BEYOND TRIAGE AT THE FUKUSHIMA DAI-ICHI NUCLEAR POWER STATION

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On Friday afternoon, March 11, Fukushima prefecture in Japan was shaken by a magnitude 9.0 earthquake whose hypocenter was 24 km deep and about 160 km to the northeast, offshore Honshu Island. At the Fukushima Dai-ichi nuclear power station, the earthquake caused three of the six nuclear reactors to "SCRAM" (Safety Control Rod Axe Man: a process of inserting control rods to absorb neutrons and shut down the nuclear chain reaction). Three of the reactors were already in shutdown mode for inspection and maintenance. The design basis for the six nuclear power plants was for an earthquake of magnitude 8.2. The earthquake caused the operating plants to enter a standard shutdown cooling mode in order to remove the heat generated by the radioactive decay of fission product elements. This residual heat is only 3 to 6 percent of the heat generated while the fuel is in the reactor, but the rate of energy release is still on the scale of several million watts per ton of fuel. This heat must be removed in order to prevent the nuclear fuel, mainly UO_2, and supporting structural elements from melting in the core of the reactor. The melting point of UO_2 is approximately 2900 °C.

Within an hour, however, a tsunami, variously reported as between 8 and 14 meters high, hit the six nuclear power plants at Fukushima Dai-ichi. The design basis for a tsunami hitting the plants was reported to be 5.7 meters. The tsunami cut off electricity from the backup diesel generators that powered the water pumps used to maintain water circulation around the cores of the reactors; the failure of the generators was probably due to a loss of fuel. Backup battery power was used to operate the pumps, but this source lasted only about eight hours and then went dead, creating a complete station blackout. During the next ten days, the world followed the heroic efforts of plant operators, fire fighters, and the Self-Defense Forces to deal with an escalating series of potentially catastrophic events resulting from power loss: melting cores in three of the reactors; probably three hydrogen explosions; and the loss of water from the pools in which spent or used fuel is stored, which could lead to rising temperatures and ultimately ignition of the zirconium metal alloy that clads the fuel elements (this is an exothermic reaction and is written as $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$). In an extraordinary effort to cool both the reactor cores and the used fuel in the pools, seawater was pumped into the reactor cores and the used-fuel storage pools. Fluctuating levels of radiation, as well as smoke and fires, hampered the effort to stabilize the conditions of the reactors and storage pools. The Japanese government evacuated hundreds of thousands of people within a 20 km radius. All of these events took place against a backdrop of devastation and death that will probably claim the lives of several tens of thousands of Japanese.

As I write today, the situation remains serious. The sequence of events at the Fukushima Dai-ichi power plant, up to March 30, are beautifully illustrated on the accompanying figure provided by Rama Hoetzlein. The situation for the nuclear power plants and fuel storage pools has been stabilized by the initial triage, but it will take many weeks of intensive care before the release of radioactivity to the environment is stopped. After this period, the authorities will have to reconstruct the sequence of events, estimate the damage, evaluate the environmental impact, and develop strategies for remediation. This last step does not have the nerve-jangling attraction of a possible meltdown or explosion at a nuclear power plant, but over the long term the environmental impact of the destroyed nuclear reactors may be just as serious. Each reactor core contains approximately 100 metric tons (tonnes) of fuel (mostly UO_2). The fuel from reactor #4 had recently been moved to a spent-fuel pool. Thus, there are approximately 500 tonnes of nuclear fuel in the reactors (three of which have at least a partially melted core due to the loss of coolant and resulting high temperatures). Each reactor has its own spent- or used-fuel storage pool, with estimates ranging from 50 to 150 tonnes of used fuel per pool; thus, there are an estimated 600 tonnes of used fuel in these storage pools. A separate shared pool contains approximately 1000 tonnes of fuel. Importantly, most of the nuclear fuel is located in storage pools, not in the reactors. In addition, 70 tonnes of nuclear materials are in dry storage on site. In total, there are some 1700 tonnes of nuclear fuel at Fukushima Dai-ichi—a site of "inadvertent, near-surface geologic disposal."

The state of the fuel is not known, but with the mechanical and thermal shocks to the spent-fuel pools, one expects that much of the metal cladding (less than a millimeter thick) has failed. For average burnups of 40–50 megawatt-days/kilogram of uranium, a measure of the amount of energy extracted from the uranium fuel, one can roughly estimate that about 3% of the uranium has been fissioned and 1% has been converted to transuranium elements—mostly plutonium, with lesser amounts of neptunium, americium, and curium—formed by neutron capture and decay reactions. Much has been said about the mixed oxide fuel (MOX) in reactor #3, but only about 5% of the fuel assemblies in the reactor were MOX fuel elements. The MOX fuel is reported to have contained ~6% plutonium as a mixture of plutonium and uranium oxide. In total, the site has approximately 15 tonnes of plutonium that is in the nuclear fuel, mostly ^{239}Pu with a half-life of 24,100 years. The very strong radiation field, mainly gamma and beta radiation, and the source of most of the thermal energy, comes from short-lived radionuclides, such as ^{137}Cs and ^{90}Sr, which have half-lives of about 30 years.

The most important environmental decision to be made at the site will be whether to try to remove all the fuel for safe storage and disposal, such as was done with the fuel after the melting of the core at Three Mile Island in 1979, or whether to simply seal the reactors in a concrete sarcophagus, as was done at Chernobyl. It may well be that much of the fuel can be removed, particularly from the least affected storage pools, but some may finally remain on site. This decision will have to be guided by a thorough understanding of the "mineralogy" of the fuel and the geochemistry of the fission product elements, particularly ^{135}Cs and ^{129}I, both of which have very long half-lives, and the actinides, mainly plutonium, in this near-surface environment.

Natural events—an earthquake and a tsunami—caused this devastating nuclear accident, and natural geochemical and hydrological processes will determine its environmental impact.

The reader should note that much of this information has been pieced together from a variety of sources, including newspaper reports. The numbers I quote are only rough estimates and are given so that readers can appreciate the scale of the accident. An exact understanding of what happened at the Fukushima Dai-ichi nuclear power station will be developed over the next year.

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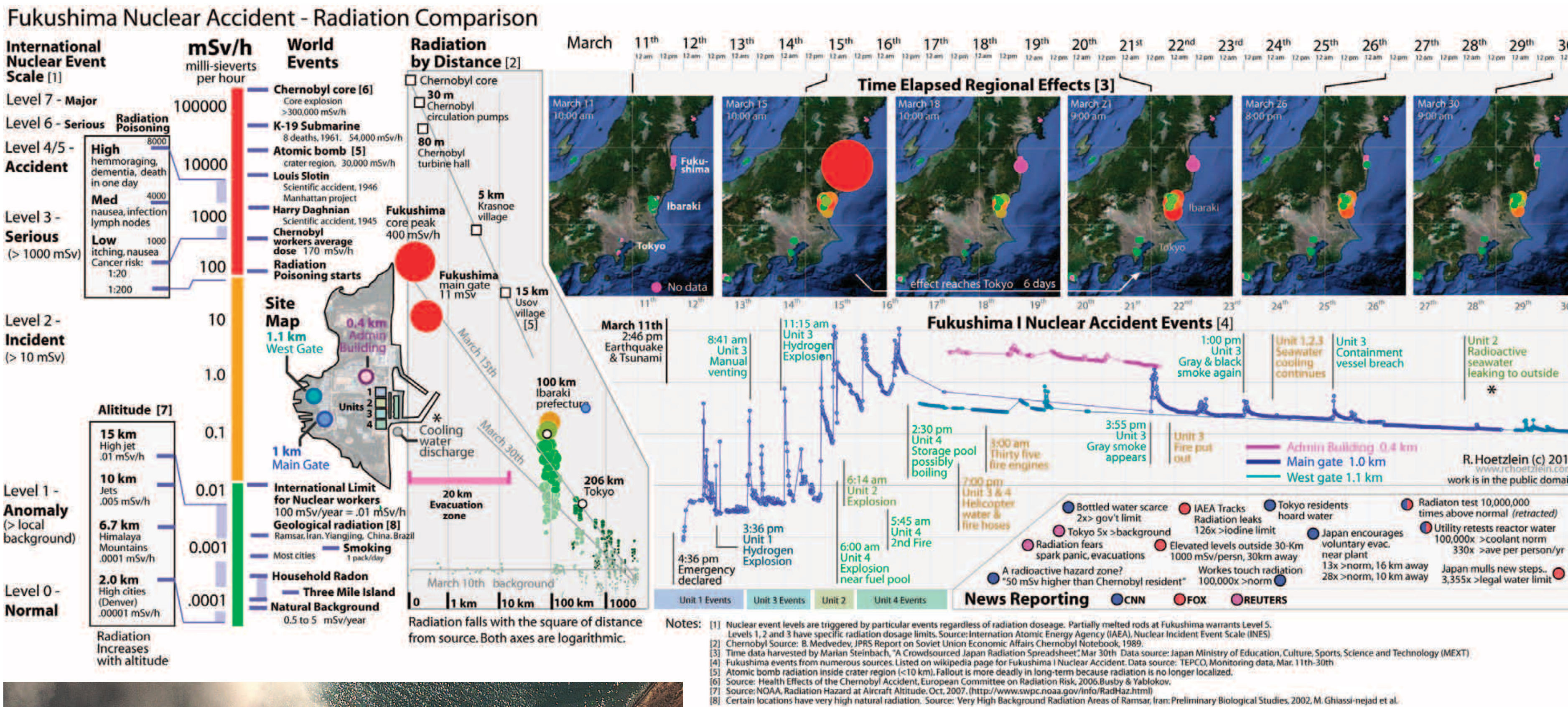
Suggested Readings

Bruno J, Ewing RC (2006) Spent nuclear fuel. Elements 2: 343-349 (http://elements.geoscienceworld.org/cgi/content/full/2/6/343)

Hedin A (1997) Spent Nuclear Fuel – How Dangerous Is It? SKB Technical Report 97-13, Swedish Nuclear Fuel and Waste Management Co., 60 pp (www.skb.se/upload/publications/pdf/TR97-13webb.pdf)



This visualization of the relation between radiation doses reported at the Fukushima Dai-ichi nuclear power station and typical exposures to radiation was created by Rama Hoetzlein. The graphical representation also includes a time series visualization of regional effects, a local site map, and data from selected news reports through March 30. All units are converted to mSv/h (millisieverts per hour) and plotted on a logarithmic scale. Normal background, chest CT scans, and food levels are usually expressed in mSv/y (millisieverts per year). Higher radiation doses, such as those found in nuclear disasters, are commonly given in Sv/h (sieverts per hour).

From an analysis of data in 64 media reports, Hoetzlein concludes that news reports have presented an inconsistent view of the doses and events. The most significant problem appears to be in the correct reporting of radiation levels. Reported radiation doses have been inconsistent in terms of units of measurement, the radiation levels used for comparison, and radiation background levels.

We extend our sincere thanks to Rama C. Hoetzlein, who made the graphic available for reprint as part of this Breaking News article. Created March 30, 2011, an extensive analysis of this visualization is available at www.rchoetzlein.com/theory/. PUBLIC DOMAIN DOCUMENT

Satellite image of the Fukushiwa nuclear power station taken on March 14. Several images taken at different dates are available at www.digitalglobe.com/index.php/27/Sample+Imagery+Gallery. © DIGITALGLOBE