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Editorial: The Fukushima Dai-ichi Accident and its Implications for the Safety of Nuclear Power

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Five years ago the dramatic events in Fukushima that followed the massive earthquake and subsequent tsunami that struck Japan on March 11, 2011 sharpened the focus of scientists, engineers and general public on the broad range of technical, environmental and societal issues involved in assuring the safety of the world's nuclear power complex. They also called into question the potential of nuclear power to provide a growing, sustainable resource of CO₂-free energy. The issues raised by Fukushima Dai-ichi have provoked urgent concern, not only because of the potential harm that could result from severe accidents or from intentional damage to nuclear reactors or to facilities involved in the nuclear fuel cycle, but also because of the extensive economic impact of those accidents and of the measures taken to avoid them.

Such measures could potentially include the abandonment of nuclear power in various countries. Just as Chernobyl led to the closing of the Austria nuclear industry, Fukushima Dai-ichi led to a similar action by Germany. Another accident could lead to abandonment of nuclear power *in toto*.

Every design of a nuclear energy facility embodies safety as one of its primary characteristics and as the basis for operational procedures and protocols. Over the past forty years, much has been done to advance measures for and evaluation of safety, including, notably, the probabilistic risk assessment approach that was formalized in the United States by the WASH-1400 "Rasmussen Study" of 1975 and by the independent evaluation of Light-water Reactor Safety by a study group of the American Physical Society.²

In addition to the manufacturers of nuclear reactors, operators of nuclear power plants and fuel cycle facilities devote significant resources to understand and to improve the operational safety of their facilities. These safety measures are typically legally mandated and are regulated by a national Nuclear Regulatory Commission (NRC) or its equivalent. Despite these measures, serious reactor accidents, although rare, continue to occur.

¹ Coordinating Editor-in-Chief of NIM-A

² "Report to the APS by the Study Group on Light-water Reactor Safety," by H.W. Lewis, R.L. Garwin, et al, *Reviews of Modern Physics*, 47, Supplement 1, June 1975.
<http://link.aps.org/doi/10.1103/RevModPhys.47.S1>

Examples are the Windscale fire (UK, 1957), Three-Mile Island (United States, 1979), Chernobyl (Soviet Union, 1986), and Fukushima Dai-ichi (Japan, 2011).

The economic loss caused by the Three-Mile Island (1979) accident was borne by the operating company to the extent of about a billion dollars³. The Chernobyl (1986) accident spread intense radioactivity over an area⁴ of $\sim 8 \times 10^5$ km². The consequent economic loss was borne by the Soviet Union and the other countries that received the radioactive fallout. The accident demanded immediate evacuation of roughly 400,000 people and the eventual resettlement and support of many thousands of people from the high-radiation areas. It continues to make tens of thousands of square km of land unavailable to the public. The cost of Chernobyl has been estimated⁵ as “hundreds of billions of dollars.” Costly measures to entomb the reactor and to begin its safe demolition will add billions of dollars to the economic consequences of the accident.

The accident at Fukushima Dai-ichi⁶ in March 2011 was initiated by a magnitude 9.0 earthquake and powerful tsunami that struck Japan, directly killing $\sim 22,000$ people. Japan’s sixteen nuclear reactors, including the three operating reactors at Fukushima Dai-ichi, shut down immediately, as planned, by automatically inserting their control rods into the reactor core. Removal of the residual waste heat in the reactor pressure vessels was left to circulating electrical pumps powered by emergency diesel generators. About an hour following the earthquake, a huge tsunami struck Fukushima Dai-ichi with a water level roughly 15 m above mean sea level. The tsunami flooded over the 10 m high seawall and destroyed the diesel generators.

The Fukushima Dai-ichi accident involved multiple aspects of the fuel cycle. The melting of the reactor cores in Reactors 1, 2, and 3, at Fukushima Dai-ichi – driven by ~ 20 MW of waste heat from the fission products – occurred within hours of the tsunami once the diesel generators had been flooded and after battery-driven, reactor-core isolation pumps had failed. The overheated zirconium sheath of the fuel reacted with steam above the water in the reactor pressure vessel, producing hydrogen gas from the chemical reaction of zirconium. Within days after the tsunami, the massive “primary containment” of the reactors had to be vented, releasing radioactive materials that had escaped from the reactor core, in addition to the hydrogen that was over-pressurizing the containment.

³ We note without comment a study (Socio-Economic Planning Sciences, Vol.18, no. 3, pp. ISS193, 1984) estimated health-related costs to the residents of only \$200,000 for lost-work-days and visits to physicians.

⁴ V. Kortov, Yu. Ustyantsev, “Chernobyl accident: Causes, consequences and problems of radiation measurement,” Radiation Measurements, Volume 55, August 2013, Pages 12-16. In contrast the contaminated area in Japan is of order of 10^4 km².

⁵ <http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf>

⁶ For a more complete description of the sequence of events see R.L. Garwin, “Learning More from Fukushima Dai-ichi,” <http://fas.org/rlg/2011%20Erice%20Fukushima1a.pdf>, August, 2011

Hydrogen explosions within the buildings further augmented the dispersion of radioactivity.

Further concern about the potential hazard of Fukushima Dai-ichi focused on the “spent fuel pool” of reactor Unit 4, which had many full-core-equivalents of reactor fuel. Had that pool lost its water, analyses⁷ indicate enormous potential consequences:

“A 1997 study done for the NRC estimated the median consequences of a spent-fuel fire at a pressurized water reactor (PWR) that released 8–80 MCi of Cs-137. The consequences included: 54,000–143,000 extra cancer deaths, 2000–7000 km² of agricultural land condemned, and economic costs due to evacuation of \$117–566 billion.”

The economic losses of the nuclear accident to the operator, Tokyo Electric Power Company (TEPCO), are in the range of tens of billions of dollars. They have led to the bankruptcy and nationalization of TEPCO. The destruction of the four boiling water reactors at Fukushima Dai-ichi led to the shutdown of the entire Japanese nuclear power enterprise for the ensuing 3-plus years and required the costly import of foreign fossil fuels to compensate for the loss of nuclear electric power that had provided 27% of Japan’s total electrical energy in 2009.

With respect to the human cost, whatever the number of long-term cancer deaths that may result from this accident, other consequences such as social disruption, disease, psychological impairment, and the like are likely to be more important. Based on the 2006 report of the U.S. National Academy of Sciences⁸ which estimates in general one lethal cancer per 20 person-sieverts (Sv) of population exposure, one can estimate⁹ about 1550 lethal cancers.¹⁰ Fukushima Dai-ichi. For the Chernobyl accident¹¹, using the well established numbers for exposure of the world’s population published by United Nations specialized organizations, one can estimate about 30,000 lethal cancers.

Tsunechisa Katsumata, president of TEPCO, attributed some of the responsibility for the Fukushima Dai-ichi disaster to an inadequate safety culture in his company:

Katsumata said TEPCO's nuclear power division had become "a homogeneous and exclusive circle of engineers who defied checks by other divisions, including the management." Rules covering fitness for service of equipment were "not clear," he

⁷ http://www.princeton.edu/sgs/publications/sgs/pdf/11_1Alvarez.pdf

⁸ BEIR-IV. At: http://www.nap.edu/catalog.php?record_id=11340

⁹ http://www.cipi.com/PDF/tmi_Full_Report_1.pdf

¹⁰ “Evaluating and Managing Risk in the Nuclear Power Sector,” by R.L. Garwin, March 9, 2012.

<http://www.fas.org/rlg/Evaluating%20and%20Managing%20Risk.pdf>

¹¹ A more extensive comparison of the environmental impact of the Chernobyl and Fukushima accidents maybe found in G. Steinhäuser, Alexander Brandl, and Thomas E. Johnson, “Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts,” *Science of The Total Environment*, Volumes 470–471, 1 February 2014, Pages 800–817.

said, and didn't allow for flaws as equipment aged, encouraging personnel to ignore the rules. Media attacks on problems at nuclear facilities, he said, put the engineers "on the defensive" and encouraged them to hide faults as long as those faults didn't immediately threaten safety -- leading to 16 cases of falsification of inspection and repair records at TEPCO 's BWRs.

Compounding this was the engineers' attitude that "stable supply of electricity (was) the ultimate objective," leading them to make "personal decisions based on their own idea of safety," Katsumata said.¹²

Already in a 2003 article¹³ the chairman of the World Association of Nuclear Operators, WANO, is quoted as saying,

Chairman Hajimu Maeda warned that "a terrible disease" threatens nuclear operating organizations from within. It begins, he said, with "loss of motivation to learn from others...overconfidence... (and) negligence in cultivating a safety culture due to severe pressure to reduce costs following the deregulation of the power market."

Those troubles, if ignored, "are like a terrible disease that originates within the organization" and can, if not detected, lead to "a major accident" that will "destroy the whole organization,"

Responding to the reactor safety problems revealed by the accident at Fukushima Dai-ichi, both the U.S. and France have committed to deploy additional systems at each nuclear plant that would be far more survivable than the existing safety systems, and that would ensure plant safety in the event of earthquake, tsunami, or other severe insult. In particular, battery backup for instrumentation has been expanded from the inadequate 4-8 hours, and multiple diesel generators have been deployed at reactor sites.

Similarly, Japan itself has specified measures to be taken; other countries have made similar commitments. In the United States, through orders by the NRC, the process has begun to implement several new, near-term safety requirements. Others will certainly follow in the near future. The European Community (EC) has required each member state to perform an evaluation (a so-called "stress test") of each nuclear power plant to search for safety vulnerabilities related to the issues emerging from the Fukushima accident. These "stress test" evaluations have also been performed at many other nuclear power stations outside the EC.

The response of scientists, engineers and technologists to the Fukushima accident has

¹² <http://fas.org/rlg/Evaluating%20and%20Managing%20Risk.pdf>

¹³ MacLachlan, Ann, , October 16, 2003, 'Complacency, negligence threaten nuclear industry, WANO warns', Nucleonics Week, Volume 44 / Issue 42

ranged across a broad array of disciplines leading to a multitude of analyses, technical reports and peer-reviewed papers. Much more needs to be done, most often on a plant-by-plant basis as part of dedicated program of upgrading both the plants and their operations. In addition to case-by-case responses, more general studies are needed across several fronts:

- a) A new generation of reactor instrumentation and advanced simulation and modeling tools may also allow plant operators deeper insight into potential safety concerns long before they pose a threat to plant operation or public safety
- b) In addition to strengthening the analysis of the technical control of the safety in nuclear facilities, detailed study is needed to identify the issues that impact the safety culture of current and emerging nuclear industries and to strengthen nuclear oversight institutions.
- c) The risks associated with the relicensing of nuclear plants beyond their initial design life to operation for 80 or even 100 years require considerable study to quantify the scientific unknowns and the scope of the experimental capabilities that will be needed to gain sufficient understanding of radiation induced aging. Issues have been identified in a recent American Physical Society study.
- d) Beyond safety and economics, the world nuclear power enterprise must put into operation transparent, reliable, long-term programs for managing and final disposition of used nuclear fuel from the existing reactor fleet and from those to come.

This list is far from exhaustive.

To encourage and facilitate further technical, environmental, medical and societal studies, Elsevier has collected the papers concerning the Fukushima Dai-ichi that it has published into a Virtual Special Issue issued on the fifth anniversary of the accident. It is our hope that this collection, which will grow in time, will be of direct help to those working to strengthen the safety and security of the world's nuclear power complex.

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