REPORT IN BRIEF

NATIONAL ACADEMY OF SCIENCES
NATIONAL ACADEMY OF ENGINEERING
INSTITUTE OF MEDICINE
NATIONAL RESEARCH COUNCIL

NUCLEAR AND RADIATION STUDIES BOARD
JULY 2014

Lessons Learned from the Fukushima Nuclear Accident for Improving Safety of U.S. Nuclear Plants

Why did the National Research Council do this study?
The Blue Ribbon Commission on America's Nuclear Future, which was completing an assessment of options for managing spent nuclear fuel and high-level radioactive waste in the United States at the time of the Fukushima Daiichi accident, recommended that the National Academy of Sciences (NAS) conduct an assessment of lessons learned from the accident. The U.S. Congress subsequently directed the U.S. Nuclear Regulatory Commission (USNRC) to contract with NAS for the study.

How was the study carried out?
NAS appointed a committee of 21 experts to carry out this study. The committee held 39 meetings to gather information and develop the report, including a meeting in Tokyo, Japan, to enable in-depth discussions about the accident with Japanese technical experts from industry, academia, and government. The committee also visited the Fukushima Daiichi, Fukushima Daini, and Onagawa nuclear plants to learn about their designs, operations, and responses to the earthquake and tsunami. Subgroups of the committee visited two nuclear plants in the United States that are similar in design to the Fukushima Daiichi plant to learn about their designs and operations.

Source: Tokyo Electric Power

THIS REPORT IDENTIFIES LESSONS LEARNED for the United States from the accident at the Fukushima Daiichi nuclear plant initiated by the March 11, 2011, Great East Japan Earthquake and tsunami. The overarching lesson is that nuclear plant licensees and their regulators must continually seek out and act on new information about hazards that have the potential to affect the safety of nuclear plants.

The Fukushima Daiichi nuclear accident was initiated by the March 11, 2011, Great East Japan Earthquake and tsunami. Personnel at the plant responded to the accident with courage and resilience; their actions likely reduced its severity and the magnitude of offsite radioactive material releases. However, several factors relating to the management, design, and operation of the plant prevented plant personnel from achieving greater success and contributed to the overall severity of the accident. The overarching lesson learned from the Fukushima Daiichi accident is that nuclear plant licensees and their regulators must actively seek out and act on new information about hazards that have the potential to affect the safety of nuclear plants.

IMPROVING NUCLEAR PLANT SYSTEMS, RESOURCES, AND OPERATOR TRAINING

Many national governments and international bodies initiated reviews of nuclear plant safety following the Fukushima Daiichi accident and are beginning to take useful actions to upgrade nuclear plant systems, operating procedures, and operator training. In the United States, several actions are being taken by the USNRC and the nuclear industry in response to the accident. As they implement these actions, the nuclear industry and the USNRC should give specific attention to improving plant systems in order to enable effective responses to beyond-design-basis events (see Box 1), including, when necessary, developing and implementing ad hoc responses to deal with unanticipated complexities. Attention to availability, reliability, redundancy, and diversity of plant systems and equipment—for example DC power, reactor heat removal, and reactor depressurization and containment venting systems and protocols—are specifically needed. Attention should also be paid to improving resource availability and operator training, for example, staffing levels for emergencies involving multiple reactors at

Box 1 ***What happened at the Fukushima Daiichi Plant***

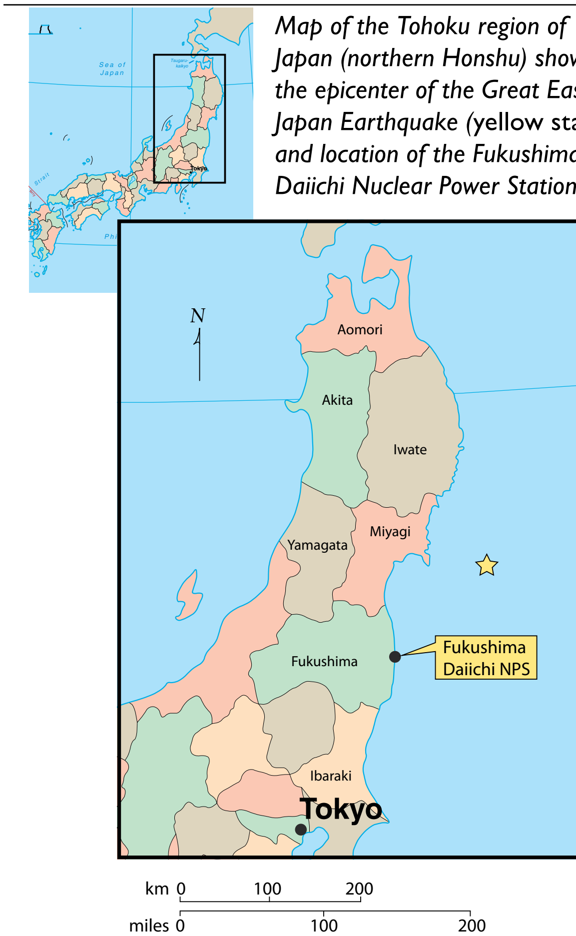
On March 11, 2011, a magnitude 9.0 earthquake occurred off of eastern Honshu, Japan's main island. The earthquake knocked out offsite AC power to the Fukushima Daiichi plant, and a tsunami inundated portions of the plant site. Flooding of critical plant equipment resulted in the extended loss of onsite AC and DC power with the consequent loss of reactor monitoring, control, and cooling functions in multiple units. Three reactors sustained severe core damage (Units 1, 2, and 3); three reactor buildings were damaged by hydrogen explosions (Units 1, 3, and 4); and offsite releases of radioactive materials contaminated land in Fukushima and several neighboring prefectures. The accident prompted widespread evacuations of local populations and distress of the Japanese citizenry; large economic losses; and the eventual shutdown of all nuclear power plants in Japan. The Great East Japan Earthquake and tsunami were "beyond-design-basis events" that challenged the design of the plant's structures and components and led to a loss of critical safety functions.

a site, that last for extended durations, and/or that involve stranded plant conditions. The quality and completeness of these changes should be adequately peer reviewed.

STRENGTHENING CAPABILITIES FOR ASSESSING RISKS FROM BEYOND-DESIGN-BASIS EVENTS

Beyond-design-basis events can produce severe accidents (Box 2) at nuclear plants that damage reactor cores and stored spent fuel, result in the generation and combustion of hydrogen within the plant, and the release of radioactive material to the offsite environment. There is a need to better understand the safety risks that arise from such events and take appropriate countermeasures to reduce them.

The U.S. nuclear industry and the USNRC should strengthen their capabilities for identifying, evaluating, and managing the risks from beyond-design-basis events. Particular attention is needed to improve the identification of such events; better account for plant system interactions and the performance of plant operators and other critical personnel in responding to such events; and better estimate the broad range of offsite health, environmental, economic, and social consequences that can result from such events.



Map of the Tohoku region of Japan (northern Honshu) showing the epicenter of the Great East Japan Earthquake (yellow star) and location of the Fukushima Daiichi Nuclear Power Station.

Four decades of analysis and operating experience have demonstrated that nuclear plant core-damage risks are dominated by beyond-design-basis accidents. Such accidents can arise, for example, from multiple human and equipment failures, violations of operational protocols, and extreme external events. Current approaches for regulating nuclear plant safety, which have been traditionally based on deterministic concepts such as the design-basis accident, are clearly inadequate for preventing core-melt accidents and mitigating their consequences. Modern risk assessment principles are beginning to be applied in nuclear reactor licensing and regulation. The more complete application of these principles in licensing and regulation could help to further reduce core melt risks and their consequences and enhance the overall safety of all nuclear plants, especially currently operating plants.

IMPROVE OFFSITE EMERGENCY RESPONSE CAPABILITIES

Japan is known to be well prepared for natural hazards; however, the earthquake and tsunami caused devastation on a scale beyond what was expected and prepared for. The Fukushima Daiichi accident revealed vulnerabilities in Japan's offsite emergency management. The competing demands of the earthquake and tsunami diminished the available response capacity for the accident. Implementation of existing nuclear emergency plans was overwhelmed by the extreme natural events that affected large regions, producing widespread disruption of communications, electrical power, and other critical infrastructure over an extended period of time. The events in Japan raise the question of whether a severe nuclear accident such as occurred at the Fukushima Daiichi plant would challenge U.S. emergency response capabilities because of its severity, duration, and association with a regional-scale natural disaster.

The nuclear industry and organizations with emergency management responsibilities in the United States should assess their preparedness for severe nuclear accidents associated with regional-scale disasters. Emergency response plans, including plans for communicating with affected populations, should be revised or supplemented as necessary to ensure that there are scalable and effective strategies, well-trained personnel, and adequate resources for responding to long-duration accident/disaster scenarios involving

- Widespread loss of offsite electrical power and severe damage to other critical offsite infrastructure, for example communications, transportation, and emergency response infrastructure.
- Lack of real-time information about conditions at nuclear plants, particularly with respect to releases of radioactive material from reactors and/or spent fuel pools.
- Dispersion of radioactive materials beyond the 10-mile emergency planning zones for nuclear plants that could result in doses exceeding one or more of the protective action guidelines.

The nuclear industry and organizations with emergency management responsibilities in the United States should also assess the balance of protective actions (e.g., sheltering-in-place, evacuation, relocation, and distribution of potassium iodide) for offsite populations affected by severe nuclear accidents and revise the guidelines as appropriate. Particular attention should be given to the following issues:

- Protective actions for special populations (children, ill, elderly) and their caregivers.
- Long-term impacts of sheltering-in-place, evacuation and/or relocation, including social, psychological and economic impacts.
- Decision making for resettlement of evacuated populations in areas contaminated by radioactive material releases from nuclear plant accidents.

Box 2. Nuclear Plant Accident Terminology

Nuclear plant accidents are classified according to their implications for safety and the specific type of events that initiate them, known as an "accident sequence." Nuclear plants are designed with extensive safety features and operators are trained to handle a wide range of normal and abnormal conditions, including conditions caused by equipment failure, loss of power, and loss of reactor core cooling capability.

The USNRC provides extensive guidance to cover a specified set of failures or abnormal events, referred to as "design-basis accidents." For such accidents, a plant design must include specific engineering safety features such as emergency core cooling systems, which are designed to limit the damage to the fuel in the reactor core and minimize the release of radioactive material from the plant's containment to levels that do not affect the health and safety of the general public.

Accidents that are not anticipated by the USNRC guidance are known as "beyond-design-basis accidents." Such accidents can be initiated by events inside the plant ("internal events") or outside the plant ("external events"). Examples of internal events include equipment failures such as stuck valves (e.g., a stuck-open valve initiated the 1979 Three Mile Island Accident), pipe breaks, and human error (e.g., the 1986 Chernobyl accident was initiated by operator actions that had unforeseen consequences). External events include terrorist attacks as well as natural events such as large earthquakes and tsunamis. Beyond-design-basis accidents may require improvised operator actions and resources beyond the standard design features. If a beyond-design-basis accident results in excessive loss of reactor cooling and heat-up of the reactor core, significant core damage can occur, resulting in a "severe accident."

IMPROVE THE NUCLEAR SAFETY CULTURE

The term "safety culture" is generally understood to encompass a set of attitudes and practices that emphasize safety over competing goals such as production or costs. There is universal acceptance by the nuclear community that safety culture practices need to be adopted by regulatory bodies and other organizations that set nuclear power policies; by senior management of organizations operating nuclear power plants; and by individuals who work in those plants.

While the Government of Japan acknowledged the need for a strong nuclear safety culture prior to the Fukushima Daiichi accident, TEPCO and its nuclear regulators were deficient in establishing, implementing, and maintaining such a culture. Examinations of the Japanese nuclear regulatory system following the Fukushima Daiichi accident concluded that regulatory agencies were not independent and were subject to regulatory capture.

The establishment, implementation, maintenance, and communication of a nuclear safety culture in the United States are priorities for the U.S. nuclear power industry and the USNRC. The USNRC and the nuclear industry must maintain and continuously monitor a strong nuclear safety culture in all of their safety-related activities. Additionally, the USNRC leadership must maintain the independence of the regulator. The agency must ensure that outside influences do not compromise its nuclear safety culture and/or hinder its discussions with and disclosures to the public about safety-related matters. Opportunities to increase the transparency of and communication about their efforts to assess and improve their nuclear safety cultures should be examined.

Locate additional information, including related reports, at http://dels.nas.edu/nrsb
Read, purchase, or download a free PDF of this report at http://www.nap.edu

Committee on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants: Norman P. Neureiter (*Chair*), American Association for the Advancement of Science, Washington, DC; **B. John Garrick** (*Vice Chair*), Executive Consultant, Laguna Beach, CA; **Robert A. Bari,** Brookhaven National Laboratory, Upton, NY; **Percy M. Beard, Jr.,** Institute of Nuclear Power Operations (*retired*), Atlanta, GA; **Jan Beyea,** Consulting in the Public Interest, Lambertville, NJ; **M. Quinn Brewster,** University of Illinois at Urbana-Champaign; **Michael L. Corradini,** University of Wisconsin-Madison; **Vijay K. Dhir,** University of California, Los Angeles; **Michael W. Golay,** Massachusetts Institute of Technology; **Barbara L. Hamrick,** University of California, Irvine Medical Center, CA; **Shelley A. Hearne,** Johns Hopkins Bloomberg School of Public Health and Big Cities Health Coalition, Baltimore, MD; National Association of County and City Health Officials, Washington, DC; **Paul A. Locke,** Johns Hopkins Bloomberg School of Public Health, Baltimore, MD; **James E. Matheson,** SmartOrg, Menlo Park, CA; **Thomas G. Moser,** Osprey Global Solutions, Wilmington, NC; **Arthur T. Motta,** Pennsylvania State University; **John A. Orcutt,** Scripps Institution of Oceanography, University of California at San Diego, La Jolla; **Emilie M. Roth,** Roth Cognitive Engineering, Menlo Park, CA; **Joseph E. Shepherd,** California Institute of Technology, Pasadena, CA; **Elizabeth Q. Ten Eyck,** ETE Consulting, Inc., Great Falls, VA; **Frank N. Von Hippel,** Princeton University; **Loring A. Wyllie, Jr.,** Degenkolb Engineers, San Francisco, CA; **Kevin D. Crowley** (*Study Director*), **Ourania Kosti** (*Senior Program Officer*), **Daniel Pomeroy** (*Postdoctoral Fellow, Dec. 10, 2012 to Sept. 1, 2013*), **Darlene Gros** (*Senior Program Assistant*), National Research Council

The National Academies appointed the above committee of experts to address the specific task requested by the U.S. Congress and sponsored by the U.S. Nuclear Regulatory Commission. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

For more information, contact the Nuclear and Radiation Studies Board at (202) 334-3066 or visit http://dels.nas.edu/nrsb. Copies of *Lessons Learned from the Fukushima Nuclear Accident for Improving Safety of U.S. Nuclear Plants* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.