

Global Implications of the Fukushima Disaster for Nuclear Power

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ABSTRACT

This paper reviews implications for the global use of nuclear power stemming from the nuclear accident at the Fukushima Dai-ichi Nuclear Power Station following the earthquake and tsunami on March 11, 2011. It includes: a) a review of numerous lessons learned from Fukushima related to accident precursors, design and operation of plant safety systems, emergency planning and nuclear plant regulation and safety culture; b) an examination of the historical frequency of severe fuel damage accidents at nuclear power plants and comparison of that frequency against the safety goals of the U.S. Nuclear Regulatory Commission; c) an examination of the population densities in the vicinity of nuclear power stations worldwide to assess the potential impact of radioactivity releases of Fukushima-scale or larger at other stations; and d) a review of reactor sites that are in areas of high risk to earthquakes and tsunamis.

Introduction

This paper follows closely and updates U.S. Senate testimony by Thomas Cochran, April 12th, which was updated in a statement by Thomas Cochran and Matthew McKinzie before the U.S. National Academies' Nuclear and Radiation Studies Board on May 26th, and again at an International Workshop on Nuclear Energy Safety in Beijing on June 29th. We also draw on several excellent reports and presentations, including:

- 1) Staff of Congressman Edward J. Markey, "Fukushima Fallout, Regulatory Loopholes at U.S. Nuclear Plants," May 12, 2011;¹
- 2) Naoto Sekimura, "Overview of the Accident in Fukushima Daiichi Nuclear Power Plants," U.S. National Academies' Nuclear and Radiation Studies Board, May 26, 2011;²
- 3) Japanese Government, "Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety: The Accident at TEPCO's Fukushima Nuclear Power Stations," June 2011;³
- 4) International Atomic Energy Agency (IAEA), "IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident Following the Great East Japan Earthquake and Tsunami," 24 May – 2 June, 2011, Report to the IAEA Member States, 16 June 2011;⁴
- 5) Charles Miller, *et al.*, "Recommendations for Enhancing Reactor Safety in the 21st Century: The Near Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," U.S. Nuclear Regulatory Commission (US NRC), SECY-11-0093, July 12, 2011;⁵

¹ <http://markey.house.gov/docs/05-12-11reportfinalsmall.pdf>

² <http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/SekimuraPresentation.pdf>

³ http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html

⁴ http://www-pub.iaea.org/MTCD/meetings/PDFplus/2011/cn200/documentation/cn200_Final-Fukushima-Mission_Report.pdf

⁵ <http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf>

- 6) Union of Concerned Scientists (UCS), “U.S. Nuclear Power after Fukushima: Common Sense Recommendations for Safety and Security, July 2011;⁶ and
- 7) Arjun Makhijani, “Preliminary review of Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident, U.S. Nuclear Regulatory Commission,” Institute for Energy and Environmental Research (IEER), July 12, 2011.⁷

Issues raised by the Fukushima disaster.

There is a long list of issues and lessons learned from Fukushima that can be found in the reports identified above:

Category A. Accident initiators:⁸

1. Need to strengthen measures to protect against:
 - a. natural external hazards:⁹
 - i. earthquakes¹⁰
 - ii. tsunamis
 - iii. floods

⁶ http://www.ucsusa.org/assets/documents/nuclear_power/ucs-rpt-nuclear-safety-recs.pdf

⁷ <http://a4nr.org/wp-content/uploads/2011/07/July-19-IEER-review-NRC-report-on-Fukushima.pdf>

⁸ See IAEA, “IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident Following the Great East Japan Earthquake and Tsunami,” 24 May – 2 June, 2011, Report to the IAEA Member States, 16 June 2011, p. 16, “Lesson 1: There is a need to ensure that in considering external natural hazards:

- the siting and design of nuclear plants should include sufficient protection against infrequent and complex combinations of external events and these should be considered in the plant safety analysis – specifically those that can cause site flooding and which may have longer term impacts;
- plant layout should be based on maintaining a ‘dry site concept’, where practicable, as a defense-in-depth measure against site flooding as well as physical separation and diversity of critical safety systems;
- 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;
- any changes in external hazards or understanding of them should be periodically reviewed for their impact on the current plant configuration; and
- an active tsunami warning system should be established with the provision for immediate operator action.”

⁹ Japan Government, “Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety: The Accident at TEPCO’s Fukushima Nuclear Power Stations,” June 2011, p. 28, Lesson 1. Also, Charles Miller, *et al.*, “Recommendations for Enhancing Reactor Safety in the 21st Century: The Near Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,” U.S. Nuclear Regulatory Commission (US NRC), SECY-11-0093, July 12, 2011, p. 30, Recommendation 2, “The Task Force recommends that the NRC require licensees to reevaluate and upgrade as necessary the design-basis seismic and flooding protection of SSCs for each operating reactor.”

¹⁰ Arjun Makhijani, “Preliminary review of Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident, U.S. Nuclear Regulatory Commission,” Institute for Energy and Environmental Research (IEER), July 12, 2011, p. 14, Recommendation 5: The US NRC should have its own independent seismology department.

- iv. hurricanes and typhoons
- v. tornadoes¹¹
- vi. the implications of predicted sea-level rise and increased storm surges due to climate change.¹²
- b. on-site hazards:
 - i. fires, including seismically induced fires¹³
- c. malevolent acts:
 - i. external assault; terrorist attacks¹⁴
 - ii. insider threats
- 2. Need to periodically review the magnitude and potential consequences of accident initiators.¹⁵
- 3. Need to improve warning systems for tsunamis and tornadoes.

Category B. Compliance with safety goals:

- 4. On a worldwide basis, power reactors are not adequately safe.¹⁶
- 5. The US NRC should create an enhanced-design-basis framework to replace the design-basis plus beyond-design-basis framework now in place;¹⁷ extend regulations to cover severe accidents;¹⁸ which additional accident scenarios should be treated as part of the design-basis?¹⁹
- 6. Determine whether old reactor designs, e.g., GE BWRs with poorly designed Mark 1 and Mark 2 containments, are sufficiently safe to continue operation or have their licenses extended, even with subsequent safety upgrades.²⁰
- 7. Apply the same type of timeliness goals to nuclear plant safety that it [the US NRC] does for business-related requests from reactor owners.²¹
- 8. Require new reactors to be safer than existing reactors.²²
- 9. Assign an appropriate value to human life in cost-benefit analyses.²³

¹¹ IEER, pp. 10-12, Recommendation 4.

¹² NRDC, see discussion in this paper.

¹³ USNRC, Near-Term Task Force Review, p. 32, Recommendation 3; UCS, "U.S. Nuclear Power after Fukushima: Common Sense Recommendations for Safety and Security, July 2011, p. 3, Recommendation: Enforce Fire Protection.

¹⁴ UCS, p. 3, Recommendation: Improve Protection against Terrorist Attacks.

¹⁵ US NRC, Near-Term Task Force Review, p. 30, Recommendation 2.2; IEER, p. 14, Recommendation 6.

¹⁶ NRDC analysis.

¹⁷ US NRC, Near-Term Task Force Review, p. 22, Recommendation 1; IEER, p. 3.

¹⁸ USC, p. 2, Recommendation: The US NRC should extend the scope of its regulations to include the prevention and mitigation of severe accidents.

¹⁹ NRDC question.

²⁰ IEER, p. 16, Recommendation 8.

²¹ UCS, p. 3, Recommendation: Set Timeliness Goals for Safety Issues.

²² UCS, p. 3, Recommendation: Strengthen Safety Standards for New Reactors; IEER, p. 18, Recommendation 12.

²³ UCS, p. 4, Recommendation: The US NRC should increase the value of human life in its analyses so it is consistent with other government agencies.

10. Probabilistic risk assessments (PRAs) should be updated;²⁴ US NRC should perform its own independent PRAs as part of the license review process.²⁵
11. Suspend relicensing and granting new licenses.²⁶
12. Consider alternatives to nuclear power.²⁷

Category C. Reactor systems to cope with severe accidents:²⁸

13. Secure AC power—offsite and emergency diesel generators and generator fuel.²⁹
14. DC power—longevity of batteries.³⁰
15. Ensuring the water tightness of essential equipment facilities.³¹
16. “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.”³²
17. “Such provisions as are identified in [Category C, Lesson 10] 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).”³³
18. “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.”³⁴
19. “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.”³⁵

²⁴ Japan Government, p. 40, Lesson 27.

²⁵ IEER, p. 17, Recommendation 10.

²⁶ *Ibid.*, pp. 19-20, Recommendation 14.

²⁷ *Ibid.*, p. 20, Recommendation 15.

²⁸ US NRC, Near-Term Task Force Review, p. 37, Recommendation 4.

²⁹ Japan Government, p. 29, Lesson 2.

³⁰ *Ibid.*

³¹ Japan Government, p. 32, Lesson 8.

³² IAEA, p. 16, Lesson 2.

³³ IAEA, p. 16, Lesson 3.

³⁴ IAEA, p. 16, Lesson 4

³⁵ IAEA, p. 17, Lesson 5.

20. Secure robust emergency core cooling systems for the reactor and the pressurized containment vessel (PCV)³⁶
21. Insure that systems are capable of coping with large volumes of contaminated water, e.g., in the event of a breach of the reactor pressure vessel (RPV).³⁷
22. Improve instrumentation for measuring status of reactors and spent fuel pools.³⁸ “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.”³⁹
23. Common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit recovery options, the utilization of 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.”⁴⁰
24. “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.”⁴¹

Category D. Spent fuel pool issues:

25. Secure robust cooling functions of spent fuel pools.⁴²
26. See Lesson 22 above.
27. Placement of spent fuel pools in new reactor and NPS designs.⁴³
28. Move spent fuel from wet pools to dry casks as soon as practicable.⁴⁴

Category E. Adequacy of the responses to severe accidents:

29. Hydrogen production due to steam cladding interactions following uncovering of the core; enhancement of prevention measures.⁴⁵ “The risk and

³⁶ Japan Government, p. 30, Lesson 3.

³⁷ NRDC Recommendation.

³⁸ Japan Government, pp. 34-35, Lesson 14 and US NRC, Near-Term Task Force Review, p. 46, Recommendation 7.

³⁹ IAEA, p. 17, Lesson 10.

⁴⁰ IAEA, p. 17, Lesson 7 and Japan Government, p. 31, Lesson 6.

⁴¹ IAEA, p. 18, Lesson 13.

⁴² Japan Government, p. 30, Lesson 4; US NRC, Near-Term Task Force Review, p. 46, Recommendation 7; and IEER, p. 16, Recommendation 9.

⁴³ Japan Government, p. 32, Lesson 7.

⁴⁴ UCS, p. 3, Recommendation: Move Spent Fuel to Dry Casks; IEER, p. 17, Recommendation 11; NRDC recommendation.

⁴⁵ Japan Government, p. 32, Lesson 9.

implications of hydrogen explosions should be revisited and necessary mitigating systems should be implemented.”⁴⁶ Consider alternatives to zircaloy fuel cladding to reduce the risk of hydrogen explosions.⁴⁷

30. Enhancement of the containment venting systems.⁴⁸
31. Training programs for responding to severe accidents.⁴⁹
32. Central control of emergency supplies and equipment and setting up rescue team.⁵⁰
33. Thorough accident management measures.⁵¹
34. Improvement of accident response environment.⁵² 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.⁵³

Category F. Adequacy of radiation monitoring:

35. Enhance radiation exposure measurement systems for routine operations and during accidents.⁵⁴
36. Adequate identification and forecast of the effect of released radioactive materials.⁵⁵
37. 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.”⁵⁶
38. “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 the experiences at Fukushima.”⁵⁷
39. Enhance radiation exposure management of members of the public.⁵⁸

⁴⁶ IAEA, p. 17, Lesson 8.

⁴⁷ IEER, p. 19, Recommendation 13.

⁴⁸ Japan Government, p. 33, Lesson 10; US NRC, Near-Term Task Force Review, p. 41, Recommendation 5; and p. 43, Recommendation 6 and IEER, p. 16, Recommendations 7 and 8.

⁴⁹ Japan Government, p. 34, Lesson 13.

⁵⁰ Japan Government, p. 35, Lesson 15.

⁵¹ Japan Government, p. 31, Lesson 5.

⁵² Japan Government, p. 33, Lesson 11.

⁵³ IAEA, p. 17, Lesson 6.

⁵⁴ Japan Government, p. 34, Lesson 12 and p. 36, Lesson 17.

⁵⁵ Japan Government, pp. 37-38, Lesson 21.

⁵⁶ IAEA, p. 18, Lesson 14.

⁵⁷ IAEA, p. 18, Lesson 15.

⁵⁸ NRDC recommendation.

Category G. Adequacy of the emergency responses:⁵⁹

40. Response to combined emergency of both large-scale natural disaster and prolonged nuclear accidents.⁶⁰
41. Establishment of clear division of labor between relevant central and local organizations.⁶¹
42. Enhancement of communication relevant to accidents.⁶²
43. Enhancement of response to assistance by other countries and communication to the international community.⁶³
44. Clear definition of widespread evacuation area and radiological protection guideline in nuclear emergency.⁶⁴
45. Determine 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.⁶⁵
46. US NRC should require a complete reevaluation of emergency planning zones, evacuation, and population protection, especially in densely populated areas where evacuation in zones extending out 30 or 40 miles will be essentially impossible and asking ten million or more people to stay indoors for extended periods of months is also equally impossible.⁶⁶
47. The US NRC needs to revamp its entire regulatory structure for emergency planning to take into account (i) the protection of children, required by Executive Order 13045, (ii) the fact that large numbers of people may not be able to return to contaminated homes and jobs for prolonged periods, if ever, and that this needs special attention in densely populated areas, (iii) the irregular nature of the high radiation areas that develop, (iv) cleanup costs in the aftermath of accidents, (v) the need for real-time monitoring equipment to be in place far beyond the 10-mile planning zone, (vi) the need to take meteorological factors into account, often in real time, when informing the population (as, for instance, about potential rainfall and milk contamination), and (vii) the need to thoroughly reevaluate the viability of nuclear power plants in densely populated zones where evacuation in a 30-, 40-, or even 50-mile radius (depending on meteorological factors) may not be feasible.⁶⁷

⁵⁹ US NRC, Near-Term Task Force Review, p. 49, Recommendation 8, p. 56, Recommendation 9, and p. 57, Recommendation 10; UCS, p. 3, Recommendation: Strengthening Emergency Planning.

⁶⁰ Japan Government, p. 35, Lesson 16.

⁶¹ Japan Government, p. 36, Lesson 18.

⁶² Japan Government, pp. 36-37, Lesson 19.

⁶³ Japan Government, p. 37, Lesson 20.

⁶⁴ Japan Government, p. 38, Lesson 22.

⁶⁵ NRDC question.

⁶⁶ IEER, p. 9, Recommendation 1.

⁶⁷ *Ibid.*, pp. 9-10, Recommendation 2.

48. The NRC needs to publish scientific guidelines for communicating radiation risks that respect the established science, notably the EPA's Federal Guidance Report 13 and the National Academies BEIR VII report.⁶⁸
49. Improve the adequacy of models used to calculate offsite environmental consequences and economic damage associated with a severe accident lasting for weeks.
50. Determine which reactor stations impose an undue economic risk to the local, regional or state economy in the event of a partial core melt accident.⁶⁹
51. "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."⁷⁰
52. "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."⁷¹

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

53. Reinforcement of safety regulatory bodies.⁷²
54. Establishment and reinforcement of legal structure, criteria and guidelines.⁷³
55. Human resources for nuclear safety and nuclear emergency preparedness and response.⁷⁴
56. Securing independency and diversity of safety system.⁷⁵ "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."⁷⁶

Category I. Safety culture:

57. Raise awareness of safety culture at the nuclear reactor station.⁷⁷
58. Need for improved safety culture at the regulatory authority.

⁶⁸ *Ibid.*, p. 10, Recommendation 3.

⁶⁹ NRDC question.

⁷⁰ IAEA, p. 17, Lesson 11.

⁷¹ IAEA, p. 17, Lesson 12.

⁷² Japan Government, pp. 38-39, Lesson 23.

⁷³ Japan Government, p. 39, Lesson 24.

⁷⁴ Japan Government, p. 39, Lesson 25.

⁷⁵ Japan Government, pp. 39-40, Lesson 26.

⁷⁶ IAEA, p. 17, Lesson 9.

⁷⁷ Japan Government, p. 40, Lesson 28.

59. “Nuclear regulatory systems should ensure that regulatory independence and clarity of roles are preserved in all circumstances in line with IAEA Safety Standards.”⁷⁸
60. Need for an industry sponsored safety program such as the U.S. Institute for Nuclear Power Operations (INPO).

Some implications for Nuclear Power Reactors Worldwide

As noted by this lengthy list of issues and lessons learned, there are numerous concerns raised by the Fukushima nuclear disaster that bear on the safe operation and regulation of nuclear power reactors worldwide. Here we will offer brief observations regarding four issues:

- Are operational nuclear power reactors safe?
- Which reactors are located in areas that represent the greatest challenge if evacuation of the surrounding population is required or impose an undue economic risk to the local, regional or national economies in the event of a partial core melt accident?
- Which reactors are located in areas that are in areas of high risk to earthquakes and tsunamis?
- What improvements should be made to address the issue of hydrogen production caused by fuel cladding interactions with steam?

Are operational nuclear power reactors safe?

To address this issue we first address what constitutes an acceptable level of safety and then compare the history of power reactor operations against this benchmark.

What constitutes an acceptable safety risk? The US NRC Inspection Manual defines safety and compliance as follows:

As commonly understood, safety means freedom from exposure to danger, or protection from harm. In a practical sense, an activity is deemed to be safe if the perceived risks are judged to be acceptable. The Atomic Energy Act of 1954, as amended [AEA], establishes “adequate protection” as the standard of safety on which NRC regulation is based. In the context of NRC regulation, safety means avoiding undue risk or, stated another way, providing reasonable assurance of adequate protection for the public in connection with the use of source, byproduct and special nuclear materials.

⁷⁸ IAEA, p. 18, Lesson 16.

The definition of compliance is much simpler. Compliance simply means meeting applicable regulatory requirements.⁷⁹

Martin G. Malsch, former US NRC Acting General Counsel, notes that the AEA was initially silent on 1) how undue risk should be defined, and 2) when non-safety considerations (such as economic costs) may be taken into account in making undue risk decisions.⁸⁰

Following the TMI accident the US NRC further defined “undue risk” in terms of safety goals. In response to industry concerns in the 1980’s about the NRC’s failure to account for the economic costs in safety decisions, the NRC developed a framework whereby economic costs would be considered in some decisions but not in others.

Prior to the US NRC formulating its safety goals, in July 1985, the US NRC Advisory Committee on Reactor Safeguards (ACRS) stated:

We believe that the Commission should state that a mean core melt frequency of not more than 10^{-4} per reactor year (one in 10,000 reactor-years) is an NRC objective for all but a few, small, existing nuclear power plants, and that, keeping in mind the considerable uncertainties, prudence and judgment will tend to take priority over benefit-cost analysis in working toward this goal.⁸¹

The following year, on August 4, 1986, the US NRC published a final policy statement on safety goals, which states in part:

Severe core damage accidents can lead to more serious accidents with the potential for life-threatening offsite release of radiation, for evacuation of

⁷⁹ US NRC, “NRC Inspection Manual,” Part 9900 Technical Guidance, Operation – Safety and Compliance, September 11, 2007. Martin G. Malsch, former US NRC Acting General Counsel, similarly notes:

The basic statute providing for the licensing and regulation of nuclear power plants in the United States is the 1954 Atomic Energy Act (AEA), which has been amended periodically.

The AEA provides that licenses will be granted only if it is shown that there is adequate protection of the public health and safety. Historically, this has always been understood to mean that there must be reasonable assurance of no undue radiological risk to public health and safety. A license may be suspended or revoked if new information indicates this reasonable assurance no longer exists.

⁸⁰ Martin G. Malsch, “US Nuclear Power Reactor Safety Goals and Protection from Natural Phenomena,” International Workshop on Nuclear Safety: Improving Safety in the Aftermath of the Fukushima Crisis, Beijing, China, June 29, 2011.

⁸¹ ACRS letter from D. A. Ward to N. J. Palladino, Subject: ACRS comments on proposed NRC safety goal evaluation report (17 July 1985); cited in David Okrent, “The Safety Goals of the Nuclear Regulatory Commission,” *Science*, **236**, 296-300 (17 April 1987).

members of the public, and for contamination of public property. Apart from their health and safety consequences, severe core damage accidents can erode public confidence in the safety of nuclear power and can lead to further instability and unpredictability for the industry. In order to avoid these adverse consequences, *the Commission intends to continue to pursue a regulatory program that has as its objective providing reasonable assurance, while giving appropriate consideration to the uncertainties involved, that a severe core damage accident will not occur at a U.S. nuclear power plant.*⁸² (emphasis added)

The policy statement also included two qualitative and two quantitative goals. With regard to the later the policy statement says:

The Commission has decided to adopt the following two health effects as quantitative objectives concerning mortality risks to be used in determining achievement of the qualitative safety goals—

- The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1 percent) of the prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed.
- The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1 percent) of the sum of cancer fatality risks resulting from all other causes.

Richard A Meserve, then Chairman of the US NRC, noted in 2001:

In 1990, the Commission provided additional guidance to the staff regarding the Safety Goals, endorsing surrogate objectives concerning the frequency of core damage accidents and large releases of radioactivity.² The numerical value of one-in-ten-thousand for core damage frequency (CDF) was cited as a “very useful subsidiary benchmark....” In addition, a conditional containment failure probability of one-tenth was approved for application to evolutionary light water reactor designs. This resulted in a large release frequency of one in one-hundred-thousand, since containment failure is necessary for a large release to occur. These values

⁸² U.S. NRC, “Safety Goals for the Operation of Nuclear Power Plants; Policy Statement,” *Federal Register* 30028, August 21, 1986. See also, U.S. NRC, *Federal Register* **51**, 28044 (4 August 1986); cited in David Okrent, “The Safety Goals of the Nuclear Regulatory Commission, *Science*, **236**, 296-300 (17 April 1987). See Also: Richard R. Meserve, Chairman, NRC, “The Evolution of Safety Goals and Their Connection to Safety Culture,” Speech before the Atomic Energy Society of Japan/American Nuclear Society Meeting on Safety Goals and Safety Culture, Milwaukee, Wisconsin, June 18, 2001 <http://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2001/s01-013.html>

have evolved into the “benchmark” values of 10^{-4} for CDF and 10^{-5} for large early release frequency (LERF), as discussed in Regulatory Guide 1.174 for use in risk informed regulatory decision-making.³

² U.S. NRC, Staff Requirements Memorandum on SECY-89-102, “Implementation of the Safety Goals,” June 15, 1990.

³ U.S. NRC, Regulatory Guide 1.174, “An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis, July 1998.

US NRC Regulatory Guide 1.174, to which Commissioner Meserve referred, states:

While there is no requirement to calculate the total CDF [core damage frequency], if there is an indication that the CDF may be considerably higher than 10^{-4} per reactor year, the focus should be on finding ways to decrease rather than increase it. Such an indication would result, for example, if (1) the contribution to CDF calculated from a limited scope analysis, such as the individual plant examination (IPE) or the individual plant examination of external events (IPEEE), significantly exceeds 10^{-4} , (2) a potential vulnerability has been identified from a margins-type analysis, or (3) historical experience at the plant in question has indicated a potential safety concern.⁸³

In sum, the US NRC now assumes the following quantitative safety goals for accident risk:

- The risk to an average individual in the vicinity of a nuclear plant of prompt fatality should not exceed 0.1% of the prompt fatality risk from other accidents (or 10^{-7} /yr), and related to the US NRC’s desire for defense in depth, two subsidiary quantitative safety goals:
 - a core damage frequency (CDF) goal of 10^{-4} /yr, and
 - a large early release frequency (LERF) goal of 10^{-5} /yr.
- And the risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1 percent) of the sum of cancer fatality risks resulting from all other causes.

Neither “core damage” nor “core damage frequency” was precisely defined when these safety goals were enunciated. We thus turned to the US NRC’s web-based glossary and a report by the Institute of Nuclear Power Operations (INPO) for further insight. In its web-site glossary, “Core damage frequency (CDF)” is defined by the US NRC to mean “An expression of the likelihood that, given the way a reactor is designed and operated, an

⁸³ NRC, Regulatory Guide 1.174, “An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis,” November 2002.
<http://www.nrc.gov/reading-rm/doc-collections/reg-guides/power-reactors/rg/01-174/>

accident could cause the fuel in the reactor to be damaged;”⁸⁴ and “Large early release frequency (LERF)” is defined as “the frequency of those accidents leading to significant, unmitigated releases from containment in a time frame prior to effective evacuation of the close-in population such that there is a potential for early health effects.”⁸⁵ As will be seen from the discussion below, INPO distinguishes major fuel damage events caused, for example, by improperly managed reactivity additions, thermal-hydraulic transients, obstructions in coolant channels and overheating, from minor fuel damage events resulting, for example, from fabrication flaws.⁸⁶

Initially the US NRC’s quantitative goals were not used in individual reactor licensing decisions because of reservations about probabilistic risk assessment. Moreover, as Martin Malsch notes, in developing the goals, no explicit consideration was given to potential environmental damage from severe accidents, the severe accident safety risk to populations (and opposed to individual safety risk), the increased severe accident risk from multi-unit sites, or the potential for large socioeconomic costs of severe accidents. Also, as Malsch notes:

Reservations about PRA [probabilistic risk assessment] are now largely resolved; for example NRC’s reactor inspection and oversight program now includes quantitative risk metrics based on the 10^{-4} /yr CDF goal; an existing reactor with a CDF significantly greater than 10^{-4} /yr would not be allowed to continue operation without further risk reduction.

Other countries’ CDF goals range from 10^{-4} /yr to 10^{-5} /yr.

Other countries’ LERF goals range from 10^{-5} /yr to 10^{-7} /yr.

But comparisons are difficult because of different definitions of core damage and large early release.⁸⁷

Reassessing the frequency of reactor core damage events. There have been enough major fuel damage events, i.e., core damage, that we can ask whether the operational nuclear power plants throughout the world are safe enough as a group. For this purpose we will use as our primary benchmark the CDF goal of 10^{-4} /yr.

As noted above, experts differ regarding the level of core or fuel damage that needs to occur before the event should be counted in assessing CDF. With this caveat in Table 1

⁸⁴ <http://www.nrc.gov/reading-rm/basic-ref/glossary/core-damage-frequency.html>

⁸⁵ US NRC Regulatory Guide 1.174, footnote 3.

⁸⁶ See Institute of Nuclear Power Operations, “In-reactor Fuel-damaging Events: A Chronology 1945-1990,” INPO 91-008, July 1991. <http://research.greenpeaceusa.org/?a=download&d=434>

⁸⁷ Martin G. Malsch, “US Nuclear Power Reactor Safety Goals and Protection from Natural Phenomena,” International Workshop on Nuclear Safety: Improving Safety in the Aftermath of the Fukushima Crisis, Beijing, China, June 29, 2011.

we record 25 instances of fuel damage that have occurred in 24 nuclear power plants.⁸⁸
The 24 reactors are:⁸⁹

1. Experimental Breeder Reactor-I (EBR-I)
2. Sodium Reactor Experiment (SRE)
3. Stationary Low-Power Reactor No. 1 (SL-1)
4. Enrico Fermi Reactor-1
5. Ågesta
6. Chapelcross-2
7. St. Laurent A-1
8. Lucens Experimental Power Reactor
9. St. Laurent A-2
10. Dresden-3
11. Three Mile Island-2
12. Hatch-1
13. Surry-1
14. Arkansas Nuclear One-1
15. Oyster Creek (two core damage events)
16. Atucha-1
17. Chernobyl-4
18. Limerick-1
19. Pickering A-1
20. Hadden Neck (Connecticut Yankee)
21. Greifswald-5
22. Fukushima Dai-ichi-1
23. Fukushima Dai-ichi-2
24. Fukushima Dai-ichi-3

Following INPO's lead, in Table 1, events involving minor fuel damage resulting from fabrication flaws or damage that occurred during fuel handling are excluded.⁹⁰ Also excluded are fuel damage events resulting from vibration or erosion from coolant flow (baffle jet impingement) because such damage could have occurred without the reactor ever being critical.⁹¹

⁸⁸ Oyster Creek Generating Station experienced two fuel failure events.

⁸⁹ Absent from this list are events at reactors that were not designed to produce electricity, including events with major fuel damage at research and test reactors—National Research Experiment (NRX) (December 12, 1952) and Heat Transfer Reactor Experiment (HTRE-3) (November 8, 1958), Westinghouse Testing Reactor (WTR) (April 3, 1960), Oak Ridge Research Reactor (July 1, 1963)—and at military production reactors that were not dual-use and connected to the grid—Hanford (October 3, 1954), Hanford (January 5, 1955), Windscale (October 7, 1957). Windscale Pile 1, an air-cooled, graphite-moderated plutonium production reactor, was destroyed by a fire in October 1957. Windscale Piles 1 and 2 were both permanently shut down following the fire in Pile 1.

⁹⁰ See Institute of Nuclear Power Operations, "In-reactor Fuel-damaging Events: A Chronology 1945-1990," INPO 91-008, July 1991.

⁹¹ *Ibid.*

All 24 reactors produced electricity. Twenty-two of the reactors—all except EBR-I and SL-1—were connected to the grid during some period of their operation. Seven reactors—Lucens, TMI-2, Chernobyl-4, Greifswald-5 and Fukushima Dai-ichi-1, -2, and 3—were permanently shut down as a consequence of reactor accidents resulting in partial core melt or fuel damage. After 18 accidents at 17 reactors, the fuel melt or damage did not result in immediate closure of the plant; rather the damage was repaired and the reactor was restarted. However, in three cases—SER, SL-1 and Fermi-1—the reactors only operated for a short period of time following the fuel damage incident. Sixteen of the 24 power reactors are now permanently shut down. Eight reactors—Dresden-3, Hatch-1, Surry-1, Arkansas Nuclear One-1, Oyster Creek, Atuche-1, Limerick-1 and Pickering A-1—are still operational.

In assessing the historical core melt frequency among nuclear power reactors, the number counted depends on how the issue is framed. EBR-I, SL-1 and Lucens can be excluded on the basis that they were experimental reactors. EBR-I produced electricity but was not connected to the grid. The SL-1 design was abandoned after the accident. Although it was the first U.S. reactor to supply electricity to the grid, the SRE could be excluded because it was primarily a research reactor. Ågesta was an early small design. Chapelcross-2 and St. Laurent A1 and A2 were dual use military reactors, producing plutonium for weapons and electricity for civilian use. Ågesta was also intended to be a production reactor. Thus, reasoned arguments can be advanced for excluding up to eight reactors/events of the 25 events at the 24 reactors. It is difficult to make a case that any of the remaining 17 events at 16 reactors should be excluded.

Also notable is how the frequency of fuel damage events varies over time. There were two events in the 1950s, six in the 1960s, three in the 1970s, 11 in the 1980s, and three to-date in the 2010s. The absence of events between 1990 and the Fukushima events may reflect a lack of documentation rather than a lack of events. We will assume there were no, or only a few, events during this period. Thus, before Fukushima the historical CDF data suggested that power reactor operations were becoming significantly safer over time—a case that has become more difficult to make after Fukushima.

Worldwide, there have been 141 nuclear power plants that have been shut down after becoming operational with a total generating capacity of about 43,811 mega-watts electric (MWe) and about 3,077 reactor-years of cumulative operation.⁹² Excluding EBR-I and SL-1, 14 experienced fuel damage.⁹³ Thus, one in ten ($141/14 = 10.1$) shut down power reactors experienced some form of fuel damage during their operation. Even excluding experimental and dual-purpose production reactors (EBR-I, SRE, SL-1, Ågesta, Chapelcross-2, Lucens and St. Laurent A-1 and A-2, for example) one in 15

⁹² This sum excludes production reactors that were not dual-use and connected to the grid and the U.S. reactors, EBR-I, SL-1, ML-1, PM-1, PM-2A, PM-3A, SM-1, SM-1A and Sturgis. Although it produced electricity, EBR-I and SL-1 are excluded because they were not connected to the grid. The German KNK-I and KNK-II reactors are treated as one reactor.

⁹³ The 14 shut down reactors that experienced fuel damage counted here are SER, Fermi-1, Ågesta, Chapelcross-2, Lucens, St. Laurent A-1 and A-2, TMI-2, Chernobyl-4, Hadden Neck, Greifswald-5, and Fukushima Dai-ichi-1, -2 and -3.

($108/7=15.4$) shut down power reactors experienced some form of fuel damage during their operation.

Of the power reactors that have been shut down, seven—Lucens, TMI-2, Chernobyl-4, Greifswald-5, Fukushima Dai-ichi-1, -2, -3—were shut down as a direct consequence of partial or full core melt accidents—one in 20 ($141/7 = 20.1$) reactors, or one for every 440 reactor-years ($3,077/7 = 440$) of operation. Excluding experimental (e.g., Lucens) and dual-purpose production reactors, one in 18 ($108/6 = 18.0$) were shut down as a direct consequence of partial core melt accidents. With the same exclusions only about nine out of ten giga-watts (GW) ($(40,545-4,068)/40,545 = 0.9$) of nuclear power plant capacity have been closed without experiencing a fuel damage accident. One out of 10 GW ($40,545/4,068 = 10$) of nuclear power plant capacity have been closed as a direct result of a fuel melting accident.

Worldwide, there have been 593 nuclear power reactors that have operated approximately 14,400 reactor-years.⁹⁴ Thus, to date, the historical frequency of core damage is about one in 600 reactor-years ($14,400/23 = 626$). Even if one excluded nine of the fuel damage events—thus discounting the least severe core damage events—the CDF is still one in 1,000 reactor-years, or an order of magnitude greater than what the US NRC deemed acceptable.

Worldwide, there have been 433 Light Water Reactors (LWRs) that have operated, of which 74 have been shut down and 359 remain operational. Among LWRs there have been 13 core damage events in 12 LWRs. Five of these were serious partial core melt downs—TMI-2, Greifswald-5, Fukushima-1, -2, -3. More than one percent of the LWRs have experienced a serious core melt down. Four of the five generated a hydrogen explosion. One of the four hydrogen explosions (at TMI-2) was contained, but then we are not counting the hydrogen explosion at Fukushima Dai-ichi-4 which appears to have resulted from the core melt event at Fukushima Dai-ichi-3.

Worldwide, there have been 117 Boiling Water Reactors (BWRs) that have operated approximately 3,100 reactor-years. Thus, to date, the historical frequency of core-melt accidents in BWRs is about one in 1,000 reactor-years ($3,100/3 = 1,033$).

Worldwide, there have been 49 BWRs with Mark 1 containments (the type at Fukushima) and 12 with Mark 2 containments. Five with Mark 1 containment (Millstone Unit 1 and Fukushima Dai-ichi Units 1-4) have been permanently shut down. These 61 BWRs have operated for 1,900 reactor-years to date. Thus, to date, the historical frequency of core-melt accidents in BWRs with Mark 1 and 2 containments is about one in 630 reactor-years ($1,900/3 = 633$).

Clearly, the historical frequency of core damage events worldwide does not measure up to the safety objectives of the US NRC. On the whole, the operational reactors worldwide are not sufficiently safe. If one believes U.S. reactors on the whole are safer than those in most other countries, the logical conclusion is that the reactors in these other countries

⁹⁴ See footnote 92.

are somewhat less safe than indicated by the worldwide historical frequency of core damage.

If nuclear power is to have a long-term future, greater attention must be given to the safety of current operational reactors worldwide. Older obsolete designs should be phased out rather than having their licenses extended.⁹⁵ Reactors currently under construction worldwide and those on the drawing board must be made safer than operational reactors.

We offer two additional observations regarding the use of probabilistic risk assessments (PRAs) and the NRC safety goals. First, the NRC increasingly relies upon core-melt frequency estimates from PRA studies. While PRA analyses provide a useful *relative* measure of safety, given the large uncertainties of many input assumptions we do not believe quantitative risk calculations reliably measure the *absolute* frequency of low-probability catastrophic accidents. As but one example of why the absolute frequency values are unreliable, prior to Fukushima PRAs did not include scenarios where major events such as a hurricane, tornado or other severe weather conditions result in the loss of offsite power for more than 24 hours. Rather, the PRA analyses assumed offsite power would be restored within a few hours, and thus the PRAs were typically not run for more than 24 hours after the accident is initiated.

For the second observation we return to the two US NRC's quantitative safety goals:

- The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1 percent) of the prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed.
- The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1 percent) of the sum of cancer fatality risks resulting from all other causes.

While these risk limits are typically compared against PRA estimates of frequency of accident scenarios multiplied by their consequences, we have taken a different approach. We compare the Fukushima consequences to the safety goals. In this comparison the operation of the Fukushima Dai-ichi nuclear plants, even accounting for the radioactive releases from the disaster, meet these two NRC safety goals. There were no prompt radiation fatalities due to the Fukushima accident. There were about 60,000 persons living within 20 km (12.6 mi) of Fukushima Dai-ichi. Over their lifetimes one would expect about 12,000 (20 percent) cancer fatalities from other causes. One-tenth of one percent of this amount is 12 cancer fatalities. Since the population was evacuated, less than 12 cancer fatalities are expected in this population from Fukushima.

⁹⁵ In the United States 71 of the 104 operational reactors have been granted 20-year license renewals by the NRC. See US NRC, "Status of License Renewal Applications and Industry Activities," updated July 25, 2011. <http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html>

Thus, on their face, we believe these two individual-risk safety goals are inadequate. At the very least, explicit consideration needs to be given to potential environmental damage from severe accidents, the severe accident safety risk to populations (as opposed to individual safety risk), and the potential for large socioeconomic costs of severe accidents.

Which reactors are located in areas that represent the greatest challenge if evacuation of the surrounding population is required or impose an undue economic risk to the local, regional or national economies in the event of a partial core melt accident?

Immediately following the earthquake and tsunami residents within 20 kilometers (km) (12.4 miles) of Fukushima Dai-ichi were evacuated and those between 20 and 30 km (12.4 to 18.6 miles) were advised to remain in their homes as shelter or voluntarily evacuate. Subsequently, the Japanese government considered extending the evacuation zone to 30 km but ended up establishing a 20 milli-Sievert per year (mSv/y) or 2 rem/y dose limit for establishing which areas would be evacuated. Also notably, shortly after the Fukushima accident began to unfold the US NRC was so concerned regarding how the accident might progress that it recommended that U.S. citizens stay at least 50 miles away. Some criticized the US NRC Chairman for this action. Given the uncertainties at the time the decision was made, and the fact that the Japanese mandatory evacuation standard, 20 mSv/y, ultimately impacted people out to about 75 km (46.5 miles), we believe the US NRC action was appropriate.

Based on Japanese census data, we estimate that before evacuation there were 69,000 people within 20 km (12.4 miles), 160,000 within 30 km (18.6 miles), and 2 million within 80 km (50 miles) of the Fukushima Dai-ichi reactor station.

As seen from Table 2, worldwide there are 135 reactor sites that have a greater number of people residing within 30 km of the reactor station than were residing within 30 km of Fukushima Dai-ichi; including 21 reactor stations with more than one million people within 30 km.⁹⁶ Topping the list is the 125 MWe Karachi Nuclear Power Plant (KANUPP) in Pakistan, which has 8.3 million people within 30 km of the reactor. Two reactor stations on Taiwan—Kuosheng (2 operational reactors) and Chin Shan (2 operational reactors) have 5.5 million and 4.7 million people, respectively, living within 30 km; two adjacent stations in South Korea—Kori and Shin-Kori (5 operational reactors, 3 under construction and 2 planned) and two on the Chinese mainland—Guangdong/Daya Bay (2 operational reactors) and Ling’ao (4 operational reactors) have more than 3 million people within 30 km. A severe nuclear accident at any one of these stations could have devastating consequences for the entire country. Figure 1 displays a histogram of populations within 30 km of a reactor, worldwide.

⁹⁶ Calculations by Declan Butler, Senior Reporter, *Nature*, France, private communication.

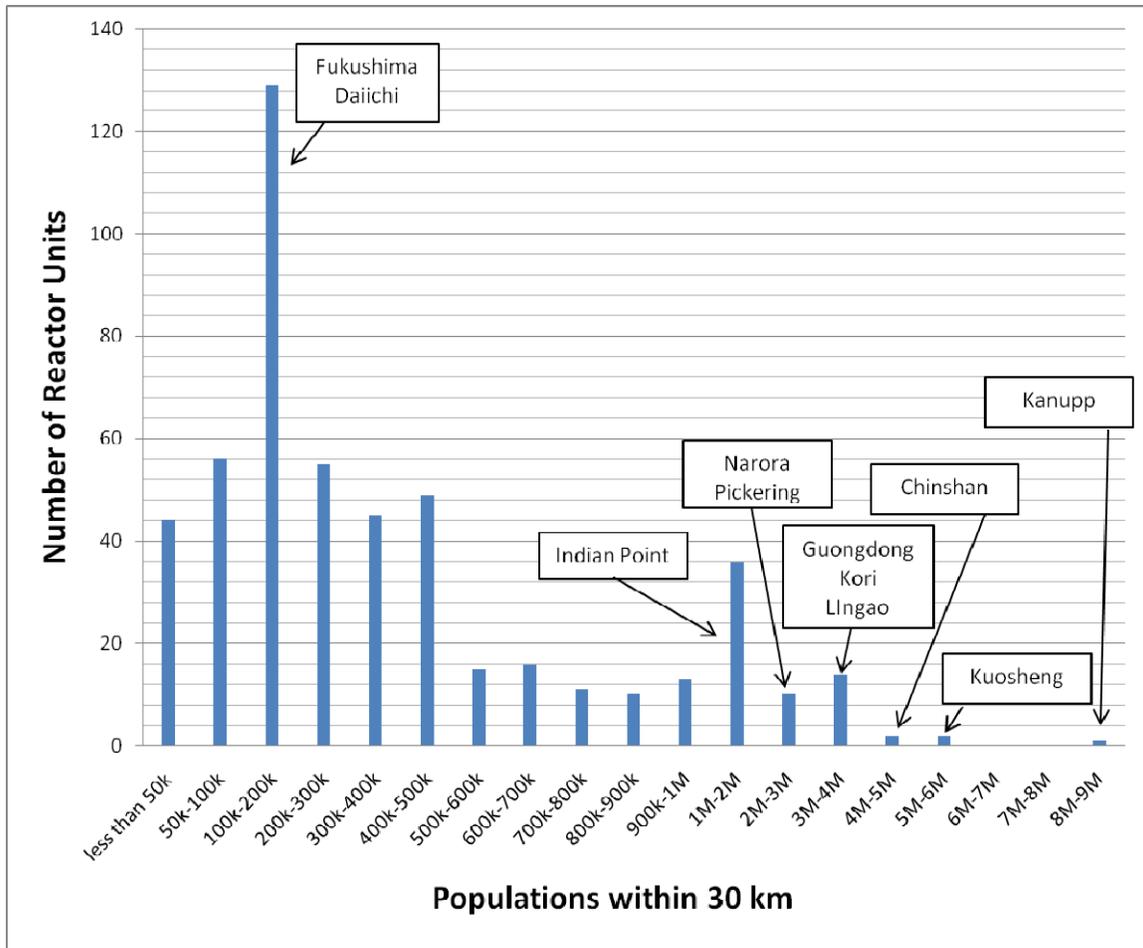


Figure 1: Histogram of populations within 30 km of nuclear power reactors, worldwide.

Which reactors are located in areas that are in areas of high risk to earthquakes and tsunamis?

In a database maintained at NRDC, we have recorded the coordinates for 442 operational reactors in 31 countries, the majority of which are in North America and Western Europe. The geographic distribution of reactors worldwide may be analyzed with respect to two natural hazards that contributed to the accident at Japan's Fukushima Dai-ichi nuclear power plant: seismic and tsunami risks.

Seismic hazard data was obtained from the Global Seismic Hazard Assessment Program (GSHAP), a demonstration program launched in 1992 by the International Lithosphere Program with the support of the International Council of Scientific Unions, and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction. The GSHAP data is available for download at <http://www.seismo.ethz.ch/static/GSHAP/global/>, and consists of gridded seismicity hazard values in 0.1 decimal degree intervals in latitude and longitude. These seismicity hazard values are given in units of Peak Acceleration (m/s^2) with 10% Probability of Exceedance in 50 Years. In these units, 0.0 to 0.8 are classified as a "Low Hazard;" 0.8 to 2.4 as a "Moderate Hazard;" 2.4 to 4.0 as a "High Hazard;" and greater than 4.0 as a

“Very High Hazard.” Figure 2 charts the number of operational reactors located in the given seismic hazard zones.

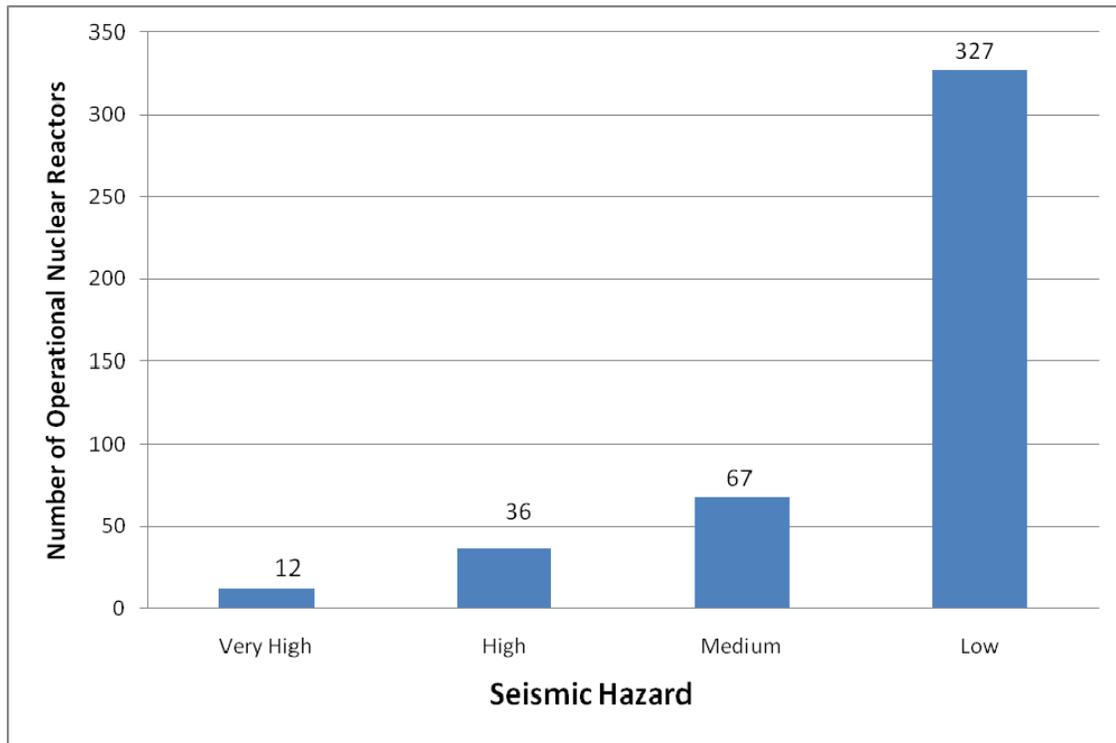


Figure 2: Numbers of operational reactors within very high, high, medium and low seismic hazard areas, as determined by the GSHAP seismic hazard data.

The 12 operational nuclear reactors within very high seismic hazard areas are listed in Table 3, and are located in Japan and Taiwan, including all of Taiwan’s six operating reactors.

In May of 2011 Japanese Prime Minister Naoto Kan requested that the Hamaoka Nuclear Power Plant be shut down, due to predictions that an earthquake of magnitude 8.0 or higher has an 87% likelihood of occurring in the area of the plant within the next 30 years. The plant remains shut and the reactors may begin decommissioning, pending the outcome of lawsuits. The three nuclear reactors at the Onagawa Nuclear Power Plant remain in cold shutdown following the March 11th earthquake and tsunami.

In addition to the six operating nuclear reactors in Taiwan located in a very high seismic hazard area, two additional reactors are under construction at Lungmen: Lungmen Unit 1 is expected to begin commercial operation at the end of 2011.

Of the 36 operating nuclear reactors in the high seismic risk category, 29 are in Japan, 4 in the United States and one each in Armenia, Iran (Bushehr) and Slovenia (Krško). The 67 operating nuclear reactors in the medium seismic risk area include 15 in Japan, 10 in

France, 5 in South Korea, and 5 in the United States. Figure 3 shows a map of seismic hazard areas in Asia and the locations of operating nuclear reactors.

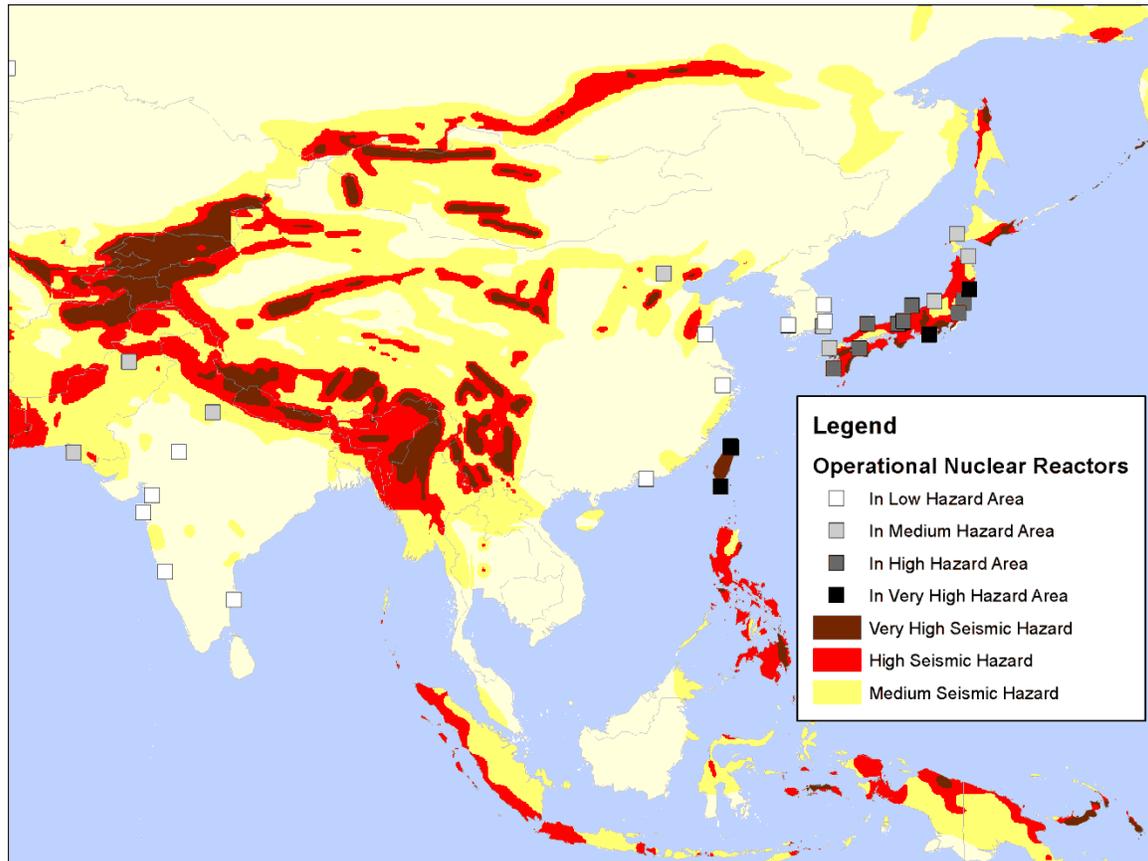


Figure 3: GSHAP seismic hazard data and operational nuclear reactors in Asia.

The degree to which an earthquake will damage a nuclear reactor depends not only on the magnitude of the earthquake, but also on the reactor's seismic design basis. We note that the reactors at Fukushima Dai-ichi appear to have withstood the March 11th earthquake, but the damage from the earthquake to the electric grid contributed to causing the station blackout conditions.

A world database of tsunami events is maintained by the US National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC), at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml. Tsunami events are mapped in Figure 4, with increasing symbol size for increasing wave height. The majority of tsunami events for wave heights greater than 10 meters have occurred in: Indonesia, the United States, Japan, Tonga (an archipelago in the South Pacific Ocean) and in the Russian Far East regions. The locations of operating nuclear reactors are also shown in Figure 4.

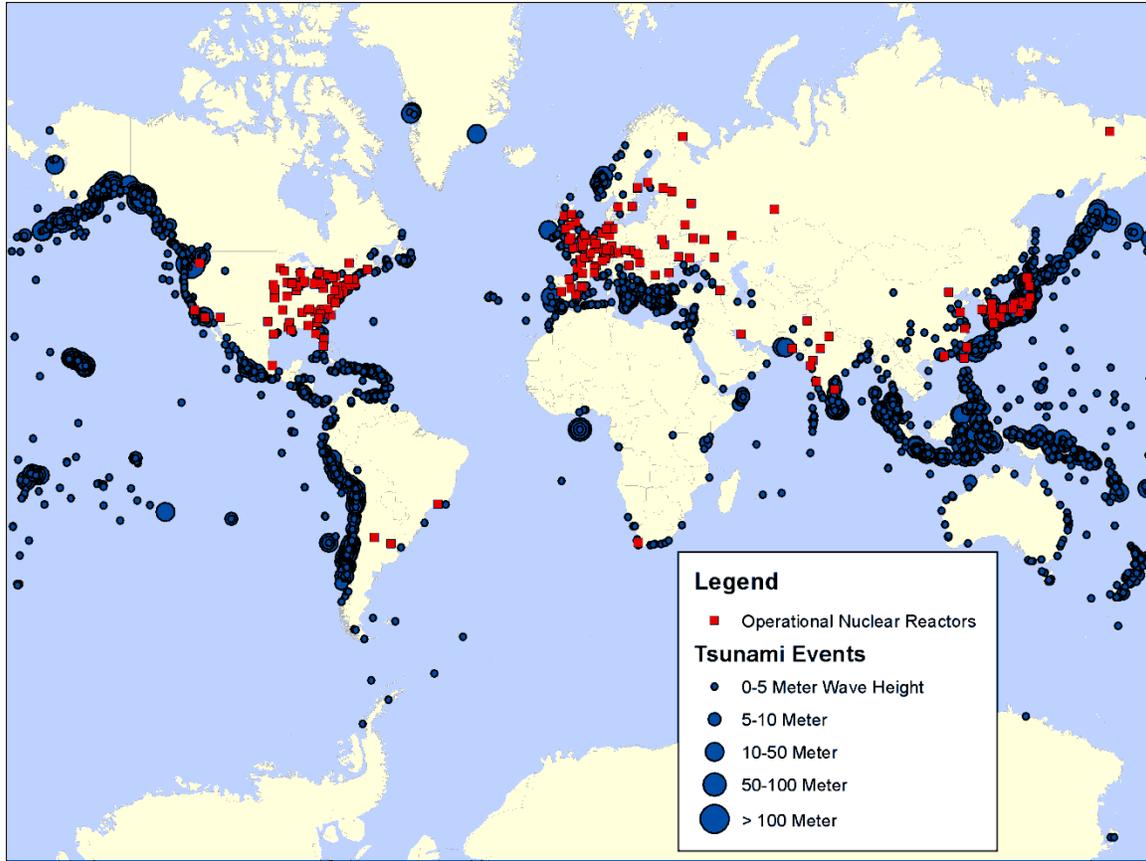


Figure 4: NOAA historical tsunami event locations and operational nuclear reactors.

With respect to earthquake and tsunami hazards, and large nearby populations, Taiwan's six reactors represent outliers in terms of high risks and consequences from a nuclear reactor accident. In order to explore these implications further, we used the US Department of Defense computer model HPAC (Hazard Prediction and Assessment Capability, version 4.0.4, April 2004, Defense Threat Reduction Agency), which can calculate a radioactive source term for incidents at commercial nuclear reactors.⁹⁷

For a given reactor HPAC permits the user to compute two pre-packaged nuclear facility scenarios:

A moderate incident involving core damage from the result of a reactor accident, assuming that the core containment is not breached. The source term mainly involve the noble gas components of the reactor inventory.

⁹⁷ The HPAC documentation describes the code as: "...a counter proliferation, counterforce tool that predicts the effects of hazardous material releases into the atmosphere and its collateral effects on civilian and military populations. HPAC assists warfighters in destroying targets containing weapons of mass destruction (WMD) and responding to hazardous agent releases. It employs integrated source terms, high-resolution weather forecasts and particulate transport algorithms to rapidly model hazard areas and human collateral effects."

A severe incident involving very serious damage to the reactor core and an associated breach in the reactor containment. This results in a large release of radionuclides to the environment.

The HPAC code contains information on specific commercial nuclear reactors used in the radioactive source term calculation, including: geographic coordinates, thermal power, and a radionuclide inventory in the core. For the severe incident calculation, HPAC computes 5 releases of radioactivity with a total duration of two days.

The Chinshan and Kuosheng nuclear power stations lie on the northern tip of Taiwan, less than 50 kilometers from downtown Taipei. The results of HPAC calculations for Chinshan-1 and Kuosheng-1 are shown in Figures 5 and 6, respectively. In each case a severe radioactivity release was assumed; historical Taiwan weather data were used—for a release beginning at noon in August—assuming no precipitation and broken cloud cover; and terrain effects were included. As can be seen from Figures 5 and 6, under these conditions the plumes would travel south from the reactors over areas of high population density in the direction of Taipei. The dose rates contours are displayed in these figures, and may be compared with the evacuation threshold used by the Japanese government with respect to the Fukushima Dai-ichi accident of 0.22 mrem per hour, or about mid-way between the orange and yellow contours in Figures 5 and 6. Population density is also shown in these figures, along with the computed expected populations within the given contour.

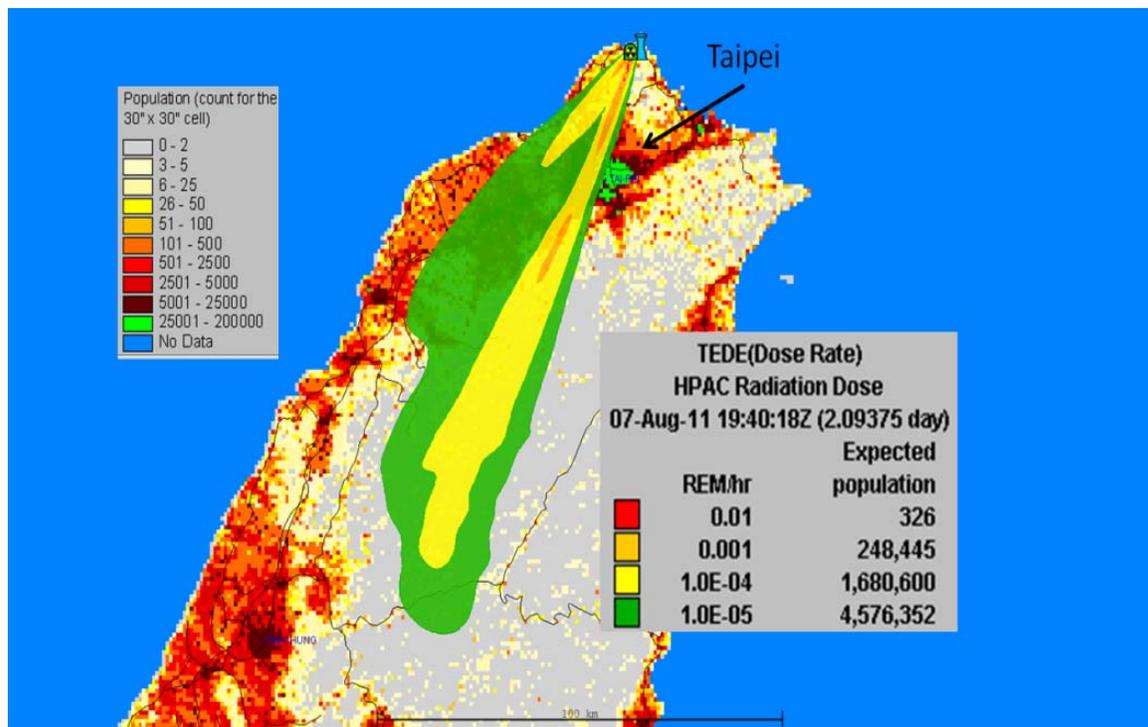


Figure 5: HPAC calculation of dose rates from a severe incident at Taiwan's Chinshan-1.

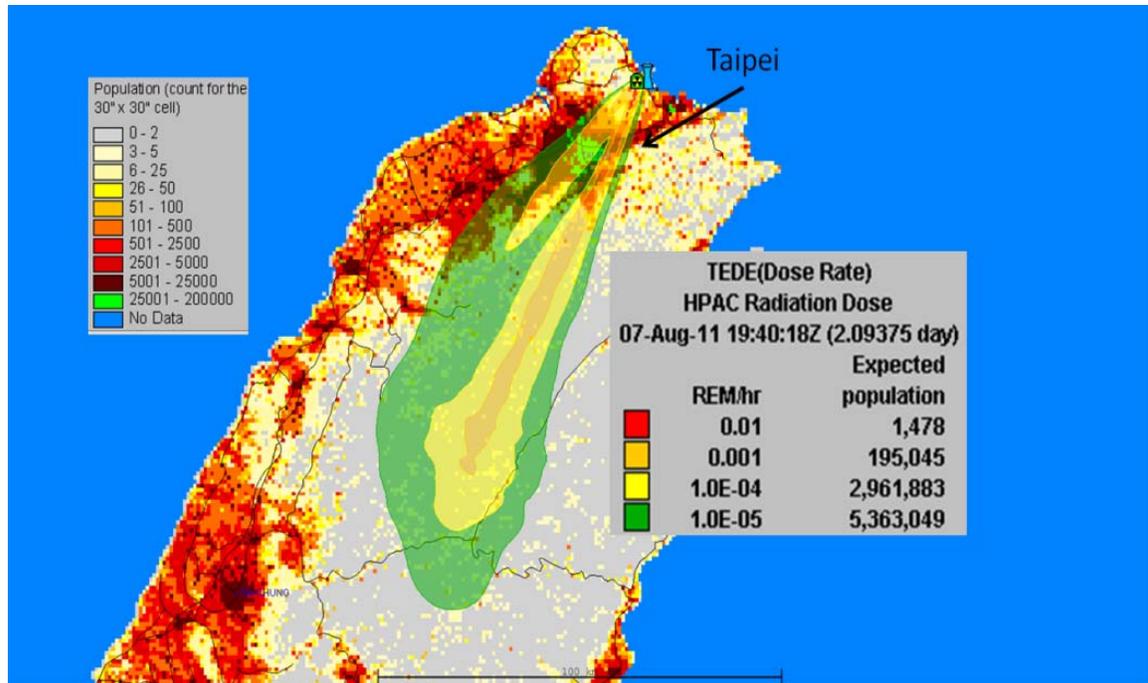


Figure 6: HPAC calculation of dose rates from a severe incident at Taiwan's Kuosheng-1.

An HPAC severe incident calculation for Maanshan-1 (not shown) predicts that the plume would travel southwards out to sea for similar weather conditions. However, the coastal residents in the vicinity of the reactor are predicted to experience a high dose rate, greater than 10 mrem per hour, a population estimated by HPAC to be 3,500 persons.

What additional improvements should be made to cope with hydrogen production in the event of Zircaloy fuel clad interactions with steam?

In 2001, the OECD Nuclear Energy Agency reported that computer analyses using “[t]he available Zircaloy-steam oxidation correlations were not suitable to determine the increased hydrogen production in the [CORA and LOFT LP-FP-2] experiments.”⁹⁸ The LOFT LP-FP-2 experiment, conducted in 1985, is considered “particularly important in that it was a large-scale integral experiment that provides a valuable link between the smaller-scale severe fuel damage experiments and the TMI-2 accident.”⁹⁹ Furthermore, an Oak Ridge National Laboratory report from 1990, discussing the CORA-16 experiment, states that “[t]he predicted and observed cladding thermal response are in

⁹⁸Nuclear Energy Agency (NEA) Groups of Experts, OECD Nuclear Energy Agency, “In-Vessel and Ex-Vessel Hydrogen Sources,” NEA/CSNI/R(2001)15, October 1, 2001, Part I, B. Clément (IPSN), K. Trambauer (GRS), W. Scholtyssek (FZK), Working Group on the Analysis and Management of Accidents, “GAMA Perspective Statement on In-Vessel Hydrogen Sources,” p. 9. <http://www.oecd-nea.org/nsd/docs/2001/csni-r2001-15.pdf>.

⁹⁹NEA. OECD, “In-Vessel Core Degradation in LWR Severe Accidents: A State of the Art Report to CSNI,” NEA/CSNI/R(91)12, January 1991, S.R. Kinnersly, *et. al.* p. 3.23. <http://www.oecd-nea.org/nsd/docs/1991/csni-r91-12.pdf>

excellent agreement until application of the available Zircaloy oxidation kinetics models causes the low-temperature [1,652-2,192°F] oxidation to be under-predicted.”¹⁰⁰

The US NRC is currently reviewing a petition for rulemaking PRM-50-93,¹⁰¹ that among other things, requests that the US NRC require that the rates of energy release, hydrogen generation, and cladding oxidation from the Zircaloy-steam reaction considered in computer analyses of postulated loss-of-coolant accidents (LOCA) be based on data from multi-rod bundle severe fuel damage experiments (*e.g.*, the LOFT LP-FP-2 experiment).

If indeed, as experimental data indicates, computer analyses under-predict the total amount of hydrogen that would be generated in an accident, the design basis accidents of light water reactors need to be reassessed to determine the extent to which their power ratings should be reduced.

We have now experienced five serious partial core meltdown accidents in light water reactors—at TMI-2, Greifswald-5 and Fukushima Dai-ichi-1, -2, and -3—more than one percent of the total that have operated. Four of these (Greifswald-5 being the exception) were accompanied by a hydrogen explosion, with the three at Fukushima causing serious damage.

The United States Department of Energy is funding research and development of advanced fuel cladding designs based on silicon carbide (SiC). SiC is a ceramic material that has high strength and very low chemical reactivity at high temperatures when compared to zirconium alloys. SiC decomposes at 4900°F compared to a melting point of 3370°F for zirconium. The use of such fuel cladding materials would substantially diminish the likelihood of hydrogen production in core melt accidents. Consequently the development, qualification and required use of these advanced fuel cladding materials should be accelerated.

Principal Conclusions

The historical frequency of core melt accidents worldwide does not measure up to the safety objectives of the US NRC. On the whole the operational reactors worldwide are not sufficiently safe. If nuclear power is to have a long term future greater attention should be given to current operational reactors. Older obsolete designs should be phased out rather than having their licenses extended. We should also revisit whether the newer reactors currently under construction worldwide and those on the drawing board are safe enough. Because of differences in the number of reactors, the reactor safety cultures and the quality of regulatory oversight the next nuclear power plant disaster is more likely to occur somewhere outside of the United States.

¹⁰⁰ L. J. Ott, Oak Ridge National Laboratory, “Report of Foreign Travel of L. J. Ott, Engineering Analysis Section, Engineering Technology Division,” ORNL/FTR-3780, October 16, 1990, p.3.

<http://www.osti.gov/bridge/servlets/purl/6434331-64LUUI/6434331.pdf>

¹⁰¹ Mark Leyse, PRM-50-93, November 17, 2009, located at www.nrc.gov, ADAMS Public Documents (Accession No.: ML093290250).

In light of an improved scientific understanding of the full range of natural and man-made “beyond design basis” events that could strike nuclear plants, the risk of core melt followed by failure of containment should be stringently reevaluated for existing and new reactors located in areas of high population density and high risk from natural disasters. Under these revised conditions, the feasibility of an adequately protective evacuation and the potential for severe economic damage extending 30 km and beyond should be reassessed. The severity of the resulting radiological and other risks to life, property, and natural resources should inform regulatory decisions regarding which units should have their operating licenses shortened or construction permits revoked.

Countries should make comprehensive reassessments of the risks due to all the principal severe accident precursors, including the risks associated with earthquakes (beginning with those in areas of known high seismic risk), flooding, fires and malevolent acts at all reactor sites, and tsunamis, hurricanes and typhoon of coastal reactors. These studies and assessments should be conducted before further reactor license extensions are granted.

Table 1: Nuclear Power Reactors that have Experienced Fuel Damage.¹⁰²**1. Experimental Breeder Reactor I (EBR-I)****Location:** Idaho National Laboratory, Idaho, USA**Reactor type:** Liquid Metal Fast Breeder Reactor (LMFBR)**Power:** 1.2 MWt; 0.2 MWe**History:** initial criticality: December 20, 1951; world's first electricity generating nuclear power plant; on November 29, 1955 a slow scram instead of a required fast scram was activated manually to terminate a planned transient. (For these experiments, the automatic fast scram capability, which was added to the reactor to compensate for a design weakness, was bypassed in the automatic mode.) About 50 percent of the core melted. The sodium-potassium coolant boiled, forcing molten fuel into the blanket-reflector region. Reactor shut down December 30, 1963.**2. Sodium Reactor Experiment (SER)****Location:** Santa Susana Field Laboratory, California, USA**Reactor type:** sodium-cooled graphite-moderated thermal power reactor**Power:** 20 MWt; 6.5 MWe**History:** initial criticality: April 25, 1957; first produced electricity July 1957; operated 2 years, partial core melt accident between 12 and 26 July 1959, resulting in melting of as much as one-third of the fuel; shutdown 26 July 1959 (It appears to have been operated for several days with its core partially melted.); converted to HEU-Th fuel; second core operations began September 1960; permanently shutdown February 1964.**3. Stationary Low-Power Reactor No. 1 (SL-1)****Location:** National Reactor Testing Station (now Idaho National Laboratory)**Reactor type:** experimental, gas-cooled, water-moderated**Power:** 3.3 MWt; 300 kWe**History:** initial criticality March 1961; on January 3, 1961, in the process of working on control rod mechanisms, the center control rod was lifted manually by an excessive amount. A violent power excursion (prompt criticality) resulted, impaling the operator on the ceiling of the building and causing three fatalities, the only three people present. The facility was permanently shut down May 1964**4. Enrico Fermi Unit 1 Reactor****Location:** Newport, Lagoona Beach, Frenchtown Township, Monroe County, Michigan, USA**Reactor Type:** Liquid Metal Fast Breeder Reactor (LMFBR)**Power:** 200 MWt; 65 MWe (gross); 61 MWe (net)**History:** initial criticality 23 August 1963; commercial operations began August 1966; partial fuel melt accident 5 October 1966, two of the 105 fuel assemblies melted, but no contamination was recorded outside the containment vessel; closed November 1972**5. Ågesta Nuclear Power Plant****Location:** near Farsta, Sweden**Reactor Type:** Pressurized Heavy Water Reactor (PHWR)

¹⁰² Much of the history data are from the Institute of Nuclear Power Operations, "In-reactor Fuel-damaging Events: A Chronology 1945-1990," INPO 91-008, July 1991.

Power: 80 MWt; supplied 55 MWt heat; 12 MWe (gross); 10 MWe (net)

History: grid connection and commercial operation May 1964; in 1968 15 fuel assemblies failed due to spacer grid spring relaxation and flow vibration. The reactor was returned to service with modified fuel and permanently shutdown June 2, 1974.

6. Chapelcross Unit 2 Nuclear Power Plant

Location: Annan, Dumfrieshire, Scotland, United Kingdom

Reactor Type: gas-cooled, graphite moderated; Magnox

Power: originally 180 MWt, up-rated progressively to 265 MWt, originally 23 MWe (gross) progressively up-rated to 60 MWe (gross); 50 MWe (net)

History: startup May 1959; while under evaluation for the commercial reactor program experienced a partial blockage in a single fuel channel May 1967, contamination was limited to one region of the core; shut down 29 June 2004

7. Lucens Experimental Power Reactor

Location: underground at Lucens, Moudon, Switzerland

Reactor Type: heavy water moderated gas-cooled reactor

Power: 30 MWt, 7 MWe

History: start up 1962; generated electricity for the first time in January 1968; on January 21, 1969, the reactor was damaged irreparably during a startup because fuel channels were obstructed by corrosion products from moisture leakage into the carbon-dioxide reactor coolant. Fuel cladding melted, pressure tubes ruptured, and a violent reaction of molten metal with the carbon-dioxide coolant or heavy-water moderator occurred. Two-thirds of the core fuel inventory was released into the moderator. The reactor vessel was damaged severely, and over five tons of contaminated heavy water poured into the fuel-handling room beneath the reactor. The reactor is permanently shut down.

8. Saint-Laurent A-1 Nuclear Power Plant

Location: St. Laurent-Nouan, Loir-et-Cher, Centre, France

Reactor Type: gas-cooled, graphite moderated

Power: 1570 MWt; 405 MWe (gross), 390 MWe (net)

History: grid connection 14 March 1969; commercial operation June 1969; on October 17, 1969, a coolant flow restrictor was loaded into the fuel channel by manually overriding an automatic stop on the on-line refueling machine. One hundred and eighty kilograms of fuel were melted during subsequent operation. While off-site radioactivity releases were minimal and no one was injured, the reactor was shut down for one year to complete cleanup operations and repair. The reactor was permanently shut down 27 May 1992.

9. Dresden Unit 3 Nuclear Power Plant

Location: Morris, Grundy County, Illinois, USA

Reactor Type: Boiling Water Reactor (BWR), BWR-3 (GE2), Mark 1 containment

Power: 2,725 MWt; 867 MWe (gross)

History: initial criticality January 1, 1971; on October 31, 1974, the control rods were operated in a manner intended to achieve better burnup of the fuel in the bottom of the core. The control rod movements did not adhere to guidelines provided by the fuel vendor. The technical review completed prior to positioning the control rods was inadequate. A xenon transient was started, causing power peaking near the bottom of the core. The clad was perforated in localized areas,

resulting in a minor release of radioactivity. Replacement of a number of fuel elements was required. The nuclear power plant is currently operational.

10. Saint-Laurent A-2 Nuclear Power Plant

Location: St. Laurent-Nouan, Loir-et-Cher, Centre, France

Reactor Type: gas-cooled, graphite moderated

Power: 1690 MWt; 465 MWe (gross) (uprated to 530 MWe (gross)), 450 MWe (net)

History: started November 1970; grid connection 9 August 1971; commercial operation November 1971; heat excursion causing some fuel melting 13 March 1980; permanently shut down 27 May 1992

11. Three Mile Island Unit 2 Nuclear Power Plant

Location: Londonderry Township; Dauphine County, Pennsylvania, USA

Reactor Type: Pressurized Water Reactor (PWR)

Power: 2,568 MWt, 808 MWe (gross); 776 MWe (net)

History: initial criticality December 1978; partial core melt accident March 28, 1979; decommissioned 1979; plant conditions, including reactor coolant system water inventory, were misinterpreted during a transient triggered by a minor fault in a non-safety system. The high-pressure safety injection system was prematurely shut off, reactor coolant pumps were turned off, and a stuck-open pressurizer relief valve was not diagnosed and isolated. As a result, the reactor core was severely damaged, and highly contaminated water spilled into the containment and auxiliary buildings.

12. Edwin I. Hatch Unit 1 Nuclear Power Plant

Location: Baxley, Appling County, Georgia, USA

Reactor Type: Boiling Water Reactor (BWR), BWR-4 (GE3), Mark 1 containment

Power: 2,436 MWt; 810 MWe (gross)

History: initial criticality September 12, 1974; on September 20, 1981, while operating at 100 percent power, large quantities of cold feedwater were added to the reactor vessel in a short period of time causing a power transient that was controlled by the insertion of control rods. The control rod geometry that was utilized resulted in increased local power peaking. The resultant fuel failures caused air ejector activity to rise to 0.3 Ci per second. (The reactor had been operated before the transient with a high concentration of copper in the coolant for an extended period, possibly weakening the fuel rod cladding.) The nuclear power plant is currently operational.

13. Surry Unit 1 Nuclear Power Plant

Location: Gravel Neck, Surry County, Virginia, USA

Reactor Type: Pressurized Water Reactor (PWR), 3-loop

Power: 2,441 MWt, 822.6 MWe (gross); 781 MWe (net)

History: initial criticality July 1, 1972; on March 9, 1983, fuel rods were discovered damaged due to metal chips that had been left in the reactor coolant system. The steam generators had been replaced previously, and necessary standards of reactor system cleanliness had not been maintained. Five years of operation were required to remove the resultant contamination from the reactor coolant system. The nuclear power plant is currently operational.

14. Arkansas Nuclear One Unit 1 Nuclear Power Plant

Location: Russellville, Pope County, Arkansas, USA

Reactor Type: Pressurized Water Reactor (PWR), 2-loop

Power: 2,568 MWt; 883 MWe (gross)

History: initial criticality August 6, 1974; on September 26, 1983, a control rod, which had been misaligned approximately 90 inches for 12 days, was realigned while the reactor operated at 100 percent power. The resulting xenon oscillations further increased the already high local power peaking, damaging the fuel and increasing gaseous activity. The nuclear power plant is currently operational.

15. Oyster Creek Generating Station

Location: Lacey and Ocean Townships, Ocean County, New Jersey, USA

Reactor Type: Boiling Water Reactor (BWR), GE BWR/2, Mark 1 containment

Power: 1,930 MWt; 641 MWe (gross)

History: initial criticality May 3, 1969; on December 19, 1984, control rods were withdrawn to increase power. Local power exceeded prescribed limits when the on-line core monitoring system, not properly programmed and tested, underestimated peaking power. Gaseous activity subsequently increased. Post-shutdown inspection found fuel damaged in 44 assemblies. The nuclear power plant is currently operational.

16. Atucha Unit 1 Nuclear Power Plant

Location: Lima, Buenos Aires, Argentina

Reactor Type: Pressurized Heavy-Water Cooled and Moderated Reactor (PHWR)

Power: 1,100 MWt; 357 MWe (gross); 335 MWe (net)

History: initial criticality 1974; on June 14, 1985, with the plant operating in a load-following mode (normal operating mode was base-loaded), operators were asked to increase power. Control rod motion to compensate for xenon burnout resulted in abnormally high local power peaking. Indications of this excessive power generation were misinterpreted, and reactor operation continued. The excessive local power in the core caused 46 fuel rods to fail, releasing fuel pellets into the reactor coolant system. The nuclear power plant is currently operational.

17. Oyster Creek Generating Station

Location: Lacey and Ocean Townships, Ocean County, New Jersey, USA

Reactor Type: Boiling Water Reactor (BWR), GE BWR/2, Mark 1 containment

Power: 1,930 MWt; 641 MWe (gross)

History: initial criticality May 3, 1969; on December 18, 1985, power was increased too rapidly causing both excessive flux peaks and excessive local power increase rates. Computer program data, relied upon to guide power increases, inappropriately was based on previous fuel cycle operating data. Fuel rod failures resulted in increased levels of gaseous activity. The nuclear power plant is currently operational.

18. Chernobyl Unit 4 Nuclear Power Plant

Location: Pripyat, Ukraine SSR (now Ukraine)

Reactor Type: RBMK-1000 (graphite-moderated water-cooled)

Power: 3,200 MWt; 1,000 MWe (gross); 925 MWe (net)

History: destroyed in full-core melt accident 26 April 1986; during the performance of a turbine-generator coastdown test, a severe reactivity excursion was experienced that, with the accompanying power and pressure surge and fire, destroyed the reactor and the surrounding building. The test procedure had not been reviewed adequately from a safety standpoint. Management control of the evolution was not maintained: the test procedure was not followed, control rods were withdrawn to an unauthorized configuration, and several safety functions were bypassed. These and other errors, coupled with serious design problems,

resulted in a large insertion of positive reactivity and a rapid, uncontrolled power excursion.

19. Limerick Unit 1 Nuclear Power Plant

Location: Pickering, Ontario, Canada

Reactor Type: Boiling Water Reactor (BWR), BWR-4 (GE3)

Power: 3,293 MWt; 1,138 MWe (gross)

History: initial criticality December 22, 1984; on March 25, 1988, the reactor was operated over several months with copper concentrations in the reactor coolant at twice the recommended limit, weakening the fuel rod barrier metal. Subsequent fuel rod failures caused reactor power to be limited to 50 percent for the remaining six months of the fuel cycle. The nuclear power plant is currently operational.

20. Pickering A Unit 1 Nuclear Power Plant

Location: Pickering, Ontario, Canada

Reactor Type: Pressurized Heavy-Water Cooled and Moderated Reactor (PHWR)

Power: 1,744 MWt; 540 MWe (gross)

History: initial criticality 1971; on November 22, 1988, power was raised rapidly to avoid a shutdown due to xenon buildup while operating with an abnormal control rod configuration. This abnormal reactor control rod configuration compensated for reactivity loss incurred due to the unavailability of the on-line refueling equipment. Some damage to 191 fuel rods occurred. The nuclear power plant is currently operational.

21. Hadden Neck (Connecticut Yankee) Nuclear Power Plant

Location: Hadden Neck, Connecticut, USA

Reactor Type: Pressurized Water Reactor (PWR), 4-loop

Power: 1,825 MWt, 590 MWe (gross)

History: grid connection August 7, 1967; on October 9, 1989, 480 fuel rods were damaged during the operating cycle by metal chips present in the coolant system. During the 16-month operating cycle, coolant activity indicated only minor fuel damage was occurring. The thermal shield had been repaired during the preceding outage without maintaining the necessary standards of cleanliness and imposing restrictions on forced circulation of reactor water before cleanup was completed. Some of the debris became lodged in locations in the reactor system that were difficult to inspect and clean. This debris led to the fuel damage through fretting of the cladding. The reactor was permanently shut down December 5, 1996.

22. Greifswald Unit 5 (KGR-5) Nuclear Power Plant

Location: Lubmin, GDR (now Germany)

Reactor Type: VVER-440, Model V-230, Pressurized Water Reactor (PWR)

Power: 1,375 MWt; 440 MWe (gross); 408 MWe (net)

History: grid connection 24 April 1989; commercial operation November 1, 1989; on November 24, 1989, three out of six cooling water pumps were switched off for a test; a fourth pump broke down and control of the reactor was lost; 10 fuel elements were damaged—partial core melting. The accident was reportedly attributed to sticky relay contacts. The reactor was permanently shutdown November 24, 1989.

23. Fukushima Dai-ichi Unit 1 Nuclear Power Plant

Location: Ohkuma, Fukushima Prefecture, Japan

Reactor Type: Boiling Water Reactor (BWR), GE BWR/2, Mark 1 Containment

Power: 1,380 MWt; 450 MWe (gross); 439 MWe (net)

History: initial criticality 10 October 1970; grid connection 17 November 1970; commercial operation 26 March 1971; partial core meltdown following earthquake on 11 March 2011

24. Fukushima Dai-ichi Unit 2 Nuclear Power Plant

Location: Ohkuma, Fukushima Prefecture, Japan

Reactor Type: Boiling Water Reactor (BWR), TOS1 (GE BWR/4), Mark 1 Containment

Power: 2,381 MWt; 794 MWe (gross); 760 MWe (net)

History: initial criticality 10 May 1973; grid connection 24 December 1973; commercial operation 18 July 1974; partial core meltdown following earthquake on 11 March 2011

25. Fukushima Dai-ichi Unit 3 Nuclear Power Plant

Location: Ohkuma, Fukushima Prefecture, Japan

Reactor Type: Boiling Water Reactor (BWR), TOS1 (GE BWR/4), Mark 1 Containment

Power: 2,381 MWt; 794 MWe (gross); 760 MWe (net)

History: initial criticality 28 January 1978; grid connection 24 February 1978; commercial operation 12 October 1978; partial core meltdown following earthquake on 11 March 2011

Excluded from this list because there is no report that the fuel failed is:

1. Shika Unit 1 Nuclear Power Plant

Location: Shika-machi, Ishikawa, Japan

Reactor Type: Boiling Water Reactor (BWR)

Power: 11,593 MWt; 540 MWe (gross)

History: grid connection January 12, 1993; commercial operation July 30, 1993; on June 18, 1999, a criticality event that occurred while the reactor was shut down for a planned inspection. The event occurred because of mismanagement of the routine testing of the hydraulic control rod system, which caused a pressure increase in the control rod withdrawal pipes. This resulted in the unwanted drop of three control rods, which lead to a local criticality event. The chain reaction was terminated by operators' intervention 15 minutes later. The reactor is currently operational.

Table 2: Population within 30 km (18.6 mi) and 75 km (46.6 mi.) of nuclear power stations worldwide.Source: Declan Butler, Senior Reporter, *Nature*, France, private communication.

Country	Site Name	Reactors	MWe	Population within 30 km	...within 75 km	Location
PAKISTAN	KANUPP	1	125	8,346,926	14,470,519	Seacoast
TAIWAN, CHINA	KUOSHENG	2	1,933	5,454,287	9,882,167	Seacoast
TAIWAN, CHINA	CHIN SHAN	2	1,208	4,687,065	9,833,555	Seacoast
KOREA, REPUBLIC OF	KORI	8	3,227	3,410,020	7,052,596	Seacoast
CHINA	GUANGDONG	2	1,888	3,247,486	27,821,860	Seacoast
CHINA	LINGAO	4	3,876	3,106,385	27,537,030	Seacoast
INDIA	NARORA	2	404	2,243,522	15,929,296	Inland near a river
CANADA	PICKERING	8	3,094	2,197,681	5,832,548	Inland near a lake
GERMANY	PHILIPPSBURG	2	2,292	1,743,695	6,373,483	Inland near a river
GERMANY	NECKARWESTHEIM	2	2,095	1,619,944	7,073,310	Inland near a river
BELGIUM	DOEL	4	2,910	1,511,575	9,034,387	Seacoast
GERMANY	BIBLIS	2	2,407	1,510,809	7,253,269	Inland near a river
TAIWAN, CHINA	LUNG MEN	2	2,600	1,498,212	9,144,323	Seacoast
KOREA, REPUBLIC OF	WOLSONG	4	2,722	1,300,745	5,378,972	Seacoast
CHINA	QINSHAN	9	6,038	1,299,506	12,772,648	Seacoast
GERMANY	KRUEMMEL (KKK)	1	1,346	1,177,741	4,173,068	Inland near a river
USA	INDIAN POINT	2	2,065	1,075,040	17,343,606	Inland near a river
UNITED KINGDOM	HARTLEPOOL	2	1,190	1,062,217	3,012,729	Seacoast
UNITED KINGDOM	OLDBURY	2	434	1,042,295	4,477,473	Inland near a river
SWITZERLAND	BEZNAU	2	730	1,027,780	5,866,058	Inland near a river
CHINA	TIANWAN	2	1,866	1,010,056	6,875,833	Seacoast
USA	LIMERICK	2	2,264	982,549	8,156,849	Inland near a river
CHINA	FUQING	3	3,000	980,280	6,934,209	Seacoast
INDIA	KAKRAPAR	4	1,664	963,906	8,192,016	Inland near a river
SWITZERLAND	GOESGEN	1	970	959,787	5,638,222	Inland near a river
FRANCE	FESSENHEIM	2	1,760	931,516	4,185,876	Inland near a river
JAPAN	TOKAI	1	1,060	919,437	4,059,660	Seacoast

Country	Site Name	Reactors	MWe	Population within 30km	...within 75km	Location
SWITZERLAND	MUEHLEBERG	1	373	892,419	3,432,574	Inland near a river
USA	THREE MILE ISLAND	1	786	836,919	2,484,072	Inland near a river
BELGIUM	TIHANGE	3	3,016	836,375	5,756,062	Inland near a river
SWITZERLAND	LEIBSTADT	1	1,190	817,983	5,829,898	Inland near a river
FRANCE	CATTENOM	4	5,200	801,518	3,226,819	Inland near a lake
ARMENIA	ARMENIA	1	375	768,816	2,474,639	Inland near a river
USA	MCGUIRE	2	2,200	758,773	2,432,640	Inland near a lake
INDIA	KUDANKULAM	2	1,834	751,613	4,772,980	Seacoast
KOREA, REPUBLIC OF	SHIN-WOLSONG	2	1,920	748,525	6,471,427	Seacoast
USA	CATAWBA	2	2,258	717,868	2,127,615	Inland near a lake
PAKISTAN	CHASNUPP	2	600	712,171	3,926,531	Inland near a river
FRANCE	BUGEY	4	3,580	698,393	3,710,199	Inland near a river
CHINA	HAIYANG	2	2,000	690,825	3,360,693	Seacoast
UNITED KINGDOM	HEYSHAM	4	2,400	657,237	5,118,870	Seacoast
CHINA	SANMEN	2	2,000	631,742	5,108,107	Inland near a river
FRANCE	ST. ALBAN	2	2,670	615,386	3,603,767	Inland near a river
USA	SAN ONOFRE	2	2,150	606,973	6,866,677	Seacoast
JAPAN	HAMAOKA	3	3,360	591,946	2,914,603	Seacoast
USA	TURKEY POINT	2	1,386	584,744	3,238,967	Seacoast
GERMANY	UNTERWESER (KKU)	1	1,345	568,175	2,726,963	Inland near a river
INDIA	TARAPUR	4	1,280	563,932	9,010,254	Seacoast
USA	R.E. GINNA	1	580	506,446	1,327,140	Inland near a lake
GERMANY	GRAFENRHEINFELD (KKG)	1	1,275	503,848	2,513,299	Inland near a river
INDIA	MADRAS	1	880	503,580	11,992,825	Seacoast
UNITED KINGDOM	HINKLEY POINT B	2	840	503,419	4,039,886	Seacoast
GERMANY	GROHNDE (KWG)	1	1,360	489,228	4,718,994	Inland near a river
CHINA	TAISHAN	2	3,400	487,558	6,860,794	Seacoast
GERMANY	EMSLAND (KKE)	1	1,329	463,105	3,520,043	Inland near a river
INDIA	RAJASTHAN	6	1,085	461,484	4,059,303	Inland near a river
FRANCE	GRAVELINES	6	5,460	457,739	2,493,458	Seacoast
CHINA	NINGDE	4	4,000	455,546	3,872,299	Seacoast

Country	Site Name	Reactors	MWe	Population within 30km	...within 75km	Location
USA	BEAVER VALLEY	2	1,738	444,404	3,415,272	Inland near a river
USA	SEQUOYAH	2	2,274	440,276	1,006,876	Inland near a river
NETHERLANDS	BORSSELE	1	487	437,946	5,647,252	Seacoast
CANADA	DARLINGTON	4	3,512	435,704	4,349,774	Inland near a lake
USA	HOPE CREEK	1	1,161	432,104	5,162,087	Inland near a river
JAPAN	SHIMANE	3	2,553	424,077	944,633	Seacoast
USA	SURRY	2	1,598	422,873	2,156,287	Seacoast
GERMANY	GUNDREMMINGEN	2	2,572	420,112	3,372,727	Inland near a river
JAPAN	KASHIWAZAKI KARIWA	7	7,965	418,769	2,111,422	Seacoast
USA	SEABROOK	1	1,245	416,677	4,336,769	Seacoast
UNITED KINGDOM	HUNTERSTON B	2	860	404,437	2,431,055	Seacoast
USA	SHEARON HARRIS	1	900	403,309	2,143,401	Inland near a lake
USA	OYSTER CREEK	1	614	401,413	3,683,604	Seacoast
USA	SALEM	2	2,332	388,084	5,030,681	Inland near a river
SLOVAK REPUBLIC	BOHUNICE V2	2	944	384,288	2,577,490	Inland near a river
USA	ENRICO FERMI	1	1,122	381,964	5,663,043	Inland near a lake
USA	WATERFORD	1	1,176	381,273	2,076,040	Inland near a river
USA	PEACH BOTTOM	2	2,224	360,539	4,986,475	Inland near a river
UKRAINE	KHMELNITSKI	4	3,800	344,228	1,112,792	Inland near a lake
USA	ST. LUCIE	2	1,678	342,226	960,085	Seacoast
GERMANY	BROKDORF (KBR)	1	1,410	338,296	4,192,615	Inland near a river
SLOVENIA	KRSKO	1	666	332,937	2,404,606	Inland near a river
USA	DRESDEN	2	1,734	332,170	6,776,346	Inland near a river
INDIA	KAIGA	4	808	324,436	2,573,287	Inland near a river
CHINA	FANGCHENGGANG	1	1,000	324,142	1,867,423	Seacoast
RUSSIA	BELOYARSKY	2	1,364	323,105	2,323,348	Inland near a lake
UKRAINE	ZAPOROZHE	6	5,700	319,467	1,535,072	Inland near a river
GERMANY	ISAR	2	2,288	315,142	3,223,271	Inland near a river
USA	SUSQUEHANNA	2	2,325	312,497	1,515,513	Inland near a river
FRANCE	TRICASTIN	4	3,660	308,661	1,712,197	Inland near a river
USA	MILLSTONE	2	2,014	308,069	2,612,274	Seacoast

Country	Site Name	Reactors	MWe	Population within 30km	...within 75km	Location
SLOVAK REPUBLIC	MOCHOVCE	4	1,654	301,510	2,036,249	Inland near a river
USA	FORT CALHOUN	1	482	299,423	944,172	Inland near a river
CZECH REPUBLIC	DUKOVANY	4	1,796	295,717	1,771,525	Inland near a river
FRANCE	ST. LAURENT	2	1,830	288,299	1,234,591	Inland near a river
UNITED KINGDOM	DUNGENESS B	2	1,040	280,216	2,858,182	Seacoast
USA	PILGRIM	1	684	274,758	4,663,188	Seacoast
JAPAN	TSURUGA	2	1,448	274,591	2,603,323	Seacoast
USA	PERRY	1	1,245	270,809	2,354,526	Inland near a lake
CZECH REPUBLIC	TEMELIN	2	1,926	270,671	1,105,062	Inland near a river
JAPAN	GENKAI	4	3,312	257,100	4,311,118	Seacoast
FRANCE	CRUAS	4	3,660	246,355	1,276,632	Inland near a river
USA	BYRON	2	2,300	238,664	989,177	Inland near a river
JAPAN	MONJU	1	10	235,566	2,544,702	Seacoast
USA	QUAD CITIES	2	1,734	232,716	697,446	Inland near a river
USA	DUANE ARNOLD	1	579	230,003	669,089	Inland near a river
JAPAN	ONAGAWA	3	2,090	229,211	2,140,841	Seacoast
JAPAN	SENDAI	2	1,692	223,259	1,681,383	Seacoast
GERMANY	BRUNSBUETTEL (KKB)	1	771	222,210	3,560,936	Inland near a river
SOUTH AFRICA	KOEBERG	2	1,800	221,647	3,482,235	Seacoast
SPAIN	VANDELLOS	1	1,045	219,310	904,569	Seacoast
IRAN	BUSHEHR	1	915	213,129	510,301	Seacoast
CHINA	HONGYANHE	4	4,000	208,820	1,990,712	Seacoast
FRANCE	CIVAUX	2	2,990	205,203	779,624	Inland near a river
JAPAN	MIHAMA	3	1,720	204,512	2,831,598	Seacoast
JAPAN	FUKUSHIMA-DAINI	4	4,268	204,250	1,585,740	Seacoast
CHINA	YANGJIANG	3	3,000	202,429	2,784,768	Inland near a river
FRANCE	CHOOZ	2	3,000	199,917	2,556,268	Inland near a river
JAPAN	SHIKA	2	1,613	198,118	1,981,451	Seacoast
UNITED KINGDOM	SIZEWELL B	1	1,188	197,616	1,595,501	Seacoast
JAPAN	TAKAHAMA	4	3,220	191,859	4,799,666	Seacoast
BULGARIA	BELENE	2	1,906	191,696	1,306,180	Inland near a river

Country	Site Name	Reactors	MWe	Population within 30km	...within 75km	Location
CHINA	CHANG JIANG	2	1,220	188,966	1,149,778	Seacoast
USA	OCONEE	3	2,538	188,819	1,236,188	Inland near a lake
CANADA	GENTILLY	1	635	184,452	653,781	Inland near a river
HUNGARY	PAKS	4	1,889	184,137	1,298,735	Inland near a river
FRANCE	GOLFECH	2	2,620	183,965	1,456,457	Inland near a river
FRANCE	PENLY	2	2,660	180,496	1,368,777	Seacoast
ARGENTINA	ATUCHA	2	1,027	180,152	2,398,222	Inland near a river
FRANCE	CHINON	4	3,620	176,411	1,644,162	Inland near a river
RUSSIA	KURSK	5	3,700	175,964	882,159	Inland near a lake
JAPAN	FUKUSHIMA-DAIICHI	6	4,546	171,563	1,727,898	Seacoast
USA	BROWNS FERRY	3	3,272	171,133	951,815	Inland near a river
KOREA, REPUBLIC OF	YONGGWANG	6	5,875	171,111	3,294,647	Seacoast
USA	MONTICELLO	1	572	164,742	2,729,560	Inland near a river
RUSSIA	VOLGODONSK	4	3,922	162,717	392,011	Inland near a river
FRANCE	FLAMANVILLE	3	2,660	162,681	488,730	Seacoast
JAPAN	OHI	4	4,494	158,938	4,780,771	Seacoast
USA	DIABLO CANYON	2	2,240	157,658	474,224	Seacoast
RUSSIA	BALAKOVO	4	3,800	157,149	479,672	Inland near a river
RUSSIA	NOVOVORONEZH	3	3,948	154,200	1,580,101	Inland near a river
USA	CALVERT CLIFFS	2	1,735	153,632	2,494,168	Seacoast
USA	DONALD COOK	2	2,069	150,775	1,150,068	Inland near a lake
BRAZIL	ANGRA	3	3,129	149,617	1,351,735	Seacoast
USA	VERMONT YANKEE	1	620	146,511	1,263,056	Inland near a river
JAPAN	IKATA	3	1,922	144,640	1,852,353	Seacoast
FRANCE	PALUEL	4	5,320	140,255	1,513,559	Seacoast
BULGARIA	KOZLODUY	2	1,906	138,341	1,356,716	Inland near a river
FRANCE	BLAYAIS	4	3,640	136,558	1,630,953	Seacoast
ROMANIA	CERNAVODA	2	1,300	130,794	1,150,730	Inland near a river
RUSSIA	NOVOVORONEZH-2	2	3,948	130,131	1,580,219	Inland near a river
USA	VIRGIL C. SUMMER	1	966	129,769	1,005,311	Inland near a lake
UKRAINE	SOUTH UKRAINE	3	1,900	127,585	534,511	Inland near a lake

Country	Site Name	Reactors	MWe	Population within 30km	...within 75km	Location
FRANCE	NOGENT	2	2,620	124,445	1,755,869	Inland near a river
FRANCE	DAMPIERRE	4	3,560	123,675	1,193,163	Inland near a river
USA	PALISADES	1	778	120,508	1,155,209	Inland near a lake
USA	BRAIDWOOD	2	2,330	118,688	3,850,666	Inland near a lake
USA	BRUNSWICK	2	1,858	118,581	375,497	Inland near a river
USA	RIVER BEND	1	978	115,926	851,030	Inland near a river
UKRAINE	ROVNO	4	2,657	115,190	757,532	Inland near a river
USA	FITZPATRICK	1	854	105,411	909,286	Inland near a lake
USA	PRAIRIE ISLAND	2	1,096	105,033	2,717,954	Inland near a river
USA	NINE MILE POINT	2	1,763	102,501	906,884	Inland near a lake
USA	LASALLE	2	2,238	100,965	1,330,267	Inland near a lake
FRANCE	BELLEVILLE	2	2,620	100,727	919,124	Inland near a river
USA	DAVIS BESSE	1	879	100,321	1,836,697	Inland near a lake
MEXICO	LAGUNA VERDE	2	1,300	100,291	1,972,320	Seacoast
SWEDEN	RINGHALS	4	3,649	99,679	1,036,661	Seacoast
USA	COLUMBIA	1	1,131	99,370	369,135	Inland near a river
USA	CRYSTAL RIVER	1	860	94,403	780,950	Seacoast
USA	NORTH ANNA	2	1,806	94,397	1,540,924	Inland near a lake
USA	WATTS BAR	2	2,288	93,378	938,600	Inland near a river
USA	FARLEY	2	1,711	93,183	406,403	Inland near a river
USA	H.B. ROBINSON	1	710	88,672	784,459	Inland near a lake
USA	POINT BEACH	2	1,026	86,898	758,409	Inland near a lake
ARGENTINA	EMBALSE	1	600	86,854	331,303	Inland near a lake
RUSSIA	SMOLENSK	3	2,775	85,944	313,388	Inland near a river
USA	ARKANSAS ONE	2	1,839	85,619	271,014	Inland near a river
KOREA, REPUBLIC OF	ULCHIN	6	5,873	81,559	613,281	Seacoast
JAPAN	TOMARI	3	1,966	77,272	1,973,708	Seacoast
RUSSIA	LENINGRAD-2	2	5,750	76,581	3,711,222	Seacoast
RUSSIA	LENINGRAD	4	5,750	76,060	3,638,403	Seacoast
JAPAN	HIGASHI DORI	1	1,067	74,970	671,750	Seacoast
FINLAND	OLKILUOTO	3	3,340	73,829	265,398	Seacoast

Country	Site Name	Reactors	MWe	Population within 30km	...within 75km	Location
USA	KEWAUNEE	1	556	71,263	743,914	Inland near a lake
SPAIN	SANTA MARIA DE GARONA	1	446	69,438	2,121,476	Inland near a river
JAPAN	OHMA	1	1,325	66,520	677,215	Seacoast
UNITED KINGDOM	WYLFA	2	980	66,112	328,046	Seacoast
SPAIN	ASCO	2	1,992	59,485	996,220	Inland near a river
USA	COMANCHE PEAK	2	2,367	59,370	1,311,105	Inland near a lake
USA	HATCH	2	1,759	56,721	358,913	Inland near a river
UNITED KINGDOM	TORNESS	2	1,205	56,458	1,505,052	Seacoast
SPAIN	ALMARAZ	2	1,964	54,384	427,834	Inland near a lake
USA	CLINTON	1	1,043	53,770	718,287	Inland near a lake
RUSSIA	KALININ	4	3,800	44,176	253,245	Inland near a lake
USA	CALLAWAY	1	1,190	41,780	470,839	Inland near a river
SPAIN	COFRENTES	1	1,064	41,015	2,545,941	Inland near a river
RUSSIA	KOLA	4	1,644	39,213	219,995	Seacoast
USA	SOUTH TEXAS	2	2,560	38,539	258,482	Inland near a river
USA	VOGTLE	2	2,302	37,899	688,888	Inland near a river
CANADA	BRUCE	8	4,693	33,900	174,682	Inland near a lake
FINLAND	LOVIISA	2	976	30,688	727,010	Seacoast
SWEDEN	OSKARSHAMN	3	2,511	27,739	152,138	Seacoast
USA	GRAND GULF	1	1,259	25,980	294,789	Inland near a river
TAIWAN, CHINA	MAANSHAN	2	1,841	25,781	479,359	Seacoast
SWEDEN	FORSMARK	3	3,138	22,043	343,174	Seacoast
CANADA	POINT LEPREAU	1	635	20,726	191,365	Seacoast
USA	COOPER	1	769	18,838	147,299	Inland near a river
USA	PALO VERDE	3	3,942	16,928	1,405,403	Inland near a lake
SPAIN	TRILLO	1	1,003	16,175	501,965	Inland near a river
USA	WOLF CREEK	1	1,160	13,185	172,300	Inland near a lake
RUSSIA	BILIBINO	4	44	276	2,253	Inland near a river

Table 3: Operational nuclear reactors analyzed to be within very high seismic hazard areas, as determined by the GSHAP seismic hazard data.

Country	Nuclear Reactor	Reactor Type, Net Capacity	Commercial Operation
Japan	Hamaoka Unit 3	BWR, 1100 MWe	September 1987
Japan	Hamaoka Unit 4	BWR, 1137 MWe	September 1993
Japan	Hamaoka Unit 5	BWR, 1300 MWe	January 2005
Japan	Onagawa Unit 1	BWR, 524 MWe	June 1984
Japan	Onagawa Unit 2	BWR, 825 MWe	July 1995
Japan	Onagawa Unit 3	BWR, 825 MWe	January 2002
Taiwan	Chin Shan Unit 1	BWR, 604 MWe	December 1978
Taiwan	Chin Shan Unit 2	BWR, 604 MWe	July 1979
Taiwan	Kuosheng Unit 1	BWR, 948 MWe	December 1981
Taiwan	Kuosheng Unit 2	BWR, 948 MWe	March 1983
Taiwan	Maanshan Unit 1	PWR, 890 MWe	July 1984
Taiwan	Maanshan Unit 2	PWR, 890 MWe	May 1985