The Fukushima Nuclear Disaster: Implications for California Nuclear Plants

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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

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Vice Dean, School of Engineering, The University of Tokyo
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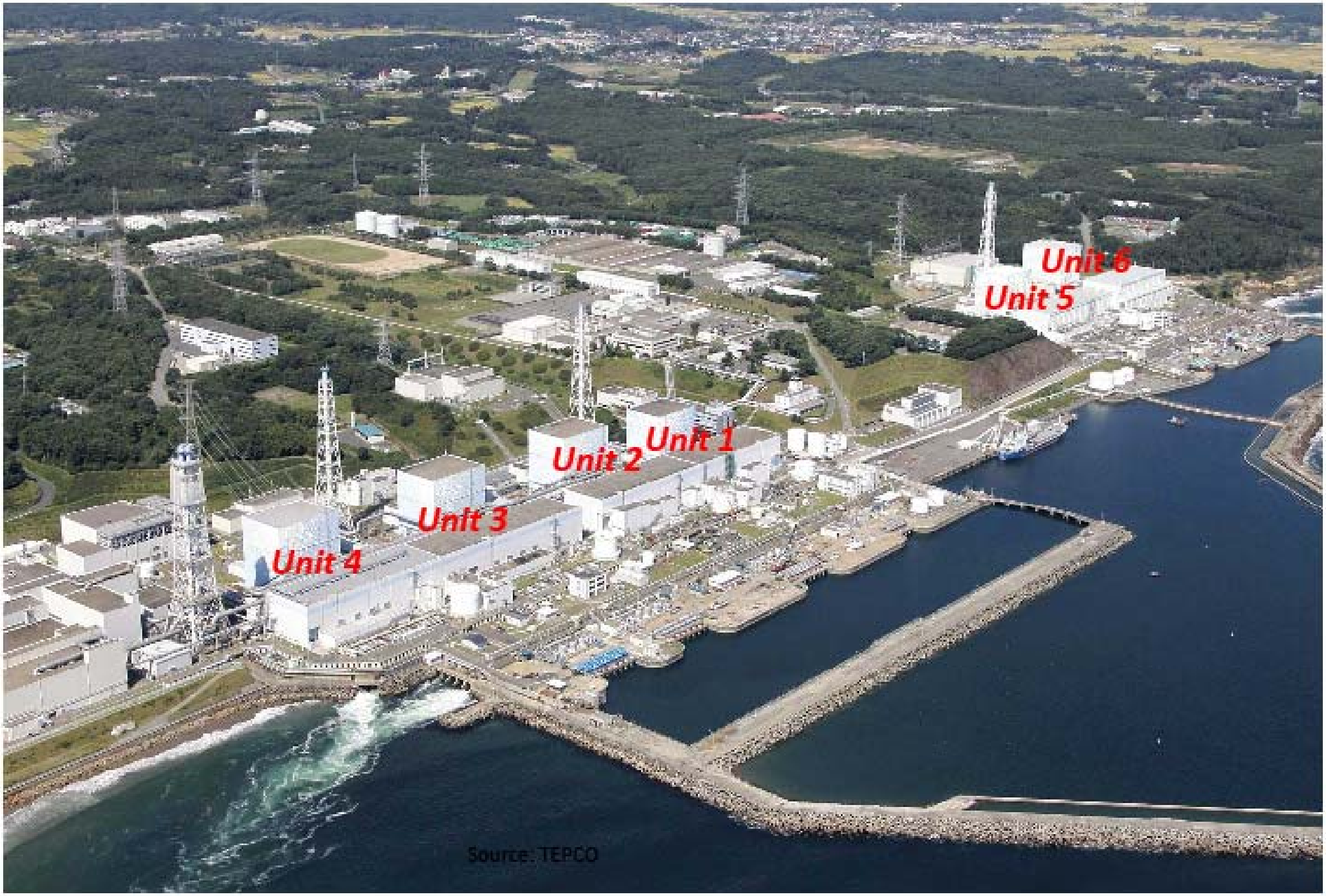
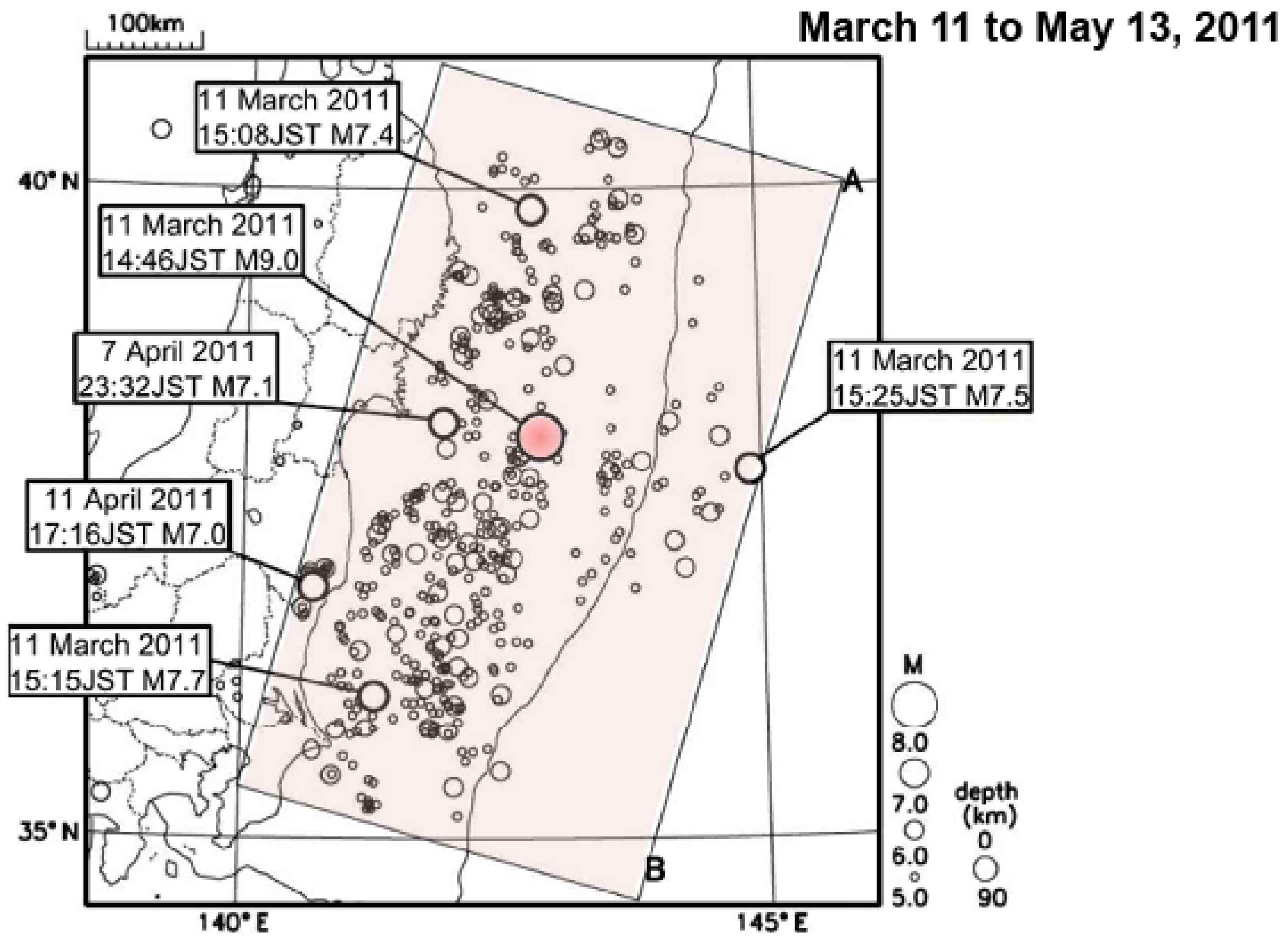
Fukushima Daiichi Nuclear Power Plants operated by TEPCO



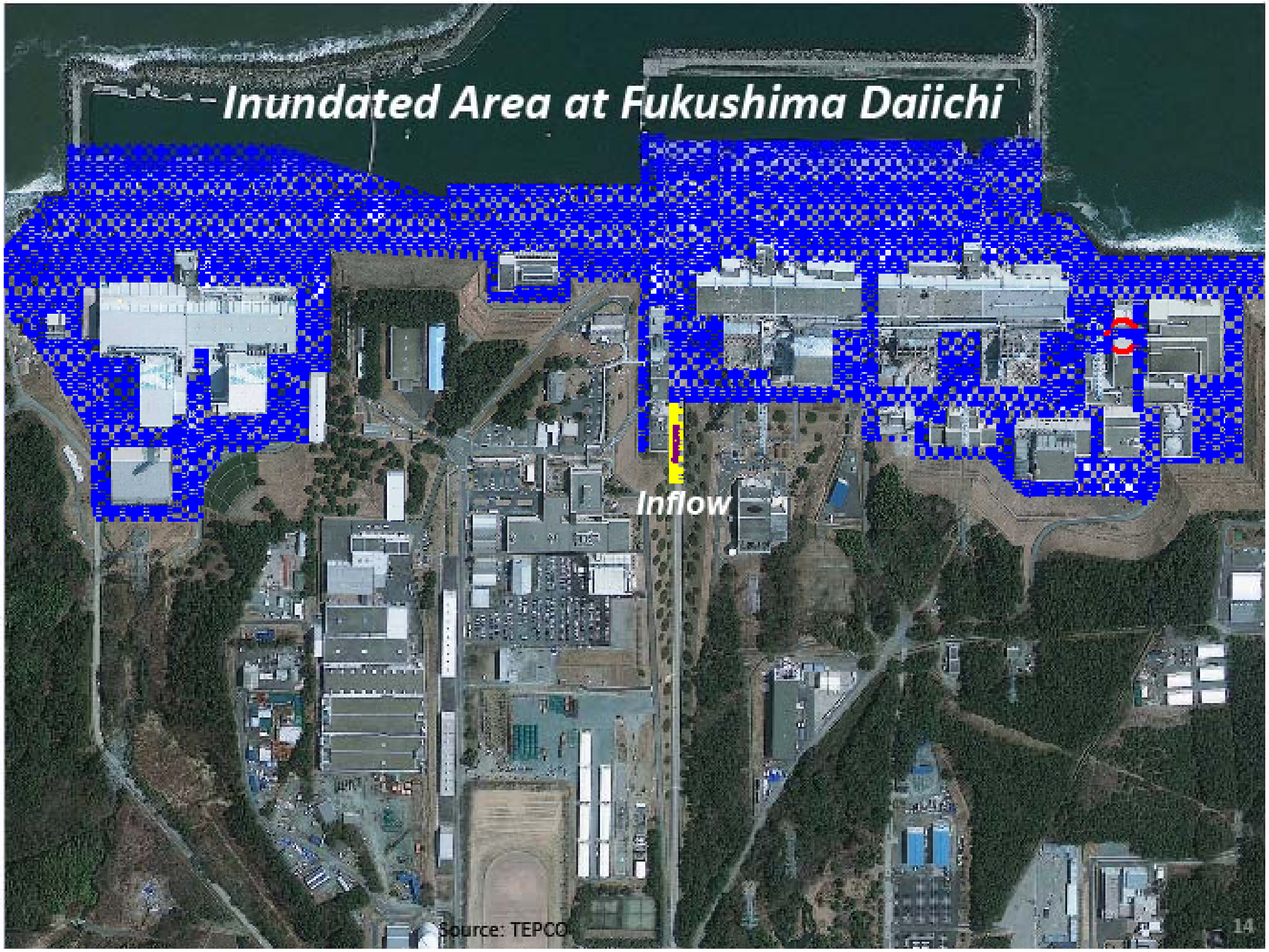
The Main Shock and Aftershock of the Earthquake on 2011.3.11



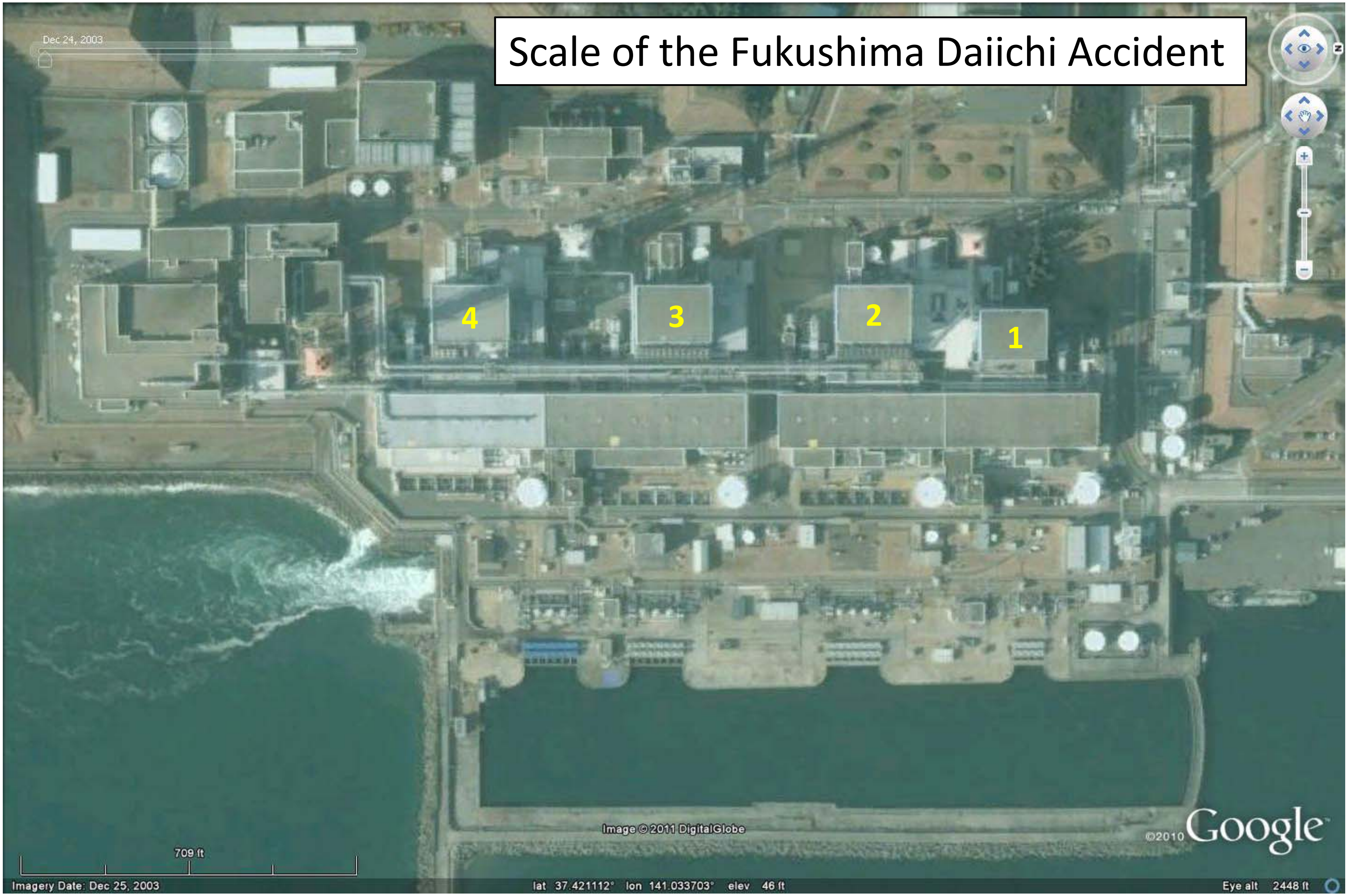
Recorded Intensity of Ground Motion and Basic Earthquake Ground Motion

		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

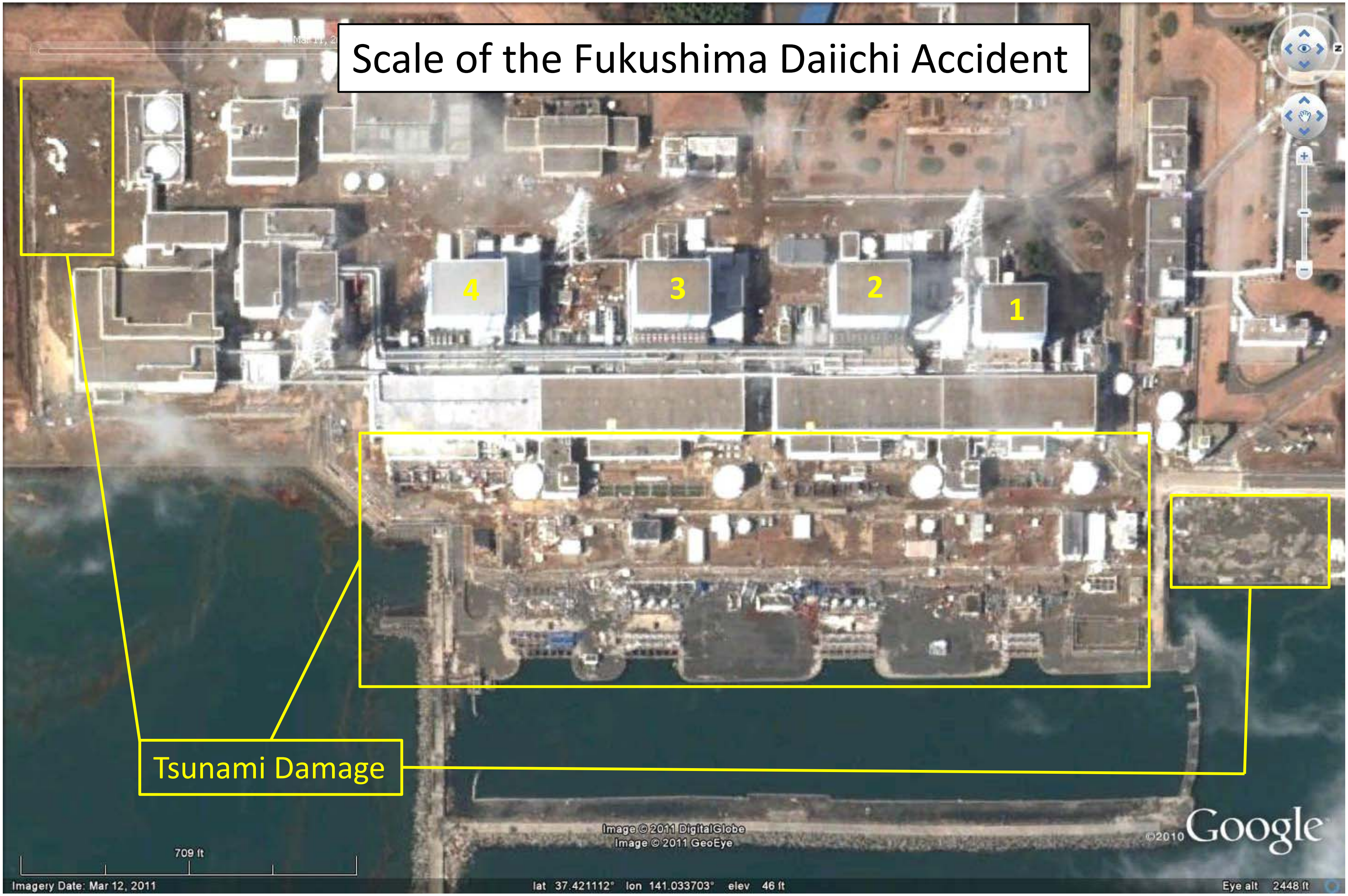
* At the lowest basement of reactor building



Inundated Area at Fukushima Daiichi
Inflow
Source: TEPCO
14

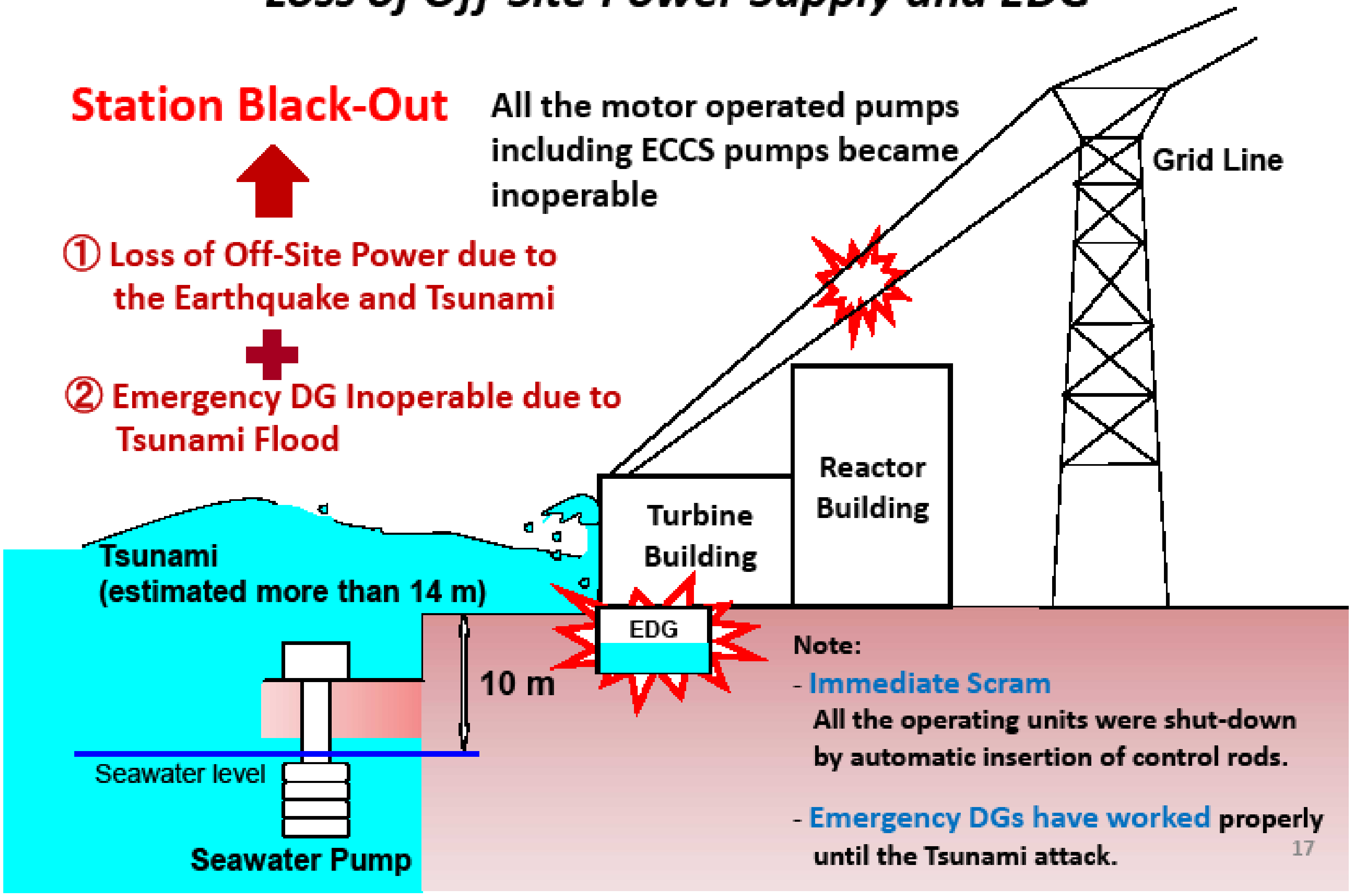


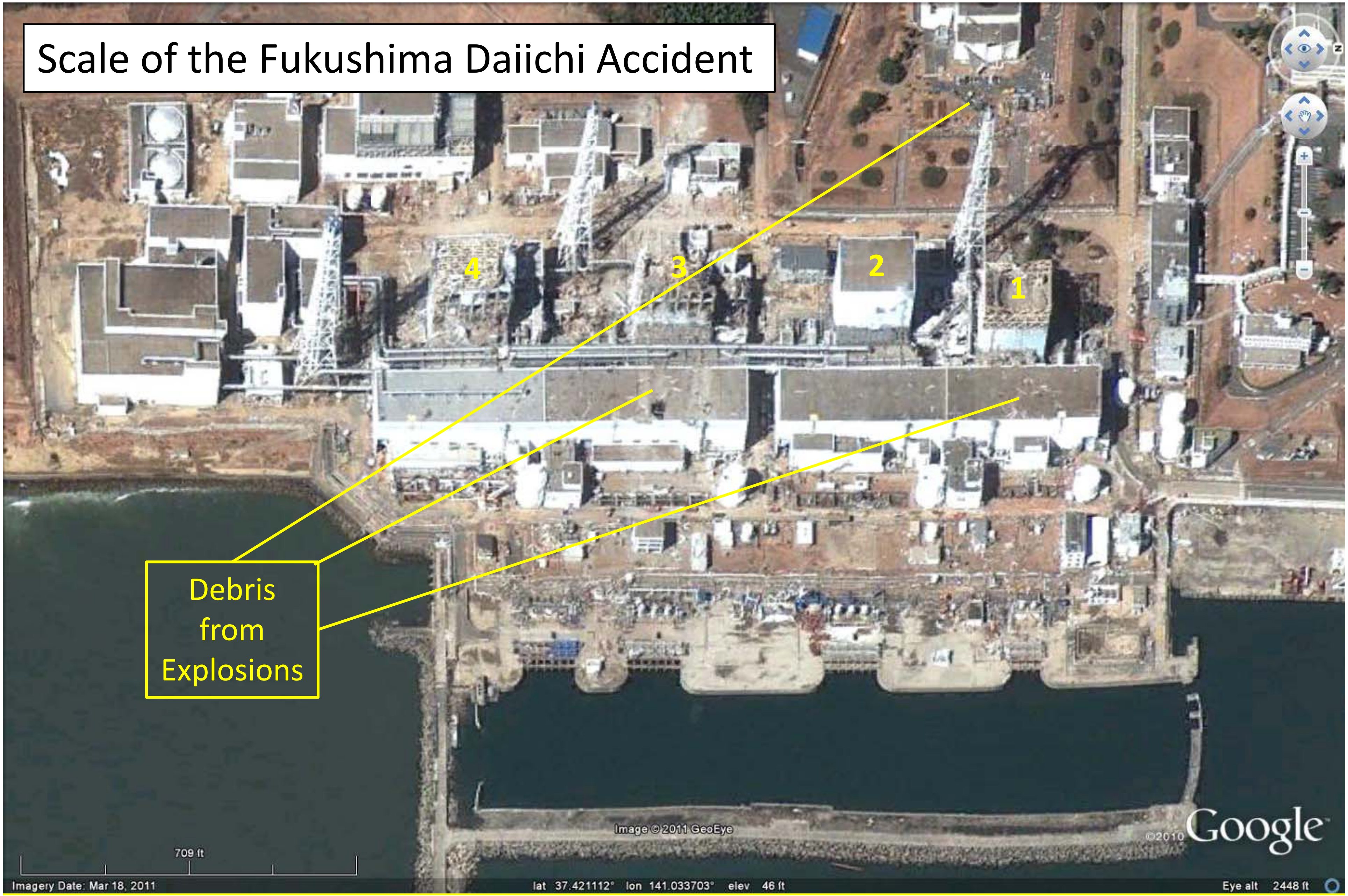
Satellite image of Fukushima Daiichi, photographed about seven years before the 2011 earthquake and tsunami.



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 -



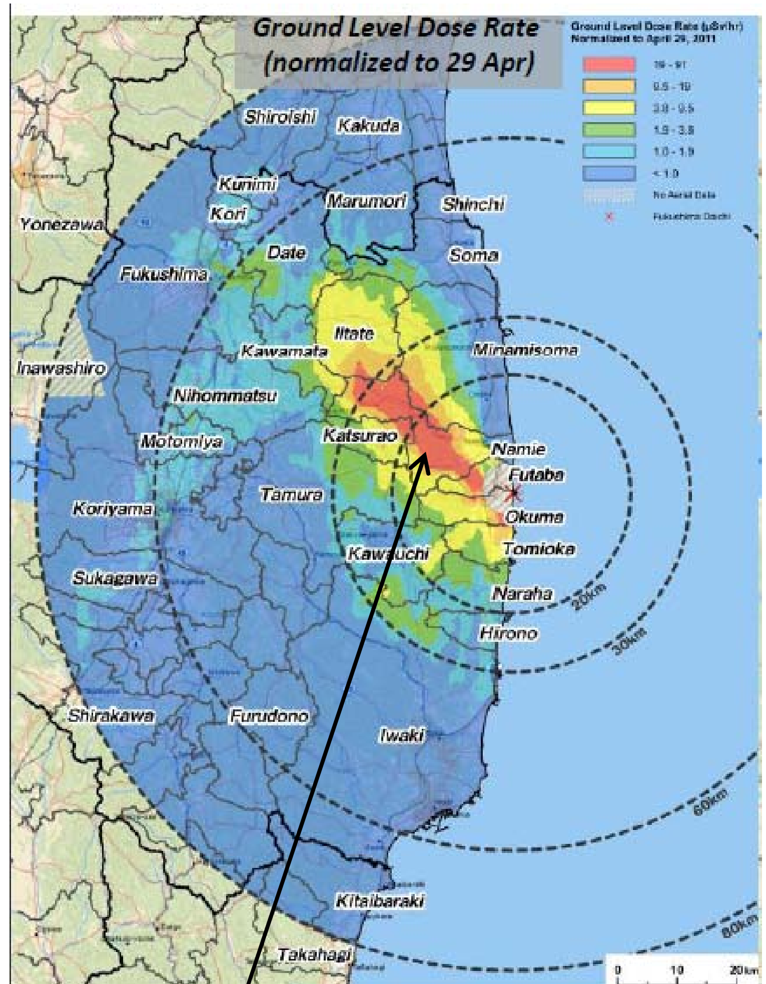


Satellite image of Fukushima Daiichi, photographed after the major sequence of explosions and fires in Units 1, 2, 3 and 4.

Limiting Radiation Exposure to Plant Workers and the Public

Mandatory evacuation of all areas where the estimated annual exposure exceeded
20 milli-Sieverts/year

- Affected people out to about 75 km from nuclear power station;
- Same dose limit established for schools and playgrounds;
- 1,000 people of mixed ages and both genders exposed to 20 mSv (2 rem – one year of exposure at the limit) would be expected to result in 2.3 excess cancers of which 1.1 would be fatal
- Frequency of expected excess cancers to 10 year old children due to 20 mSv exposure is one excess cancer per 250 children.



Dose rate at the centerline of the plume was in the range between 21.7 and 125 microSv/h (0.2 to 1.1 Sv/y)

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Immediate Response to the Accident in United States

NRC's regional and resident inspectors staff have conducted walk down inspections at all the operational reactors in response to NRC Temporary Instruction 2515/183:

Diablo Canyon

- The plant had a single diesel-driven pump to provide emergency cooling water to a single reactor in case an earthquake cut off normal water flow. The pump could not have serviced both of the plant's reactors if they lost normal water supply simultaneously, the NRC staff said.
- Some doors at the plant required to protect against flooding of major safety equipment would not self-latch as required. One latch was "degraded," they said.
- The plant's six emergency diesel generators were located in the same plant area, and thus vulnerable to a "common mode" failure.
- An earthquake could cause a structural failure in the building where the fire truck is stored, and debris could block crews from using the truck.
- PG&E planned for a contractor to provide seawater for emergency cooling, but had no backup plan if an earthquake and tsunami blocked highways to the plant. PG&E intended to rely on the California National Guard to deliver diesel fuel for emergency generators if roads were impassable, but had no memorandum of understanding in place for the deliveries.
- Four 20-foot extension cables, used to operate fans that cool portable generators, were missing from their storage location.

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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

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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.

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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?

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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**

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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

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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

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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.

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C. Reactor systems to cope with severe accidents.

7. Central control of emergency supplies and equipment and setting up rescue team. 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. Need for systems to cope with large volumes of contaminated water in the event of a breach of the reactor pressure vessel (RPV).
10. 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.

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C. Reactor systems to cope with severe accidents.

11. 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.
12. 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.

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D. Spent fuel pool issues

1. Secure robust cooling functions of spent fuel pools
2. See Category C, Lesson 10 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

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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. Enhancement of the containment venting system.
2. Training responding to severe accident
3. See Category C, Lesson 7
4. Thorough accident management measures.
5. 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.

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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?

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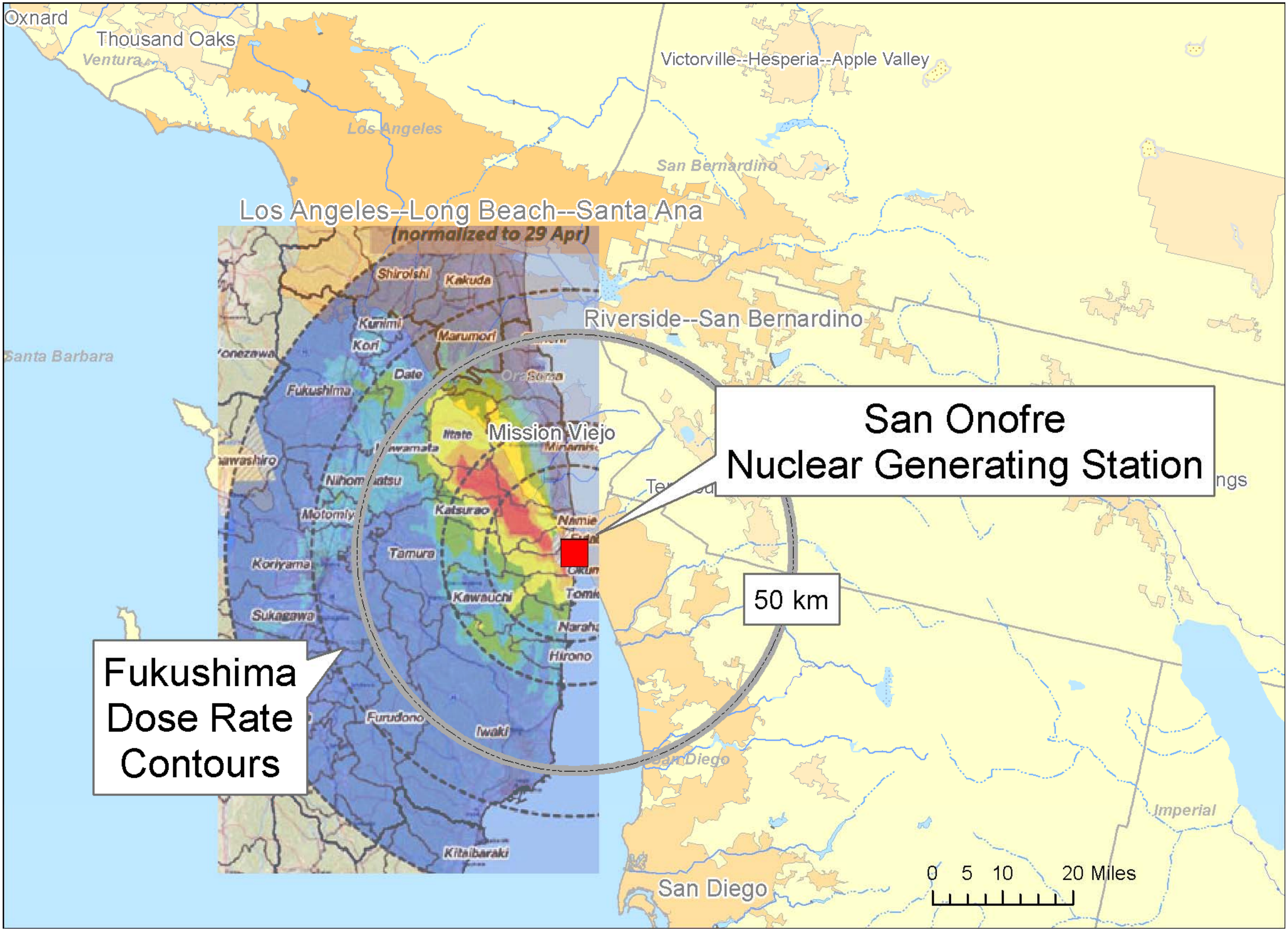
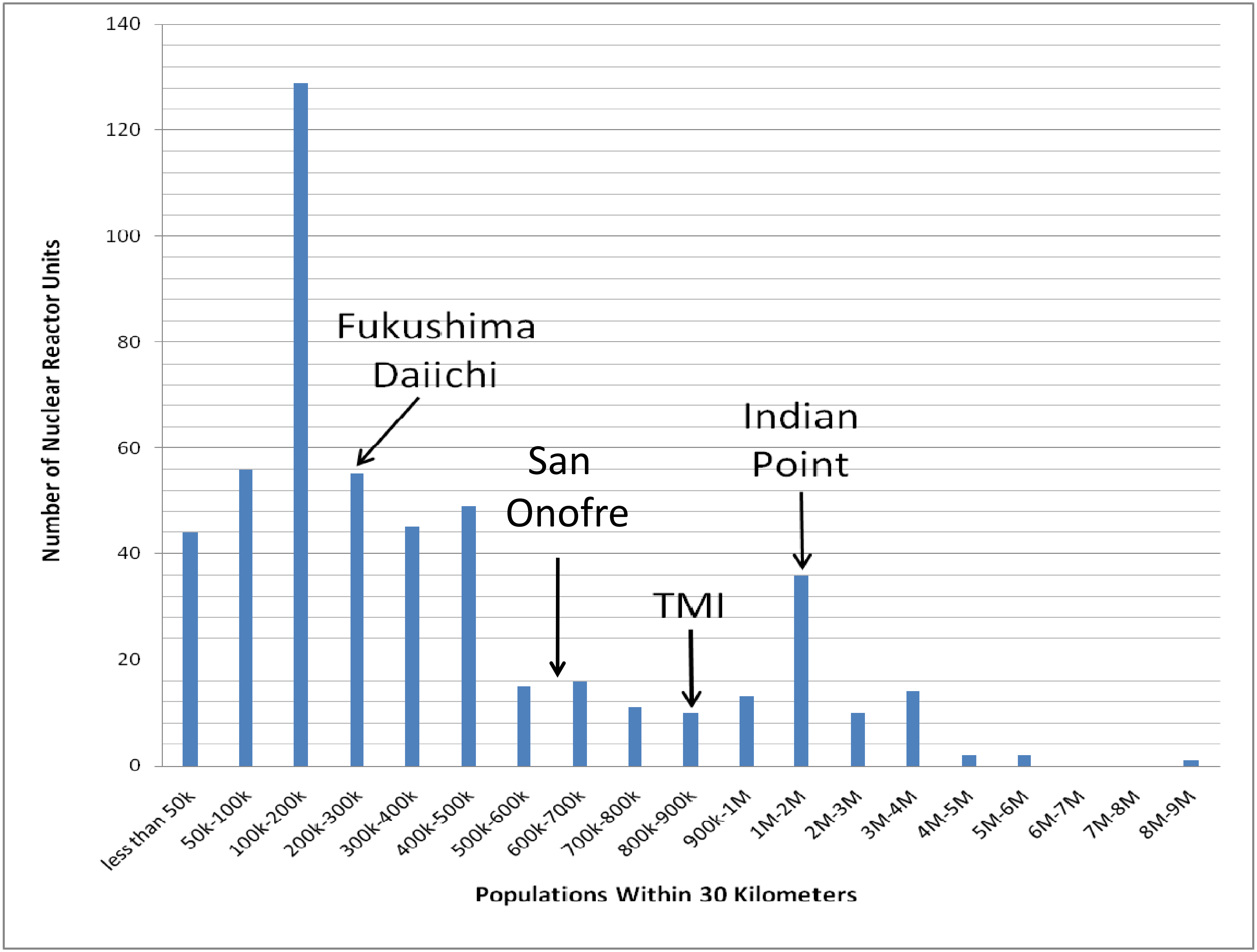


San Onofre Nuclear Generating Station
Fukushima Dose Rate Contours
50 km
(normalized to 29 Apr)
Oxnard
Thousand Oaks
Ventura
Los Angeles
Victorville--Hesperia--Apple Valley
San Bernardino
Los Angeles--Long Beach--Santa Ana
Riverside--San Bernardino
Santa Barbara
Mission Viejo
San Diego
Imperial
0 5 10 20 Miles
Shiroishi
Kakuda
Kunimi
Kori
Marumori
Date
Fukushima
Iitate
Nihonmatsu
Motomiya
Katsurao
Namie
Tamura
Koriyama
Kawauchi
Sukagawa
Naraha
Hirono
Furudono
Iwaki
Kitaibaraki


140
120
100
80
60
40
20
0
Number of Nuclear Reactor Units
Fukushima
Daiichi
San
Onofre
TMI
Indian
Point
less than 50k
50k-100k
100k-200k
200k-300k
300k-400k
400k-500k
500k-600k
600k-700k
700k-800k
800k-900k
900k-1M
1M-2M
2M-3M
3M-4M
4M-5M
5M-6M
6M-7M
7M-8M
8M-9M
Populations Within 30 Kilometers

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.

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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.

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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)

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