ARTICLES

Thermal Rise Time in Nuclear Reactors after Loss of Coolant or Loss of Power Accidents

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[Prof. Hafemeister's manuscript was prepared on March 22, 2011, just eleven days after the Japanese earthquake and tsunami. The situation at the Fukushima Daiichi nuclear power plant will no doubt evolve rapidly over the coming weeks. For readers wishing to keep up with the latest developments, updates on the situation in Japan prepared by the MIT department of Nuclear Science and Engineering are available at http://mitnse.com/. Information on safety and oversight at US nuclear plants in 2010 is given in a Union of Concerned Scientists (UCS) website at http://ucsusa.org/nuclear_power/nuclear_power_risk/safety/nrc-and-nuclear-power-2010.html?utm_&utm_medium=Lochbaum&utm_campaign=SP-Lochbaum-3-17-11. Another UCS website, http://allthingsnuclear.org/tagged/Japan_nuclear, has successive news stories and helpful graphics, as well as links to other useful sites – Ed.]

On March 11, 2011, a magnitude 9.0 earthquake from a "reverse fault" struck northeastern Japan. The Fukushima Daiichi site on the Pacific Ocean, 240 km north-east of Tokyo, houses six boiling water reactors, three of which were in operation and three in maintenance at the time of the earthquake. It appears that the three-operating reactors shut down without a loss of coolant accident (LOCA), but the accompanying tsunami, which arrived 15 minutes later, disabled back-up electrical generators. This prevented pumping of cooling water to the reactors and their spent fuel ponds. The ensuing damage and radioactive release is the worst accident since the Chernobyl accident in Ukraine on 26 April 1986. The Chernobyl accident was particularly bad since the burning of its carbon moderator propelled 3-4% of the radioactive core into the atmosphere from a reactor without a containment dome. The radioactive releases from the Fukushima site will, most likely, be far less than was the case Chernobyl, but the clean-up of the Fukushima reactors and spent fuel ponds will be very significant. The Three Mile Island Accident of 28 March 1979 released only minor amounts of radioactivity, but the cleanup cost $1 billion and took eight years.

In this article, I use some basic reactor and thermal physics to estimate the available response time before a light water reactor core begins to melt. I consider two types of accidents: A loss of coolant accident (LOCA) and a loss of power accident (LOPA). The calculated response time for a LOCA is about 1 minute, and, for a LOPA, about 0.5-1 day, but individual circumstances cause variations on these results. These calculations are based on material presented in Ref. 1.

Helicopters and water cannons failed to cool the reactors and the spent fuel ponds. As a last-gasp effort, corrosive seawater with boric acid was flooded on reactors 1, 2 and 3, but without the use of their internal pumps. It is speculated that rapid deployment of portable generators on land or ships to give power to the reactors' pumps could have lessened the severity of the Fukushima accident. First, I will summarize the status, one week after the earthquake-tsunami of March 11, of the six Fukushima Daiichi (FD) reactors and spent fuel ponds [2]:

FD-1: Hydrogen from oxidation of zircaloy cladding (over 95% zirconium) exploded on March 12, destroying the secondary confinement roof, but the primary containment was said to be intact.

FD-2: Hydrogen explosion on March 15 breached primary containment, causing a partial meltdown. Iodine-131 (8-day half-life) was observed in Tokyo at a distance of 240 km on March 19 and its level in spinach at a distance of 70 km was 27 times the limited level. On March 20, electrical power was reestablish at unit 2, with the other units to follow. Water was added to the pond 2 on March 20.

FD-3: Hydrogen explosion on March 14 destroyed the secondary confinement roof and walls. Pond 3 was filled on March 20.

FD-4: Reactor was shut down three months ago with the transfer of all of its spent fuel to the spent fuel pond. Full-core discharges are rarely done in the U.S., where only the oldest fuel is usually removed. The young, very hot spent fuel heated pond water to boiling, with a report that pond had no water, starting a fire. This is consistent with the last-measured temperature of 84°C (183°F), as compared to the usual temperature of 25°C (77°F). Pond 4 was filled on March 20.)

FD-5: Reactor was shut down, but the pool's last-measured temperature was 63°C (145°F), as compared to the usual temperature of 25°C (77°F).

FD-6: Reactor was shut down, but the pool's last measured temperature was 60°C (140°F), as compared to the usual temperature of 25°C (77°F).

Loss-of-Coolant Rise Time

) I first calculate the thermal rise time of a light water reactor (LWR) core after a loss-of-coolant accident. Thermal rise is the time for the core to get sufficiently hot to begin an exothermal reaction between zircaloy and water. The calculation is based on the following assumptions [1]:

- \ Emergency core-coolant water (ECCS) water does not arrive until fuel rods are over 1370°C, when zircaloy cladding and water exothermically release hydrogen. This happens below its melting point of 2200°C.
- \ Core mass is 105 kg UO_2 for 1 GWe reactor. [Fukushima reactor #1 is rated at 460 MWe, reactors 2-5 at 784 GWe, and reactor 6 at 1.1 GWe].
-) LWR thermal efficiency is = 1/3.
-) Average fuel temperature is 400°C before a LOCA.)
-) Thermal power from beta decay after LOCA (P_o = 3 GWt):

$$P = P_o(0.0766t^{-0.181}) \qquad 0 < t < 150 \text{ sec}, \qquad (1)$$

$$P = P_o(0.130t^{-0.283}) \qquad 150 \text{ sec} < t < 4 \times 10^6 \text{ sec}. \qquad (2)$$

These equations give 7.7% of operating thermal power at 1 second, 3.7% at 1 minute, 1.3% at 1 hour, 0.5% at 1 day, 0.3% at 1 week, and 0.2% at one month, all of which conform to the measured data.

The thermal rise time is obtained by equating the heat needed to raise the core to 1370°C to the time integral of thermal power P. The heat needed to raise the core to 1370°C is

$$Q = Nc(\Delta T), \qquad (3)$$

where N is the number of moles of UO_2, c is the UO_2 molar specific heat, and ΔT is the temperature rise for the core to be 1370°C, that is, ΔT = 1370°C – 400°C = 970°C. The number of moles of UO_2 in the core is

$$N = (10^8 \text{ g})/(238 + 32)\text{g/mole} = 3.7 \times 10^5 \text{ moles}. \qquad (4)$$

The high-temperature specific heat, c = 3R = 24.9 J/mole-°C, is used since the temperatures are considerably above the UO_2 Debye temperature of 100 K. Thus, the heat needed to raise the core to its critical temperature is

$$Q_{rise} = Nc(\Delta T) = (3.7 \times 10^5 \text{ moles})(24.9 \text{ J/mole-°C})(970°\text{C}) = 8.9 \times 10^9 \text{ J}. \qquad (5)$$

The thermal rise time is obtained by equating Q_{rise}, to the time integral of the beta decay power,

$$Q_{beta\ decay} = \int_0^t \eta P\, dt = \int_0^t \eta\, 0.0766(3 \times 10^9)t^{-0.181}dt = (2.8 \times 10^8)t^{0.819} \text{ J} = 8.9 \times 10^9 \text{ J}. \qquad (6)$$

Solving for t gives a thermal rise time of 68 sec, which is close to the published values of 1 minute, calculated with the heat equation [3]. Since the time scale for a LOCA is only a minute, essentially all beta-decay heat is trapped in the core.

Loss-of-Power Rise Time

A more gradual LOCA almost happened in 1975 when a workman at the Brown's Ferry, Alabama, boiling water reactor (BWR) used a candle to check airflow and inadvertently set fire to electrical cables, cutting off electrical power for cooling pumps. Beta-decay heat began evaporating the water coolant, which in turn initiated a process that would have uncovered the core and begun a LOCA. The beta-decay heat needed to evaporate 700 tonnes of water is

$$Q_{evap} = mL_{evap} = (7 \times 10^5 \text{ kg})(2.27 \text{ MJ/kg}) = 1.6 \times 10^{12} \text{ J}. \qquad (7)$$

Setting Q_{evap} equal to the integrated beta-decay heat, over the two time regions, gives t = 19 hours, similar to the stated 13 hours available to recover the situation.

LOCA in Spent Fuel Ponds

The Fukushima spent fuel ponds are 12 meters deep, with 8 meters of water over the tops of the spent fuel assemblies. Pond water can be lost through holes in the concrete and by evaporation from the radioactive heat of the spent fuel. After one year, spent fuel radioactive heating is 15 kW/tonne, and at 10 years it falls to 2 kW/tonne. The spent fuel problem was exacerbated in the United States because the density of spent fuel in the ponds was increased as a result of the 1977 decision not to reprocess spent fuel. Increasing the density of fuel rods gives additional heating density and reduces the paths to remove heat by radiation and convection. Some parameters give can temperatures over 900°C in a spent fuel pond after a LOCA, a point where zircaloy cladding spontaneously ignites in air [4]. The problem could be lessened by moving some rods to a geological repository, or by placing them in surface storage, which is happening in the U.S. at this time. Damage could be mitigated after loss of coolant in the ponds by plugging pond holes with quick-setting material, pouring water on the ponds, or using large air blowers.

A Final Comment

Further data and analysis by experts are needed before serious conclusions on the Fukushima accident can be made. However, it initially seems that rapid deployment of portable generators on trucks or on ships to the Fukushima site could have made a considerable difference. Cables would be needed to deliver the power, but this should have been possible. Crews would experience some radiation, but less than that received by the fifty workers inside the plants. These generators could have provided electricity to drive the internal pumps at the reactors to bring water into the reactors and the spent fuel ponds. It took nine days to establish a 1.5 km power line to reactor 2 on March 20, with power to follow at the other reactors.

References

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[4] *R. Alvarez,* et al, *"Reducing the hazards from stored spent power-reactor fuel in the United States,"* Science and Global Security *11, 1–51, 2003.*

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Where is North Korea's Nuclear Program Heading?

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[This article is an edited version of a report prepared by Dr. Hecker soon after his return from North Korea's Yongbyon Nuclear Complex in November, 2010; we are grateful for his permission to run it. A related article appeared as a "Back Page" in APS News (March, 2011)]. Dr. Hecker's full article and related reports can be found at his website, http://cisac.stanford.edu/people/siegfriedshecker/. Dr. Hecker is a Professor (Research) of Management Science and Engineering, a Senior Fellow at the Freeman Spogli Institute for International Studies, and Co-Director of the Center for International Security and Cooperation, all at Stanford University. Trained as a metallurgist, he is regarded as one of the leading experts in the world on the properties of plutonium, and served as Director of the Los Alamos National Laboratory from 1986-1997 - Ed.]

On November 12, 2010, John W. Lewis, Robert Carlin and I visited North Korea's Yongbyon Nuclear Complex. There we were shown a 25 to 30 megawatt-electric (MWe) experimental light-water reactor (LWR) in the early stages of construction, along with a modern uranium enrichment facility. This reactor is North Korea's first attempt at LWR technology. These facilities appear to be designed primarily for civilian nuclear power as opposed to boosting North Korea's military nuclear capability.

This visit allowed us to answer some questions about Pyongyang's nuclear directions, but it also raised many more. In this article I describe our visit and offer some comments on how the response of the United States and its partners to these developments may help to shape whether Pyongyang will rely more on bomb development for diplomatic leverage or begin a shift toward nuclear electricity, which it desires both for economic and symbolic reasons.

Yongbyon Nuclear Scientific Research CenterN

This trip was my seventh to North Korea and my fourth to the Yongbyon complex, which is located about 90 km north of Pyongyang. During my first visit in January 2004 I was shown a sample of plutonium metal that had been reprocessed from spent fuel rods that had been stored since 1994 as part of the Agreed Framework, and which was subsequently used as bomb fuel for North Korea's first nuclear test of 2006 [1]. During all of my previous trips to North Korea, government officials and technical specialists denied the existence of any uranium enrichment activities. Following their 2009 rocket launch and second nuclear test, Pyongyang expelled the U.S. technical team and international inspectors and declared that it would build its own light-water reactor (LWR) and produce its own fuel. For this visit, I asked to see the key nuclear sites in order to judge their current status and to see if the enrichment technology that they announced at that time was successful [2]. Our visit was supported by a number of foundations, including the Ploughshares Foundation, the Carnegie Corporation, and the MacArthur Foundation.

We were met by a small technical team and representatives of the General Bureau of Atomic Energy. The senior technical official gave the following introduction: "In the 1980s and 1990s, we agreed to give up our reactors for LWRs, 2,000 Megawatt-electric (MWe) by 2003. In the early 1990s