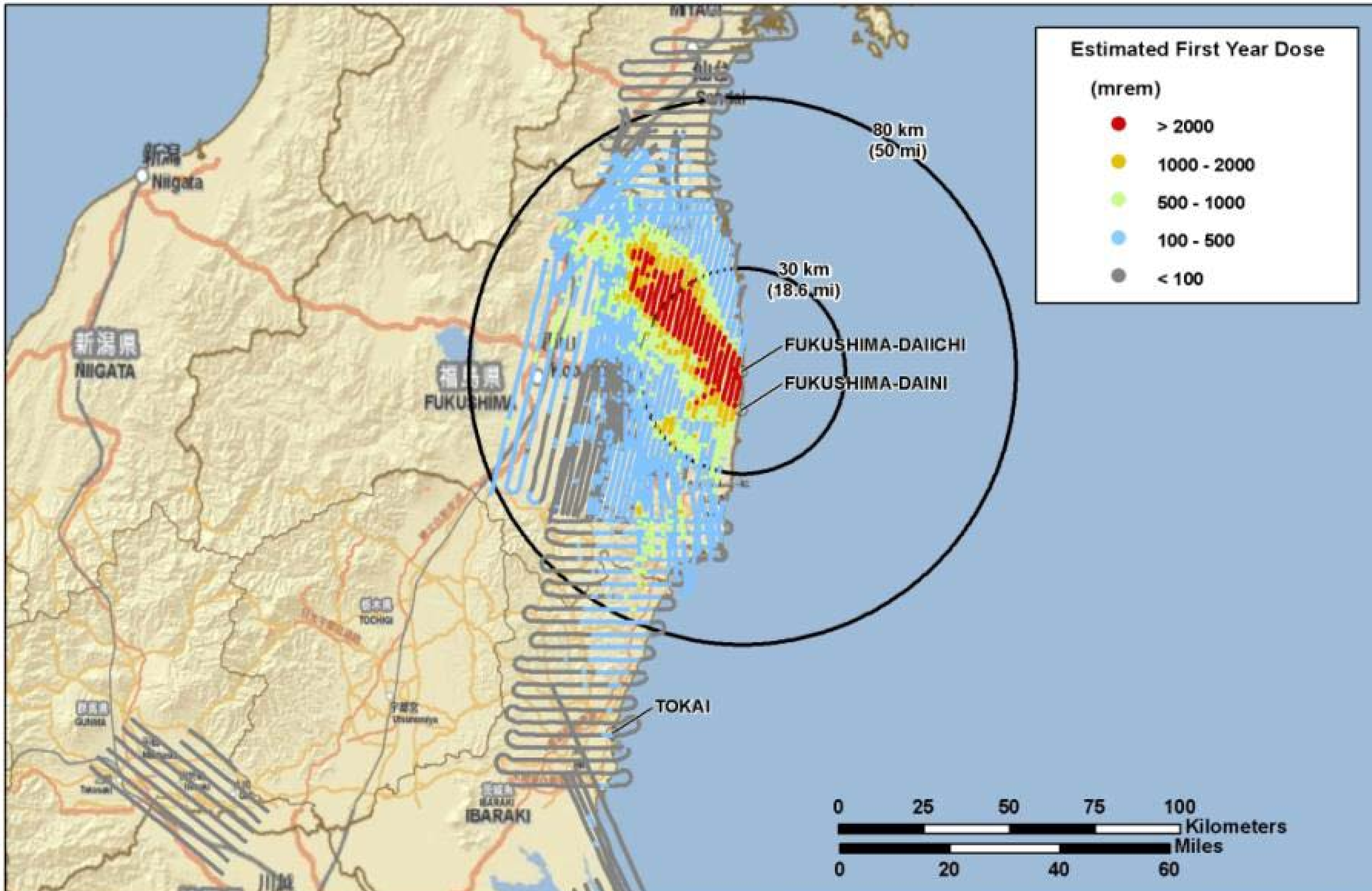
Source: OECD Nuclear Energy Agency

NNSA National Nuclear Security Administration

First-Year Dose Estimate

Dose Commencing March 16, 2011 for 365 Days

FUKUSHIMA DAIICHI
JAPAN



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Lessons for U.S. reactor safety (highlights)

- **Periodic review of natural hazards for nuclear plants (update every 10 years)**
- **Responsibility and authority to depart from procedures and enter into guidelines must be delegated at the plant level**
  - **10 CFR 50.54(x) gives licensees legal authority to depart from procedures in an emergency, when they judge such action is needed to protect the public health and safety**
- **U.S. Extensive Damage Mitigation Guidelines (EDMGs) can be strengthened further**
  - **Value of preparation and capability to connect portable pumps and power supplies clearly demonstrated**
  - **Current level of U.S. plant preparation to implement EDMGs is nonuniform**
- **Diverse lessons for extensive damage mitigation, severe accident management and emergency response (NRC 90-day report)**

Spent fuel storage safety

- **Fukushima has reactor spent fuel pools (inside secondary containment, with high density racking), a centralized pool (similar to PWR pools), and dry cask storage**
- **The centralized storage pool and dry cask storage performed well**
- **Currently, it appears that no damage occurred to spent fuel stored in the reactor pools**
  - **Pool water radioactivity levels are too low to be consistent with significant fuel damage**
  - **The largest problems were associated with difficulty for operator access during the accident and lack of wide-range water level instrumentation**
    - » **Lack of the level measurements created large uncertainties about pool water inventories and greatly complicated emergency response decision making**

Three major policy questions arise from the Sendai tsunami and the nuclear accident at Fukushima

- **How should the nuclear accident at Fukushima affect our policies for existing reactors?**
  - **Policies for regulating safety (e.g., lessons learned)**
  - **Policies for license renewal (e.g., should existing nuclear plants be shut down before, or after, existing coal plants?)**
- **Are the new, Generation III and/or IV reactor designs sufficiently safe to be built, considering lessons learned from the Fukushima accident?**
- **Are there broader lessons for protecting public health and safety?**
  - **The Japanese tsunami early warning system saved many lives**
    - » **compare the 2004 Sumatra tsunami, 230,000 fatalities, with Sendai ~28,000**
  - **The U.S. west coast from northern California to Alaska has thrust faults that can generate similar tsunamis**

Lessons from Fukushima can be expected to affect utility preferences for new reactor technologies

- **Increased preference toward passive/hybrid safety systems**
  - **Capability to provide long-term decay heat removal**
    - » **Without high-pressure water injection**
    - » **With low electrical power requirements**
  - **AP-1000, ESBWR, NuScale, mPower**
- **Increased preference for advanced seismic and structural design**
  - **Steel/concrete composite construction (AP-1000)**
  - **Seismic isolation (NuScale)**
- **Implications for Generation IV reactors:**
  - **Small modular reactors must develop clear explanation of safety approach for multi-module plants**
  - **Potential for enhanced safety using ceramic core structural materials**
    - » **Large margins to thermal damage**
    - » **Typically thermal-spectrum reactors**