An Analysis of a Hypothetical Release of Cesium-137 from a Spent Fuel Pool Fire at Kori-3 in South Korea

Jungmin Kang, Bemnet Alemayehu, Matthew McKinzie and Michael Schoeppner[1]

Natural Resources Defense Council (NRDC), 1152 15th Street NW, Suite 300, Washington, DC 20005, USA
jkang@nrdc.org; balemayehu@nrdc.org; mmckinzie@nrdc.org;
[1]Program on Science and Global Security, 221 Nassau St., 2nd Floor, Princeton, NJ 08542, USA
schoeppner@princeton.edu

INTRODUCTION

Release of Cs-137, with its 30-year half-life, from spent fuel pool fires would be potentially much larger than from reactor accidents, such as occurred during the Chernobyl and Fukushima accidents. The reason is that spent fuel pools adjacent to most power reactors but located outside of the reactor containment hold much larger inventories of Cs-137. Cs-137 is the gamma-emitting fission product that forced the evacuation of more than 100,000 people from the area surrounding Chernobyl in 1986 and more than 160,000 residents from the area surrounding Fukushima in 2011 to areas of lower contamination.

A spent fuel pool fire almost happened in Fukushima unit 4 although it was avoided due to inadvertent leakage of water into the pool from the adjacent reactor pit during the weeks after a hydrogen explosion destroyed the reactor building above the pool. If a spent fuel pool fire had happened on March 19, 2011 with winds towards Tokyo, approximately thirty-five million people within an area of 31,000 km^2, including Tokyo, would have had to be relocated [1]. Dense-packing of spent fuels greatly increases the chances for a hydrogen explosion, which can destroy the containment leading to unfiltered releases of radioactivity into the environment.

This study shows hypothetical releases from the dense-packed spent fuel pool fire of Kori-3 nuclear power reactor in South Korea, with atmospheric dispersion and deposition calculations using the HYSPLIT code [2] with historical meteorological data for the region surrounding the Korean Peninsula.

LOSS OF COOLING OF SPENT FUEL POOL

Pressurized water reactor (PWR) spent fuel pools are located in buildings adjoining the reactor containment buildings. Spent fuel pools are typically about 12 meters deep and vary in width and length. The water is cooled by a dedicated cooling system. Water is pumped through heat exchangers where heat is transferred to an intermediate cooling system, which finally rejects heat to the plant's ultimate heat sink [3].

Potential scenarios that can lead to loss of spent fuel cooling and fire include pool drainage due to a leak caused by an earthquake or terrorist attack, or by evaporation due to a prolonged loss of cooling and makeup water, for instance due to a loss of power as occurred at Fukushima.

PWR spent fuel assemblies are stored vertically in specific rack systems in the pool. Due limited storage capacities, Korean utilities have adopted dense-packed storage of spent fuel in pools, in which air-cooling is blocked by the solid rack walls surrounding each fuel assembly if the bottom of the racks is covered with water.

SPENT FUEL POOL ZIRCONIUM FIRE AND CESIUM INVENTORY RELEASE

A 2014 U.S. Nuclear Regulatory Commission (NRC) study explained that [4]:

> "If cooling of the spent fuel were not reestablished, the fuel could heat up to temperatures on the order of 1,000℃. At this temperature, the spent fuel's zirconium cladding would begin to react with air in a highly exothermic chemical reaction called a runaway zirconium oxidation reaction or autocatalytic ignition. This accident scenario is often referred to as a "spent fuel pool zirconium fire." Radioactive aerosols and vapors released from the damaged spent fuel could be carried throughout the spent fuel pool building and into the surrounding environment."

During the zirconium oxidation reaction, hydrogen is produced by reaction of water vapor with hot zirconium cladding of spent fuel. The NRC staff found that with low-density pool storage less hydrogen was produced and therefore an explosion was much less likely. And if the building above the pool is not destroyed by a hydrogen explosion, much less Cs-137 would be released to the atmosphere [5].

The NRC assumed a range of cesium inventory release fractions from fire in spent fuel pools for a PWR which is given in Table 1 [6].

Table 1. NRC-estimated cumulative cesium inventory release fractions given a PWR spent fuel pool fire at high and low-density spent fuel pool loadings

Spent Fuel Pools Loading	Low case	Base case	High case
High-density	10%	75%	90%
Low-density	0.5%	3%	5%

SPENT FUEL INVENTORIES IN POOLS IN SOUTH KOREA

As of the end of 2015, 16,289 fuel assemblies of PWR spent fuel and 408,797 fuel bundles of Canada Deuterium Uranium (CANDU) spent fuel were stored in the spent fuel storage facilities at South Korea's four nuclear power plant sites [7]. Table 2 shows the spent fuel inventories at the four sites as of the end of 2015. These PWR spent fuel assemblies and CANDU fuel bundles contain approximately 6,760 tons of heavy metal (tHM) and 7,849 tHM, respectively.

Table 2. Inventory of spent fuel in South Korea as of the end of 2015

Reactor	Reactor type	Annual spent fuel discharge (tHM)	Amount of spent fuel in pools (tHM)
Kori 1	PWR	14.4	114
Kori 2	PWR	15.9	281
Kori 3	PWR	20.5	818
Kori 4	PWR	20.5	797
Shin Kori 1	PWR	20.4	154
Shin Kori 2	PWR	20.4	98
Hanbit 1	PWR	20.5	666
Hanbit 2	PWR	20.5	456
Hanbit 3	PWR	20.4	372
Hanbit 4	PWR	20.4	378
Hanbit 5	PWR	20.4	255
Hanbit 6	PWR	20.4	254
Hanul 1	PWR	20.5	401
Hanul 2	PWR	20.5	408
Hanul 3	PWR	20.4	430
Hanul 4	PWR	20.4	404
Hanul 5	PWR	20.4	231
Hanul 6	PWR	20.4	206
Shin Wolsong 1	PWR	20.4	47
Shin Wolsong 2	PWR	20.4	20
Wolsong 1	CANDU	103.7	588
Wolsong 2	CANDU	103.7	715
Wolsong 3	CANDU	103.7	819
Wolsong 4	CANDU	103.7	800
			4,908 (dry storage)

HYPOTHETICAL RELEASE FROM THE SPENT FUEL POOL FIRE OF KORI-3

Kori-3 pool with its high-density rack contained approximately 818 tHM of spent fuel as of the end of 2015 - the largest quantity of PWR spent fuel at any South Korea reactor and therefore examined in this study as a scenario of maximum potential impact. The amount of Cs-137 in the PWR spent fuel was calculated using the ORIGEN2 code [8] while the dispersion and deposition simulations were calculated using HYSPLIT code with historic weather data for the region starting on the first day of every month in 2015 to understand seasonal variation in weather patterns [9]. We modeled the release of 1,600 PBq of Cs-137 over 3 days from the Kori-3 spent fuel pool fire, corresponding to the NRC "base" case in Table 1. Figure 1 and Figure 2 show two modeling results of contamination levels after a hypothetical fire at the Kori-3 spent fuel pool for weather patterns in January and September 2015. These two results are chosen for display from among the 12 study results because of the calculated impact to Japan. For the population relocation radiation dose threshold, we assume the approximate level of about 1 MBq/m^2 (27 Ci/km^2) similar what Japan had adopted for the Fukushima accident [1].

Table 3 shows the summary results for the Kori-3 spent fuel pool fire averaged for twelve historical weather patterns throughout 2015. For South Korea, the average and maximum calculated evacuation areas are 9,000 km^2 and 54,000 km^2, respectively, while the average and maximum number of evacuated people are 5.4 million and 24.3 million, respectively. These results may be compared with the total land area of South Korea of 100,209 km^2 and a total population of 50.6 million.

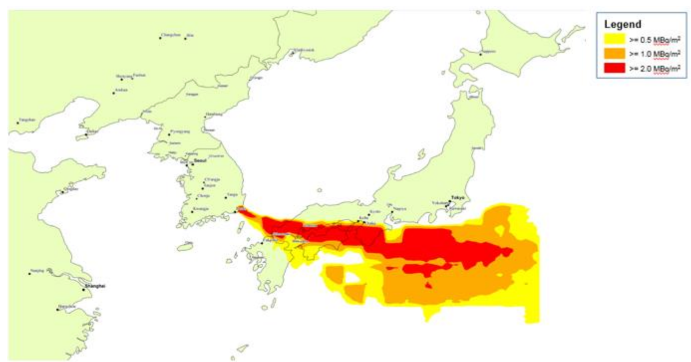

Figure 1. Contamination levels after the hypothetical fire of Kori-3 pool using weather data on Jan 1, 2015

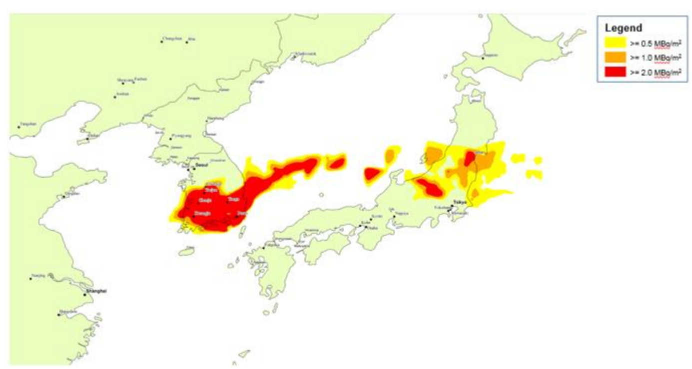

Figure 2. Contamination levels after the hypothetical fire of Kori-3 pool using weather data on Sep. 1, 2015

Table 3. Summarized results of the Kori-3 spent fuel pool fire modeling results, averaged over monthly historical weather patterns in 2015.

Country	Evacuated area (km^2)		Evacuated people	
	Average	Maximum	Average	Maximum
South Korea	9,000	54,000	5,400,000	24,300,000
North Korea	5,000	64,000	1,100,000	13,400,000
Japan	27,000	67,000	7,900,000	28,300,000
China	2,000	28,000	700,000	8,700,000

CONCLUSIONS

A hypothetical spent fuel pool fire at Kori-3 could contaminate not only a large part of South Korea, up to about a half of its area for which the surface contamination level of Cs-137 exceeds 1.0 MBq/m^2 and thus force up to about 24 million to be relocated, but also results in large areas of contamination in neighboring countries depending on prevailing weather conditions at the time of the spent fuel pool fire.

Given the enormous potential consequences of spent fuel pool fires, which could be caused by accident, natural disaster, or an act of terrorism or war, the authors recommend removing spent fuel cooled longer than five years to dry case storage and maintaining low-density storage racks for spent fuel while still in the pools.

REFERENCES

1. F. von Hippel and M. Schoeppner, "Reducing the Danger from Fires in Spent Fuel Pool," Science & Global Security, 24, 141-173 (2016).
2. A. F. Stein, et al. "NOAA's HYSPLIT atmospheric transport and dispersion modeling system," Bulletin of the American Meteorological Society, 96, 2059-2077 (2015).
3. J.G. Ibarra, et al. "Operating experience feedback report: Assessment of spent fuel cooling," NUREG-1275, U.S. Nuclear Regulatory Commission (1997).
4. "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel," NUREG-2157 Vol.1, U.S. Nuclear Regulatory Commission (2013).
5. E. Lyman, Michael Schoeppner and F. von Hippel, Science (2017); F. von Hippel and Schoeppner, "Economic Losses From a Fire in a Dense-Packed U.S. Spent Fuel Pool," Science and Global Security (2017).
6. "COMSECY-13-0030 - Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel," U.S. Nuclear Regulatory Commission (2013).
7. "Draft Basic Plan of High-Level Radioactive Waste Management," Korean Atomic Energy Commission (2016) (Korean).
8. "ORIGEN 2.1: Isotope Generation and Depletion Code Matrix Exponential Method," CCC-371 ORIGEN 2.1, Oak Ridge National Laboratory (1996).
9. S. Saha et al., "NCEP Climate Forecast System Version 2 (CFSv2) 6–hourly Products," Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory (2011).