

The Fukushima Nuclear Disaster Implications for Nuclear Power Safety

Thomas B. Cochran and Matthew G. McKinzie
Natural Resources Defense Council, Inc. (NRDC)

International Workshop on Nuclear Energy Safety:
Improving Safety in the Aftermath of the Fukushima Crisis

Beijing, China

June 29-30, 2011



What Happened at Fukushima

Some slides taken from:

*U.S. National Academy of Sciences
Washington D.C.*

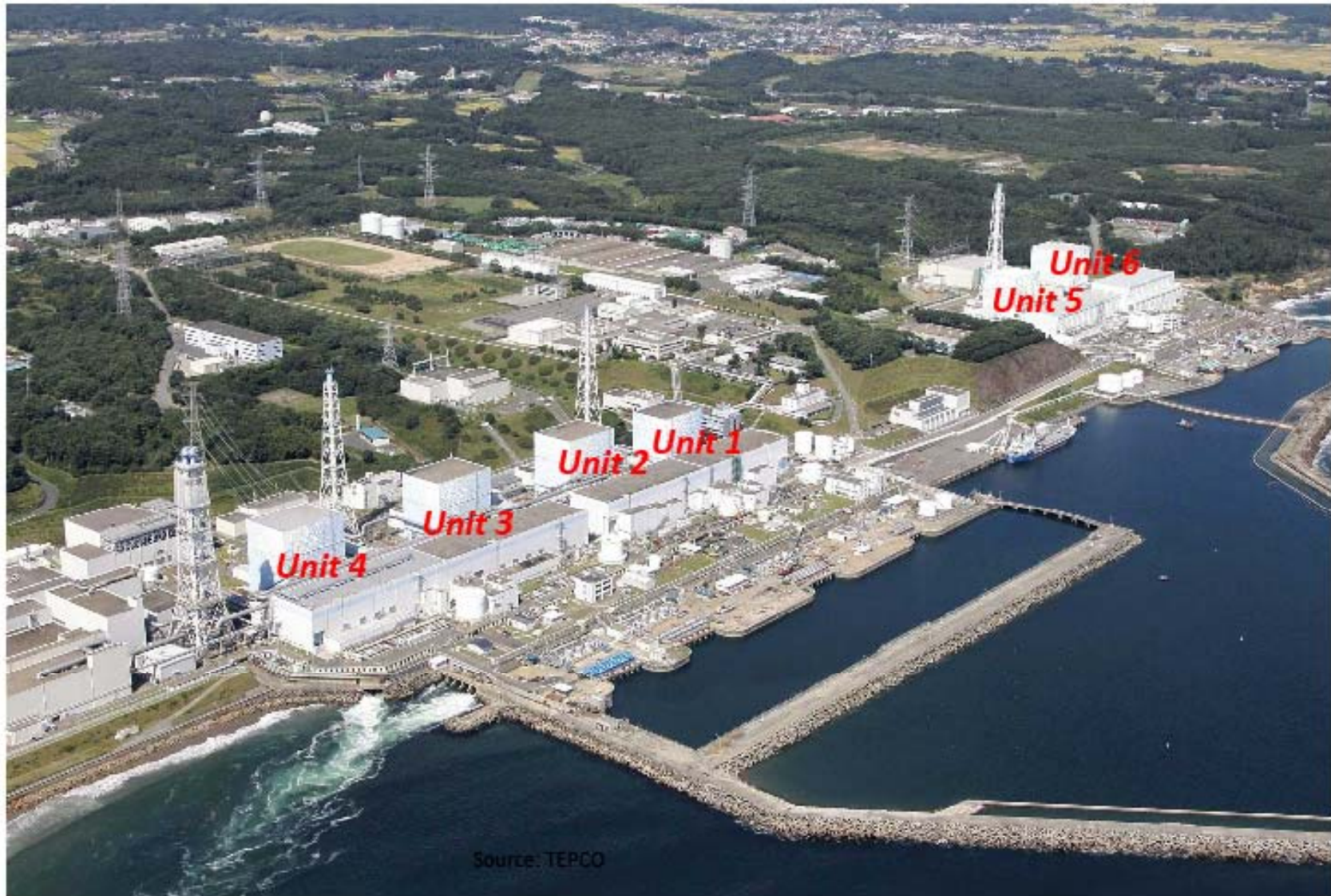
Overview of the Accident in Fukushima Daiichi Nuclear Power Plants

May 26, 2011

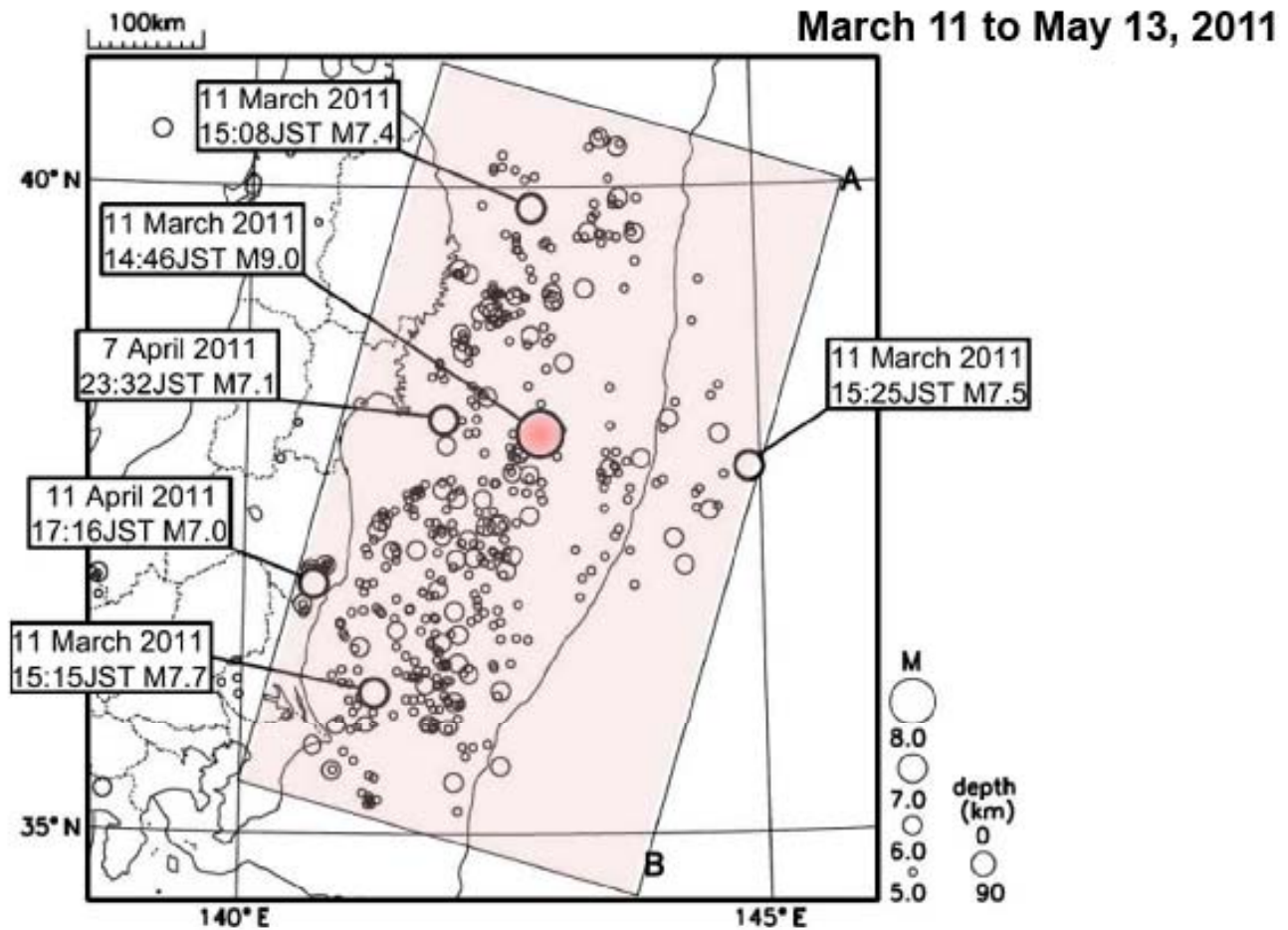
Naoto Sekimura, Prof. Dr.,

***Vice Dean, School of Engineering, The University of Tokyo
Associate Member of Science Council of Japan***

Fukushima Daiichi Nuclear Power Plants operated by TEPCO



The Main Shock and Aftershock of the Earthquake on 2011.3.11

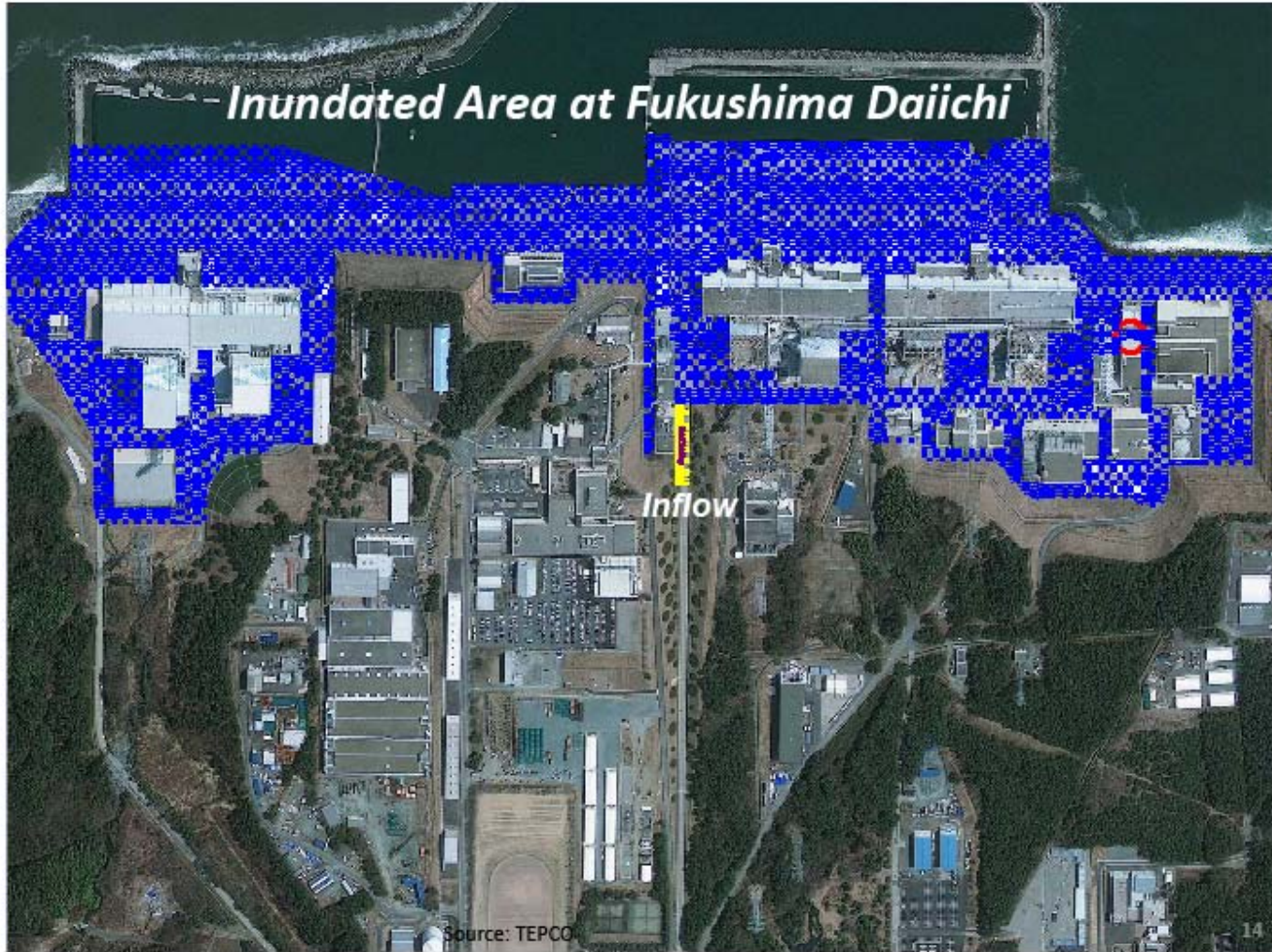


Recorded Intensity of Ground Motion and Basic Earthquake Ground Motion

		Observed Maximum Response Acceleration * (Gal)			Max Response Acceleration against Basic Earthquake Ground Motion (Gal), Ss		
		Horizontal (N-S)	Horizontal (E-W)	Vertical	Horizontal (N-S)	Horizontal (E-W)	Vertical
Fukushima Daiichi	Unit 1	460	447	258	487	489	412
	Unit 2	348	550	302	441	438	420
	Unit 3	322	507	231	449	441	429
	Unit 4	281	319	200	447	445	422
	Unit 5	311	548	256	452	452	427
	Unit 6	298	444	244	445	448	415
Fukushima Daini	Unit 1	254	230	305	434	434	512
	Unit 2	243	196	232	428	429	504
	Unit 3	277	216	208	428	430	504
	Unit 4	210	205	288	415	415	504

* At the lowest basement of reactor building

Inundated Area at Fukushima Daiichi



Source: TEPCO

Tsunami, March 11, 2011

15:42:40



15:42:46



15:43:26



15:43:36



15:43:54



15:44:18



15:44:44



15:44:58



15:46:10

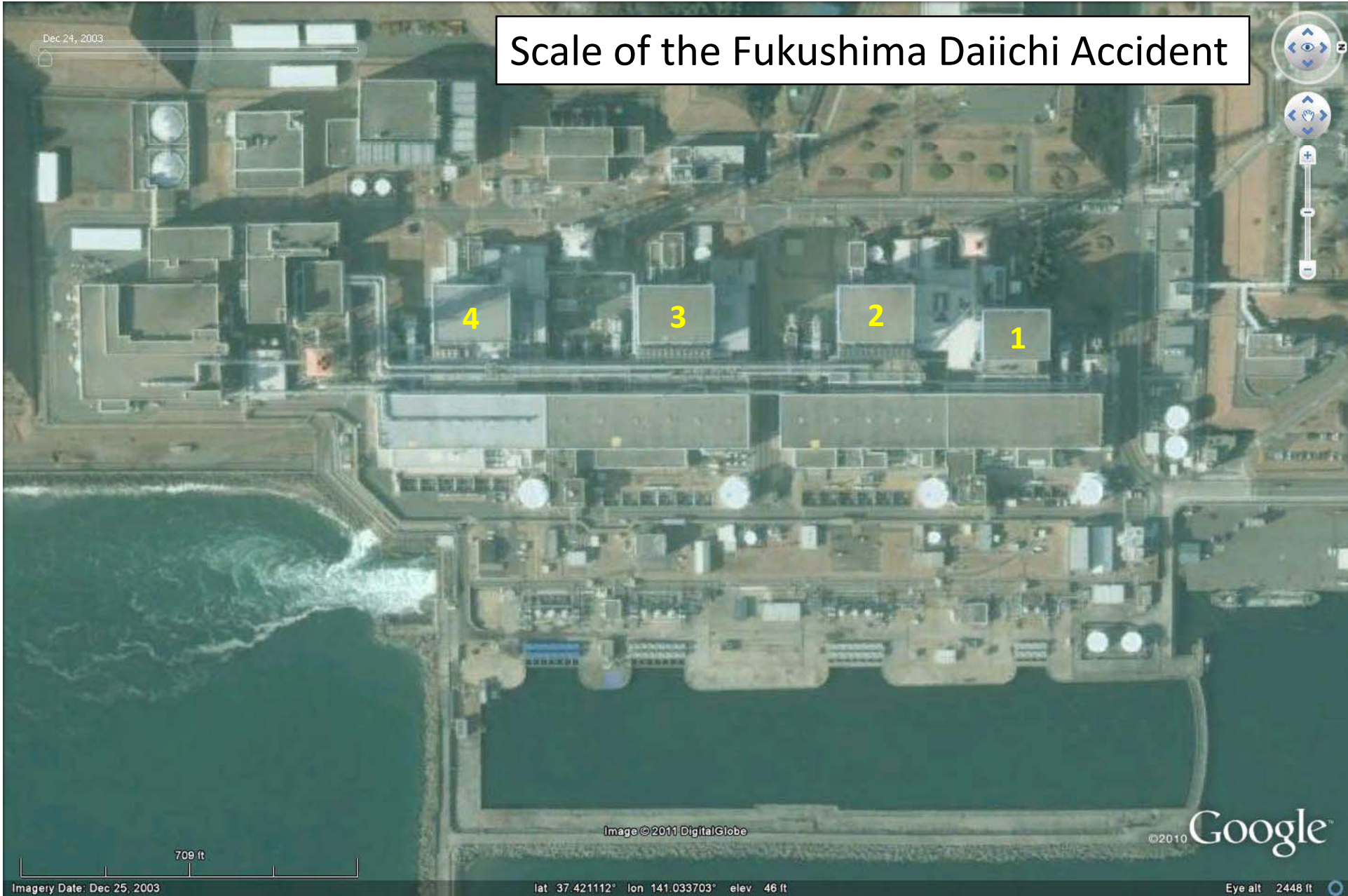


15.5 m from
the sea level



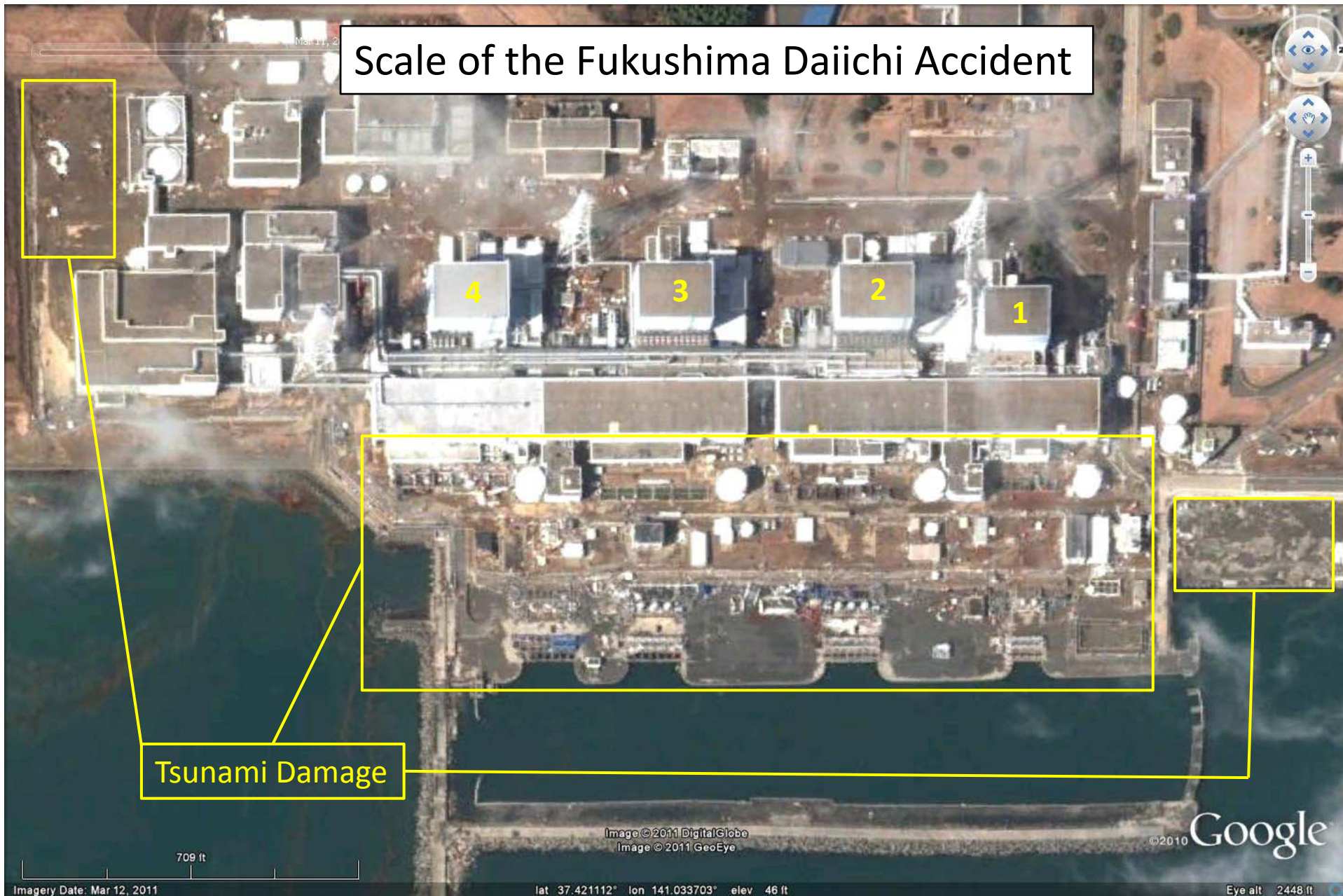
Tsunami height in Fukushima Daiichi was about 15 m.

Scale of the Fukushima Daiichi Accident



Satellite image of Fukushima Daiichi, photographed about seven years before the 2011 earthquake and tsunami.

Scale of the Fukushima Daiichi Accident



Satellite image of Fukushima Daiichi, photographed after the earthquake and tsunami, during station blackout, but before explosions and fires.

Station Black-Out in Units 1-4 - Loss of Off-Site Power Supply and EDG -

Station Black-Out

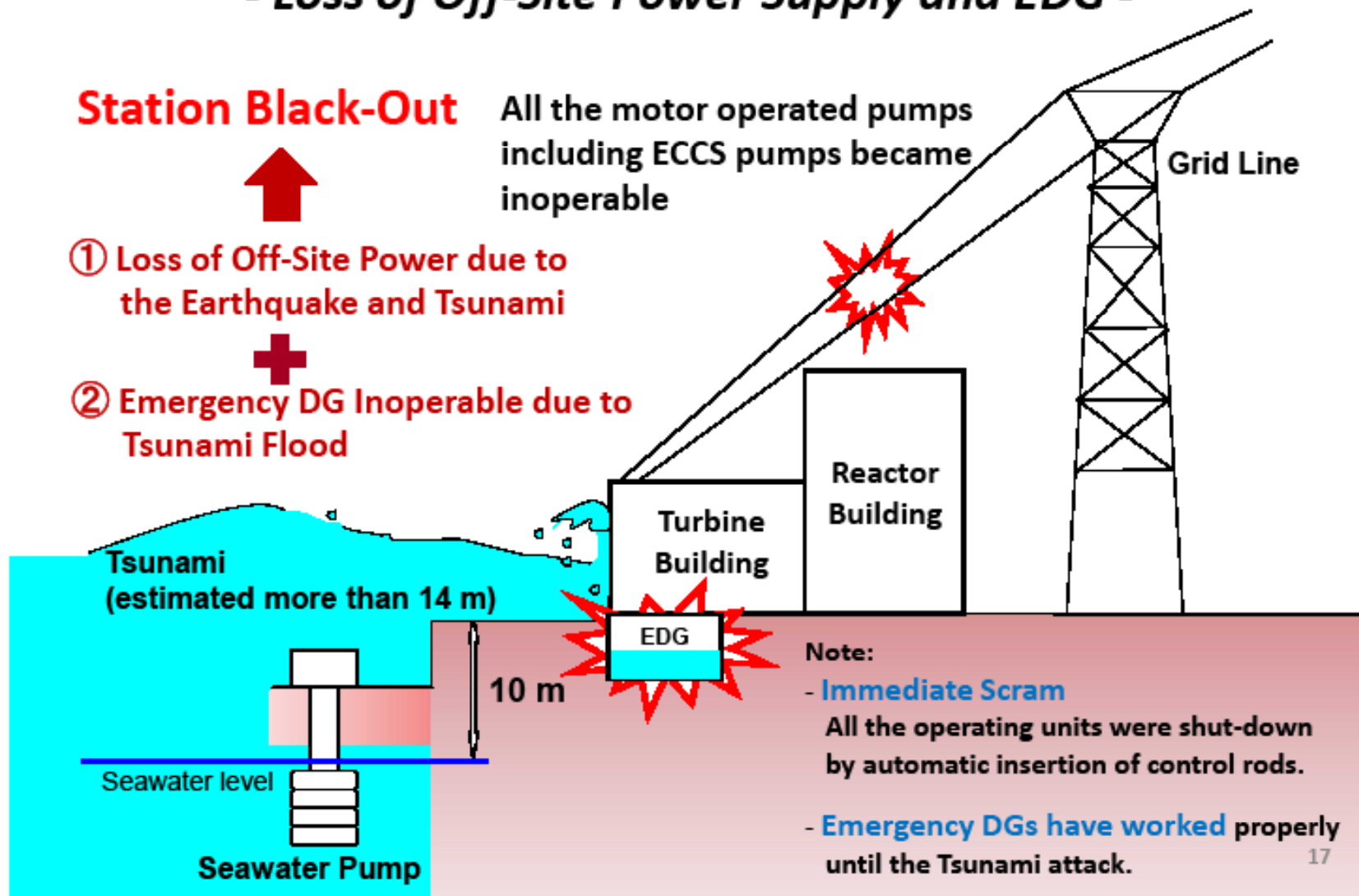
All the motor operated pumps including ECCS pumps became inoperable



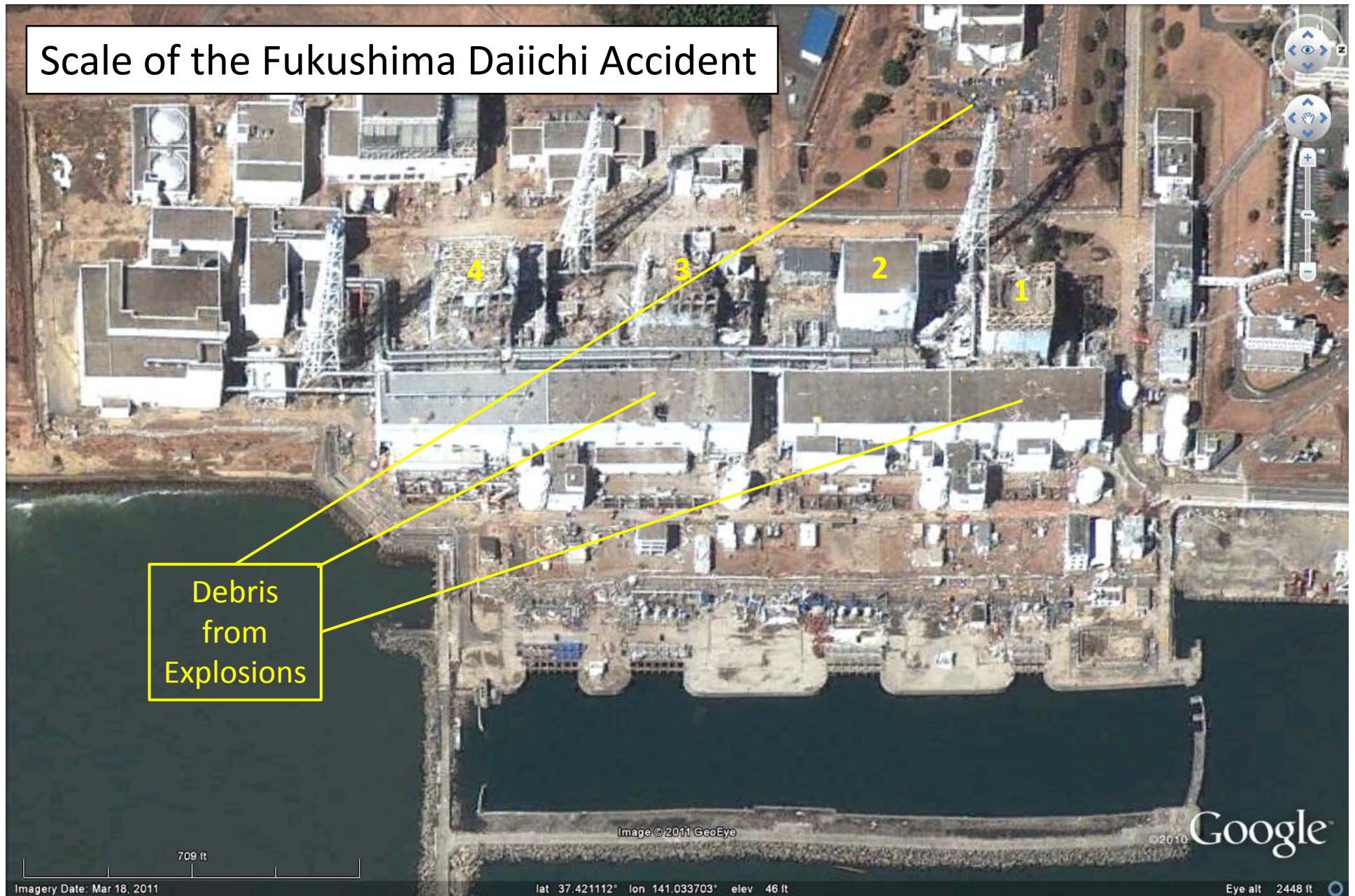
① Loss of Off-Site Power due to the Earthquake and Tsunami



② Emergency DG Inoperable due to Tsunami Flood



Scale of the Fukushima Daiichi Accident



Satellite image of Fukushima Daiichi, photographed after the major sequence of explosions and fires in Units 1, 2, 3 and 4.

Categories of Lessons from Fukushima

- A. Accident initiators
- B. Compliance with safety goals
- C. Reactor systems to cope with severe accidents
- D. Spent fuel pool issues
- E. Adequacy of the responses to severe accidents
- F. Adequacy of radiation monitoring
- G. Adequacy of the emergency responses
- H. Robustness of the safety infrastructure established at the nuclear power station
- I. Safety culture

A. Accident initiators

1. Strengthen measures to protect against:

a. natural external hazards:

earthquakes

tsunamis

hurricanes and typhoons

tornadoes

floods

the implications of predicted sea-level rise and increased storm surges
due to climate change.

b. on-site hazards:

fires

c. malevolent acts:

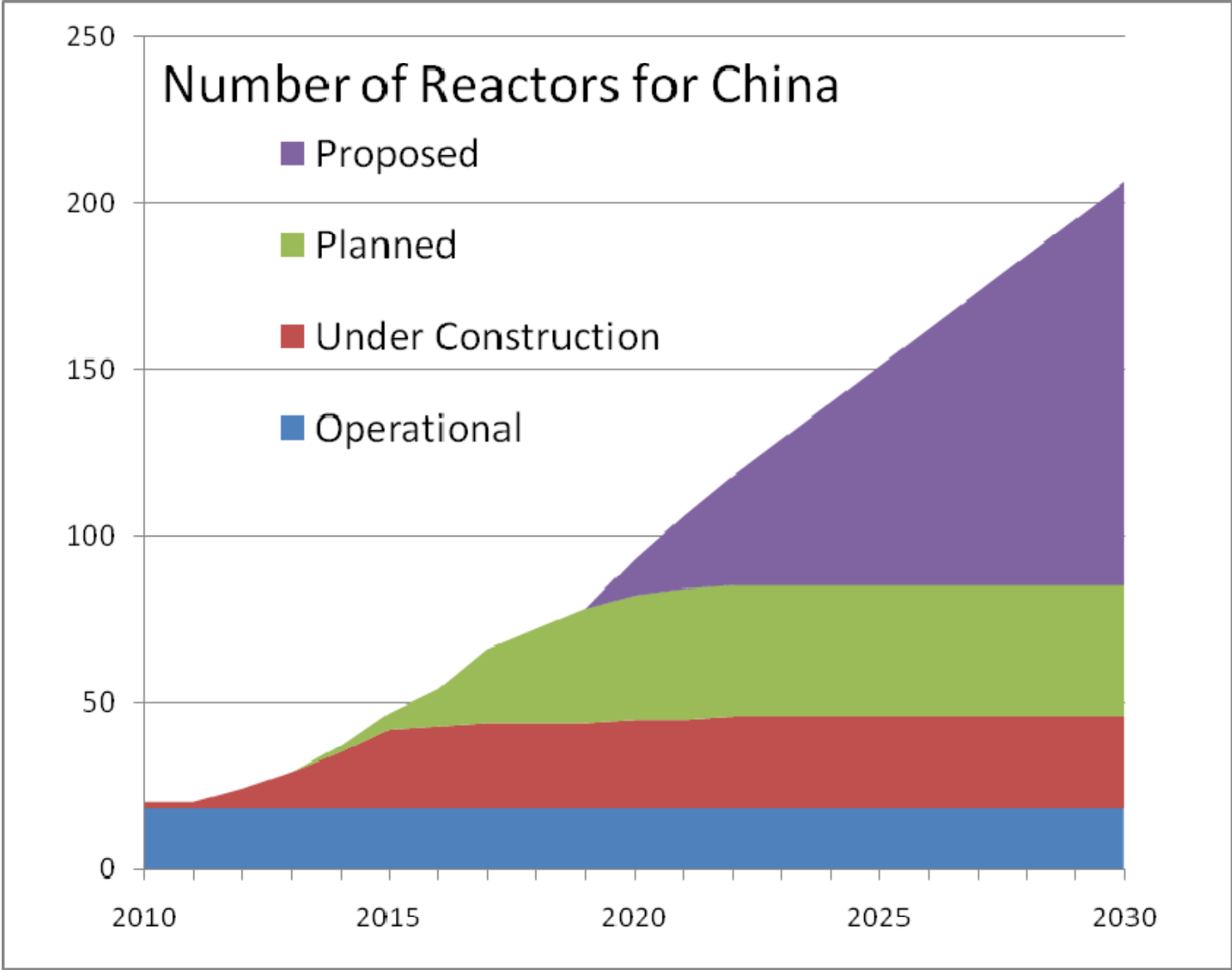
terrorist attacks

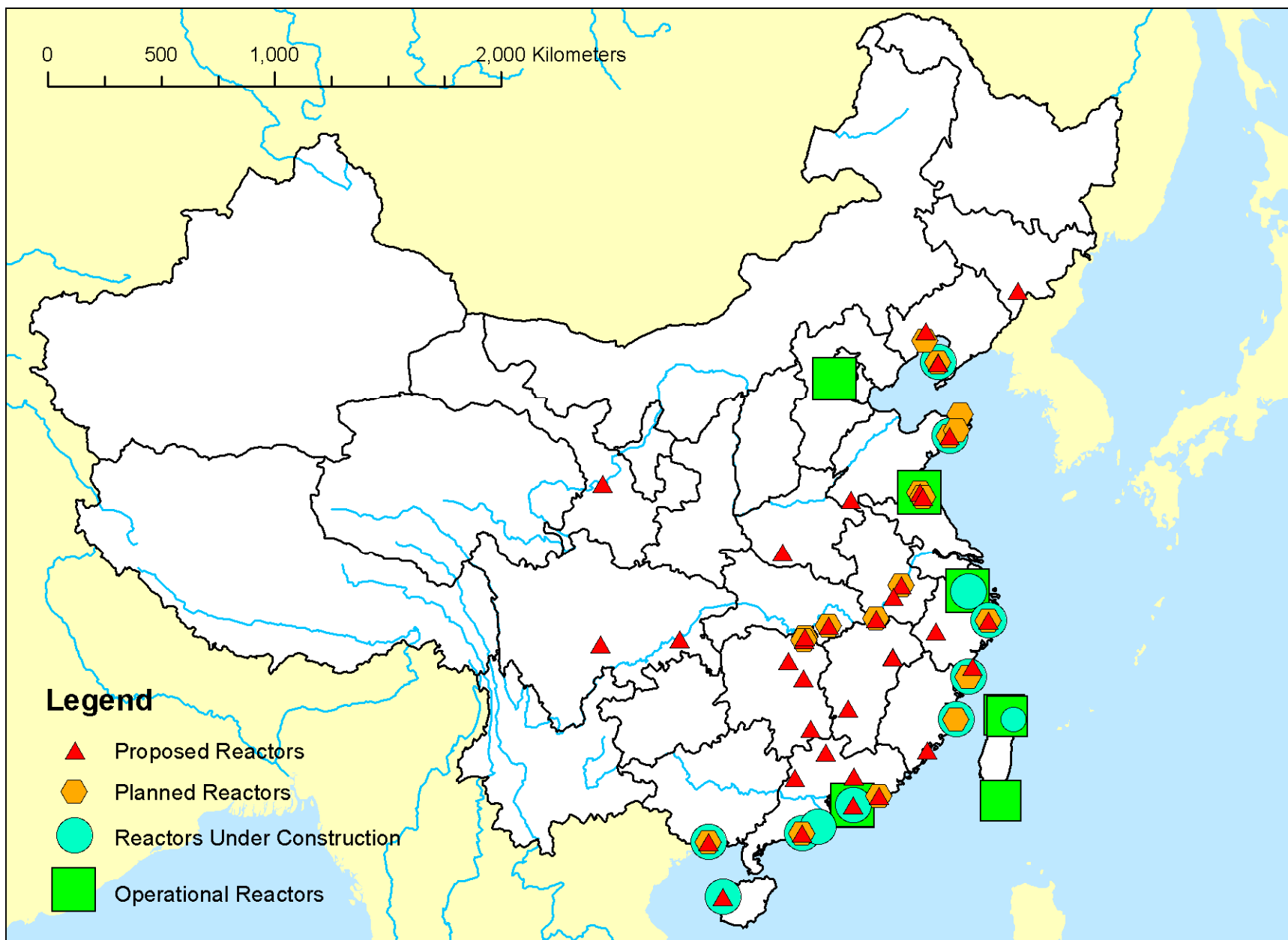
insider threats

2. Need to periodically review of the magnitude and potential consequences
of accident initiators.

3. Need to improve warning systems for tsunamis and tornadoes.

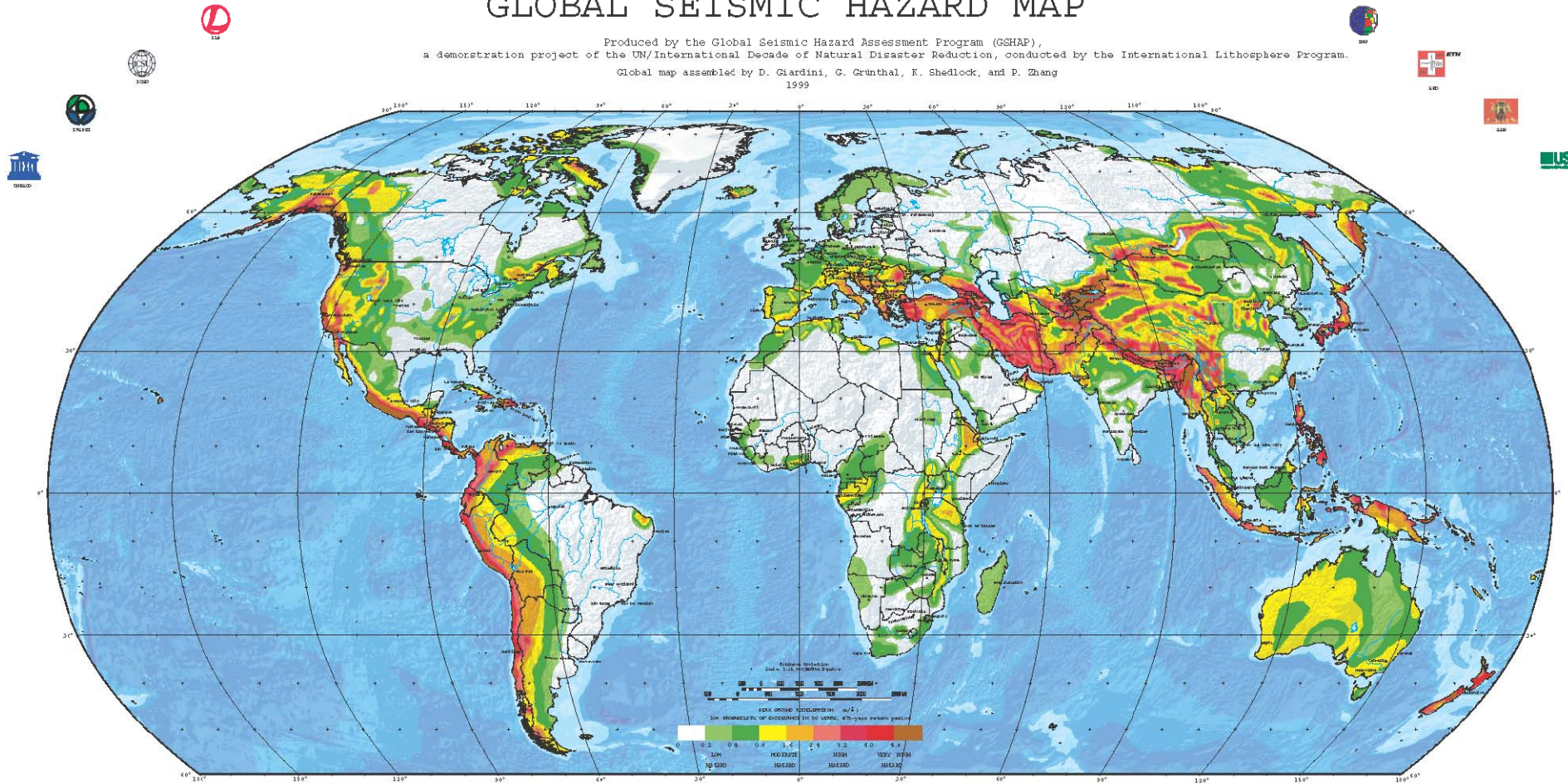






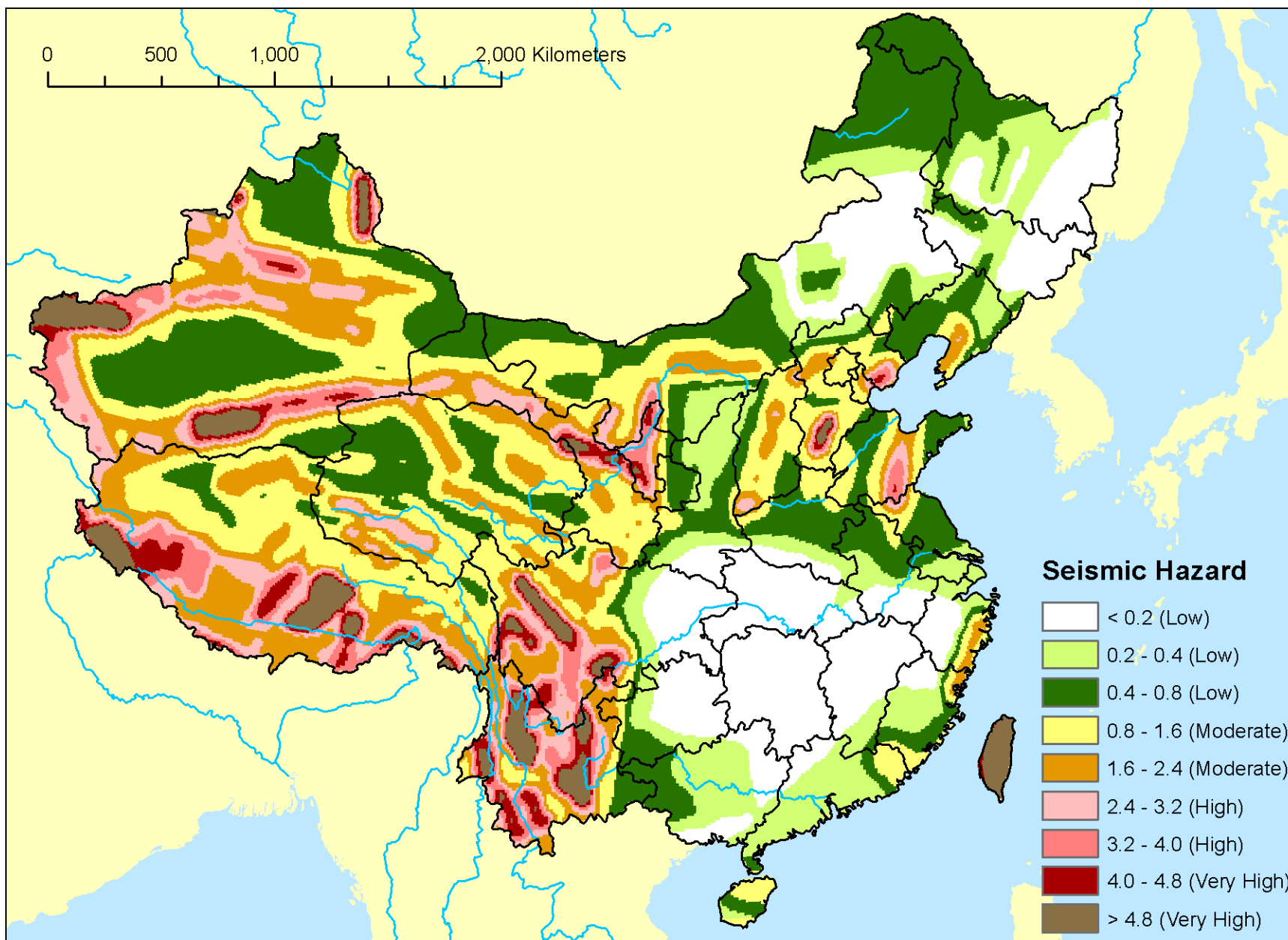
GLOBAL SEISMIC HAZARD MAP

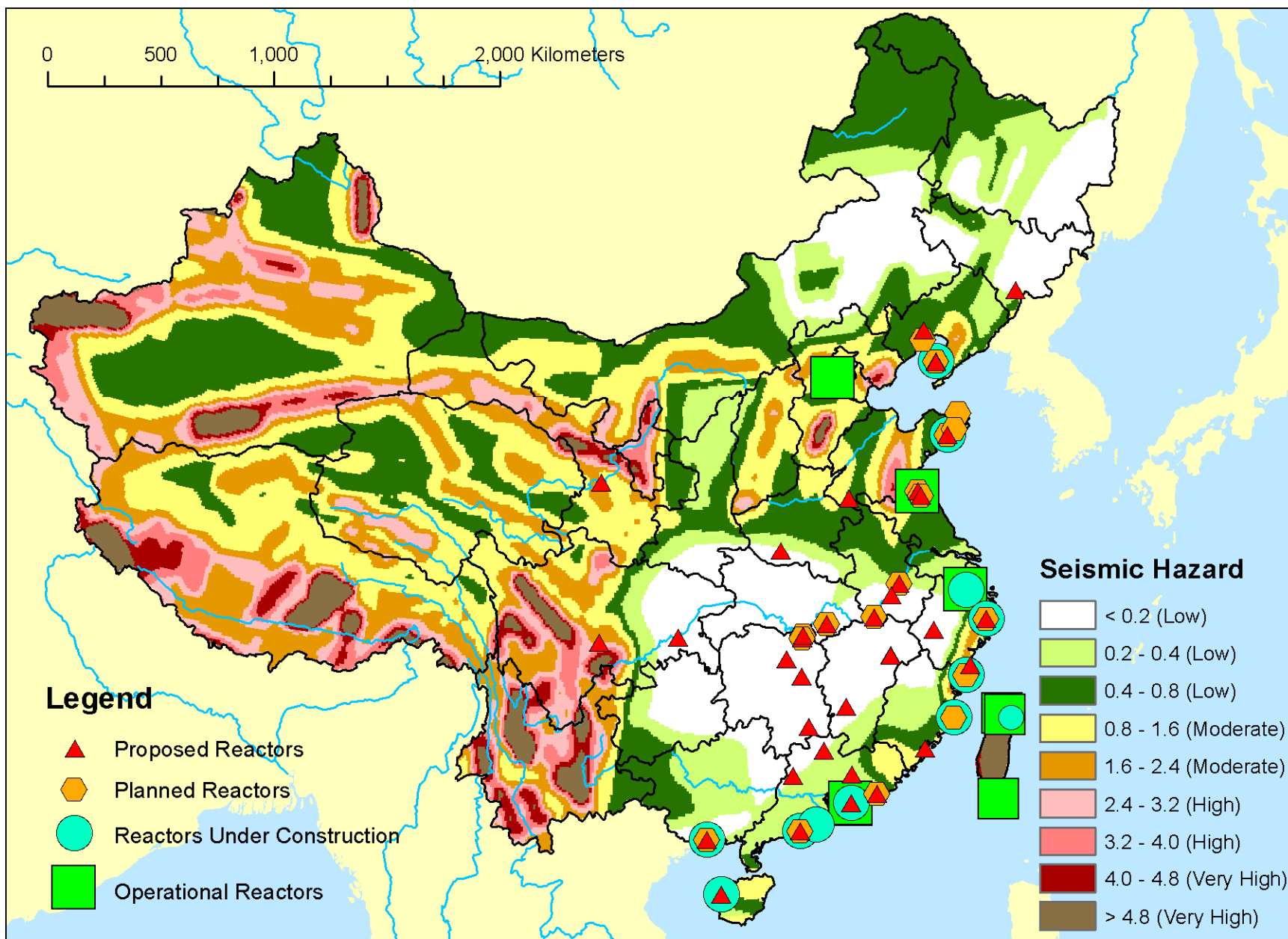
Produced by the Global Seismic Hazard Assessment Program (GSHAP),
a demonstration project of the UN/International Decade of Natural Disaster Reduction, conducted by the International Lithosphere Program.
Global map assembled by D. Giardini, G. Grünthal, K. Shedlock, and P. Zhang
1999

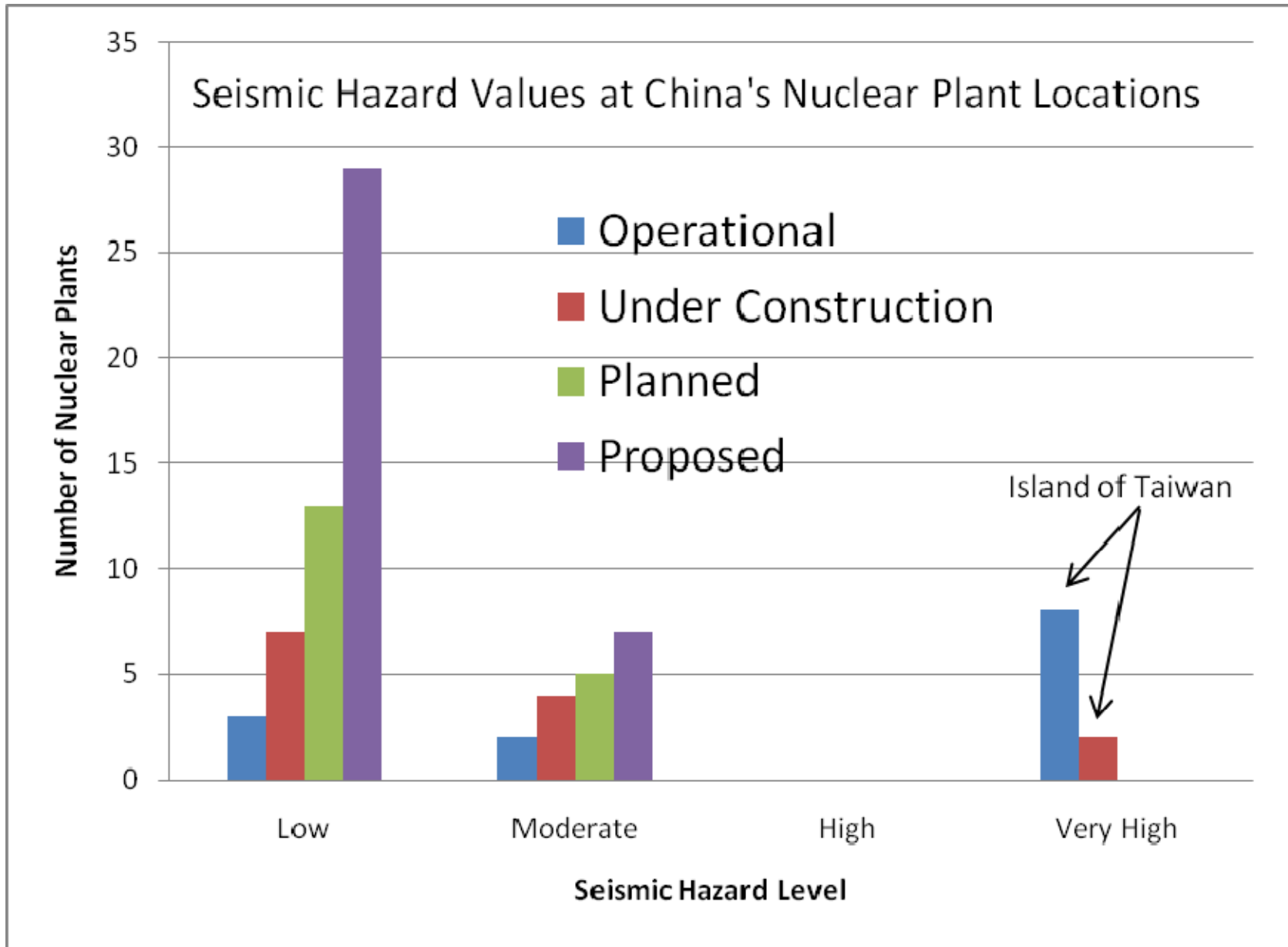


Peak Acceleration (m/s^2) with 10% Probability of Exceedance in 50 Years

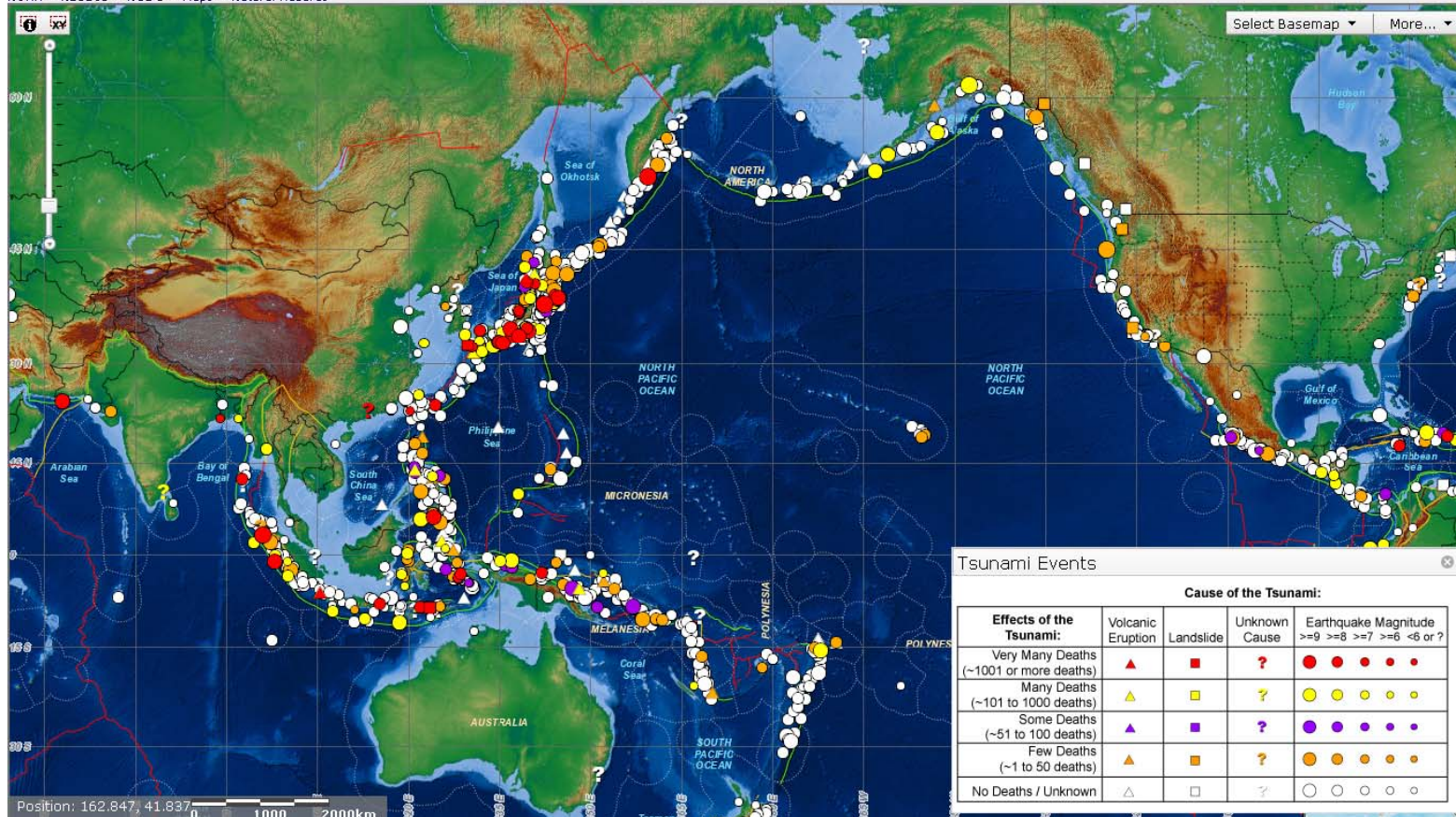
<http://www.seismo.ethz.ch/static/GSHAP/global/>







NOAA > NESDIS > NGDC > Maps > Natural Hazards



Layers

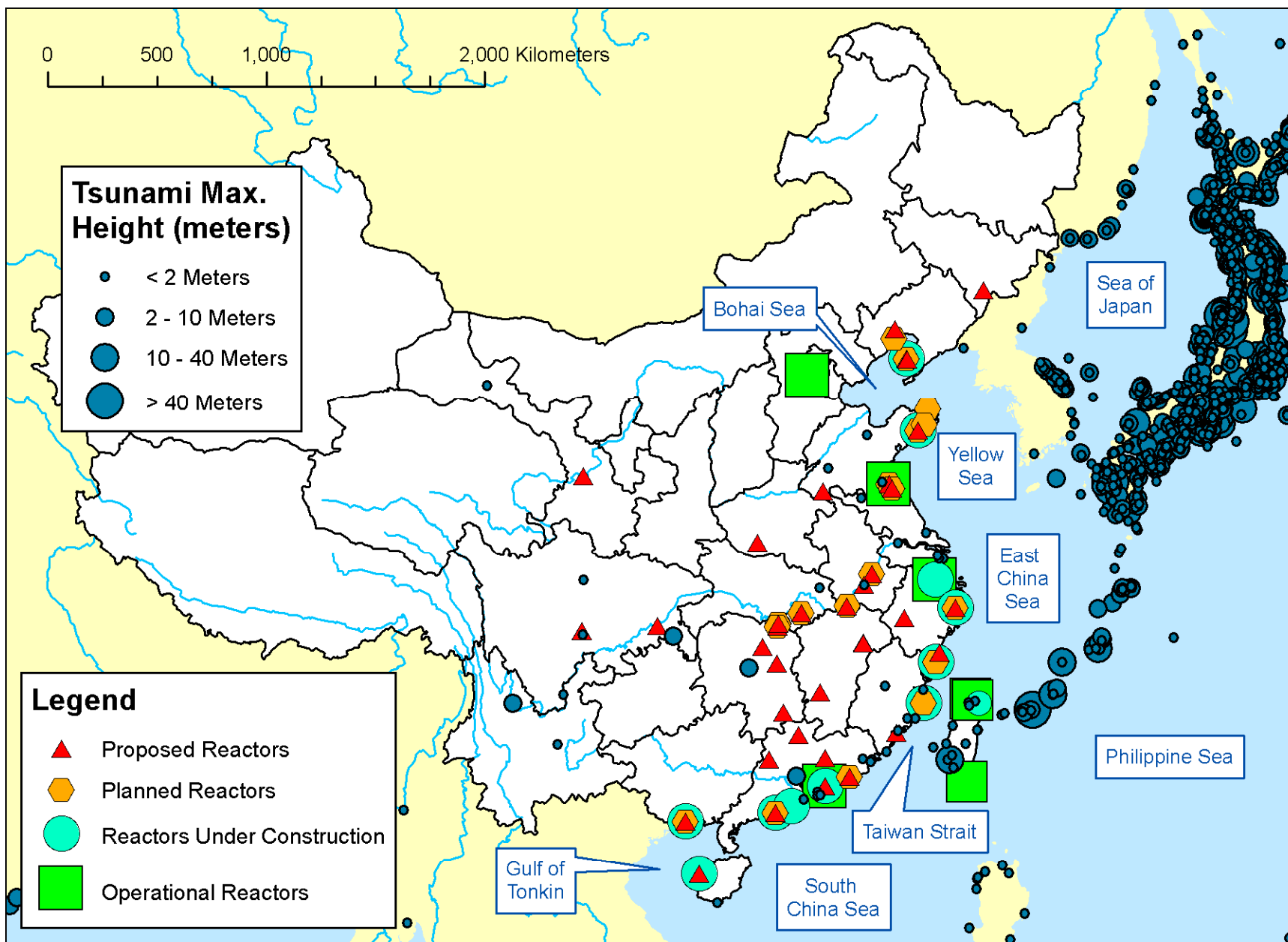
- Tsunami Events**
 Search [Reset]
 Show as:
 Symbols for Cause/Fatalities (Legend)
 Green Squares
- Tsunami Observations**
 Search [Reset]
 Show as:
 Vertical Bars for Water Height (Legend)
 Color-Coded by Measurement Type (Legend)
- Significant Earthquakes** (Legend)
 Search [Reset]
- Significant Volcanic Eruptions** ▲
 Search [Reset]
- DART Stations** (Legend)
 Search [Reset]
- NOS Tsunami Tide Gauges** ■

More Information
 Help

Tsunami Events

Effects of the Tsunami:	Cause of the Tsunami:			
	Volcanic Eruption	Landslide	Unknown Cause	Earthquake Magnitude
Very Many Deaths (~1001 or more deaths)	▲	■	?	>=9 >=8 >=7 >=6 <6 or ?
Many Deaths (~101 to 1000 deaths)	▲	■	?	>=9 >=8 >=7 >=6 <6 or ?
Some Deaths (~51 to 100 deaths)	▲	■	?	>=9 >=8 >=7 >=6 <6 or ?
Few Deaths (~1 to 50 deaths)	▲	■	?	>=9 >=8 >=7 >=6 <6 or ?
No Deaths / Unknown	△	□	?	○ ○ ○ ○ ○

<http://maps.ngdc.noaa.gov/viewers/hazards/>



B. Compliance with safety goals

- 1. Are reactors adequately safe?**
2. What accident scenarios should be within the design basis?
3. Are old reactor designs, e.g., GE BWRs with poorly designed Mark 1 and Mark 2 containments, with subsequent safety upgrades sufficiently safe to continue operation or have their licenses extended?

Reassessing the Frequency of Partial Core Melt Accidents

Worldwide, 12 nuclear power reactors have experienced fuel-damage or a partial core-melt accident:

- 1. The Sodium Reactor Experiment (SRE)**
- 2. Stationary Low-Power Reactor No. 1 (SL-1)**
- 3. Enrico Fermi Reactor-1**
- 4. Chapelcross-2**
- 5. St. Laurent A-1**
- 6. St. Laurent A-2**
- 7. Three Mile Island-2**
- 8. Chernobyl-4**
- 9. Greifswald-5**
- 10. Fukushima Daiichi-1**
- 11. Fukushima Daiichi-2**
- 12. Fukushima Daiichi-3**

Reassessing the Frequency of Partial Core Melt Accidents

Worldwide, there have been:

- 582 nuclear power reactors that have operated approximately 14,400 reactor-years.
- 115 BWRs that have operated approximately 3,100 reactor-years.
- 61 BWRs with Mark 1 and 2 containments that have operated for 1,900 reactor-years.
- 137 nuclear power plants that have been shut down after becoming operational

Reassessing the Frequency of Partial Core Melt Accidents

- 1 in 14 shutdown reactors experienced some form of fuel damage
- 1 in 23 were shut down as a direct consequence of fuel damage
- frequency of core-melt accidents is about one in 1,300 reactor-years
- frequency of core-melt accidents in BWRs is about one in 1,000 reactor-years
- frequency of core-melt accidents in BWRs with Mk 1 & 2 containments is about one in 630 reactor-years

C. Reactor systems to cope with severe accidents.

1. Secure AC power—offsite and emergency diesel generators and generator fuel
2. DC power—longevity of batteries
3. Ensuring the water tightness of essential equipment facilities.
4. For severe situations, such as total loss of off-site power or loss of all heat sinks or the engineering safety systems, simple alternative sources for these functions including any necessary equipment (such as mobile power, compressed air and water supplies) should be provided for severe accident management.
5. Such provisions as are identified in Lesson 4 above should be located at a safe place and the plant operators should be trained to use them. This may involve centralized stores and means to rapidly transfer them to the affected site(s).
6. Nuclear sites should have adequate on-site seismically robust, suitably shielded, ventilated and well equipped buildings to house the Emergency Response Centres, with similar capabilities to those provided at Fukushima Dai-ni and Dai-ichi, which are also secure against other external hazards such as flooding. They will require sufficient provisions and must be sized to maintain the welfare and radiological protection of workers needed to manage the accident.

C. Reactor systems to cope with severe accidents.

7. Emergency Response Centres should have available as far as practicable essential safety related parameters based on hardened instrumentation and lines such as coolant levels, containment status, pressure, etc., and have sufficient secure communication lines to control rooms and other places on-site and off-site.
8. Secure robust emergency core cooling systems for the reactor and the pressurized containment vessel (PCV)
- 9. Fuel melting and falling to the bottom of the PCV.**
- 10. Fuel melting through the PCV into the reactor containments**
- 11. Escape of a significant fraction of the radioisotopes from the containments into the reactor buildings and from there into the environment.**
12. Need for systems to cope with large volumes of contaminated water in the event of a breach of the reactor pressure vessel (RPV).
13. Instrumentation for measuring status of reactors and spent fuel pools. Greater consideration should be given to providing hardened systems, communications and sources of monitoring equipment for providing essential information for on-site and off-site responses, especially for severe accidents.

C. Reactor systems to cope with severe accidents.

14. Common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit recovery options, utilizing all on-site resources should be provided. “External events have a potential of affecting several plants and several units at the plants at the same time. This requires a sufficiently large resource in terms of trained experienced people, equipment, supplies and external support. An adequate pool of experienced personnel who can deal with each type of unit and can be called upon to support the affected sites should be ensured.
15. The international nuclear community should take advantage of the data and information generated from the Fukushima accident to improve and refine the existing methods and models to determine the source term involved in a nuclear accident and refine emergency planning arrangements.

D. Spent fuel pool issues

1. Secure robust cooling functions of spent fuel pools
2. See Category C, Lesson 13 above
3. Placement of spent fuel pools in new reactor and NPS designs
4. Move spent fuel from wet pools to dry casks as soon as practicable.

E. Adequacy of the responses to severe accidents

- 1. Hydrogen production due to steam cladding interactions following uncovering of the core; enhancement of prevention measures. The risk and implications of hydrogen explosions should be revisited and necessary mitigating systems should be implemented.**
2. Enhancement of the containment venting system.
3. Training responding to severe accident
4. Central control of emergency supplies and equipment and setting up rescue team.
5. Thorough accident management measures.
6. Improvement of accident response environment. Severe Accident Management Guidelines and associated procedures should take account of the potential unavailability of instruments, lighting, power and abnormal conditions including plant state and high radiation fields.

F. Adequacy of radiation monitoring

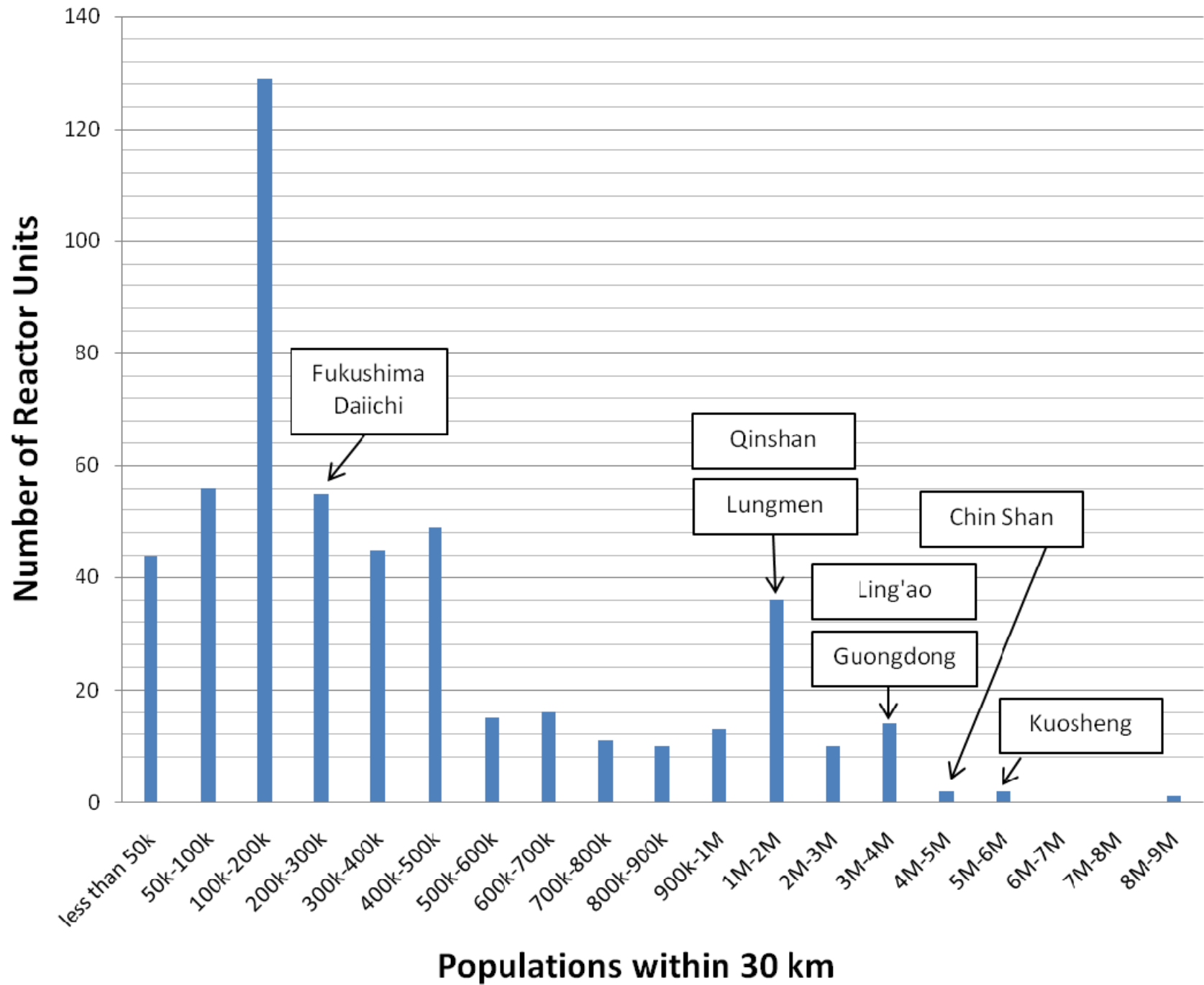
1. Enhance radiation exposure measurement systems for routine operations and during accidents.
2. Adequate identification and forecast of the effect of released radioactive materials.
3. Enhance radiation exposure management for workers. Large scale radiation protection for workers on sites under severe accident conditions can be effective if appropriately organized and with well led and suitable trained staff.
6. Exercises and drills for on-site workers and external responders in order to establish effective on-site radiological protection in severe accident conditions would benefit from taking account of experiences at Fukushima.
7. Enhance radiation exposure management of members of the public.

G. Adequacy of the emergency responses

1. Response to combined emergency of both large-scale natural disaster and prolonged nuclear accident
2. Establishment of clear division of labor between relevant central and local organizations.
3. Enhancement of communication relevant to the accident.
4. Enhancement of response to assistance by other countries and communication to the international community.
5. Clear definition of widespread evacuation area and radiological protection guideline in nuclear emergency.
- 6. Which reactor sites are located in areas that cannot be adequately evacuated, with consideration given to the need to evacuate in the immediate aftermath of a natural disaster?**
7. Adequacy of models used to calculate offsite environmental consequences and economic damage associated with a severe accident lasting for weeks.
8. Which reactor stations impose an undue economic risk to the local, regional or state economy in the event of a partial core melt accident?

G. Adequacy of the emergency responses

9. The use of IAEA Safety Requirements (such as GS-R-2) and related guides on threat categorization, event classification and countermeasures, as well as Operational Intervention Levels, could make the off-site emergency preparedness and response even more effective in particular circumstances.
10. The use of long term sheltering is not an effective approach and has been abandoned and concepts of “deliberate evacuation” and “evacuation-prepared area” were introduced for effective long term countermeasures using guidelines of the ICRP and IAEA.





Daya Bay Nuclear Power Station



H. Robustness of the safety infrastructure established at the nuclear power station

1. Reinforcement of safety regulatory bodies.
2. Establishment and reinforcement of legal structure, criteria and guidelines.
3. Human resources for nuclear safety and nuclear emergency preparedness and response.
4. Securing independency and diversity of safety system. Particularly in relation to preventing loss of safety functionality, the robustness of defense-in-depth against common cause failure should be based on providing adequate diversity (as well as redundancy and physical separation) for essential safety functions.
5. Effective use of probabilistic safety assessments (PSA) in risk management.

I. Safety culture

1. Raise awareness of safety culture at the nuclear reactor station.
2. Need for improved safety culture at the regulatory authority
3. Nuclear regulatory systems should ensure that regulatory independence and clarity of roles are preserved in all circumstances in line with IAEA Safety Standards.
4. Need for an industry sponsored safety program such as the U.S. Institute for Nuclear Power Operations (INPO)

Key messages for China

1. Operational nuclear plants have proven to be unsafe as evidenced by historical frequency of fuel damage and partial core melt accidents.
2. The safety design of nuclear plants must address the full range of precursor events that could lead to a severe nuclear accident.
3. Need to ensure against complete loss of power, i.e., station blackout.
4. Severe accident consequence mitigation capabilities, e.g., hydrogen gas venting, must be part of the licensing basis of the plant—not left to operator discretion.
5. Maximum population density and potential economic consequences of a severe accident must be criteria in siting nuclear power plants.
6. A strong safety culture is an important factor determining the safety of a nuclear power reactor.
7. A robust independent national nuclear regulatory authority is required.