Military Vulnerabilities of Civilian Nuclear Facilities: Case Studies for South Korea and Japan

Jungmin Kang, PhD

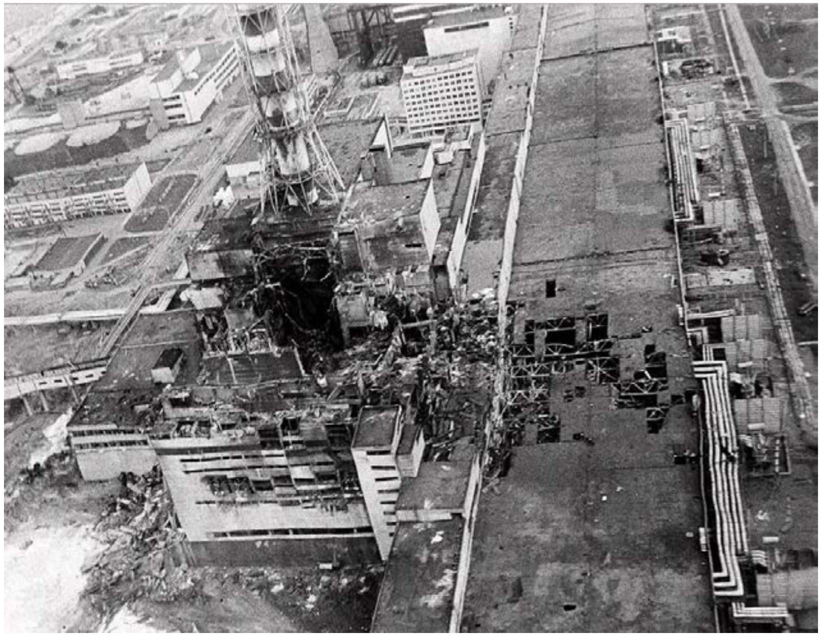
Independent Consultant

Former Chairman of ROK's Nuclear Safety and Security Commission

Virtual Seminar by REEPS

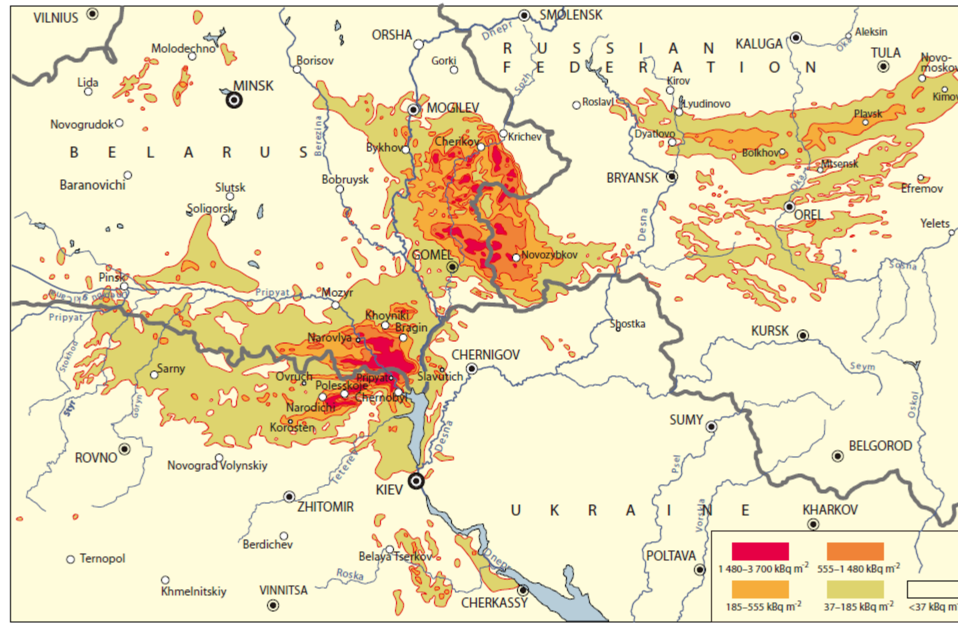
10 July 2021

April 1986 Chernobyl Accident



(Ref: Alan Taylor, "The Chernobyl Disaster: 25 Years Ago," The Atlantic, Mar 23, 2011)

Figure II. Map of ^{137}Cs deposition levels in Belarus, the Russian Federation and Ukraine as of December 1989 [I28]



(Ref: "Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2008 Report to the General Assembly with Scientific Annexes," United Nations, New York, 2011)

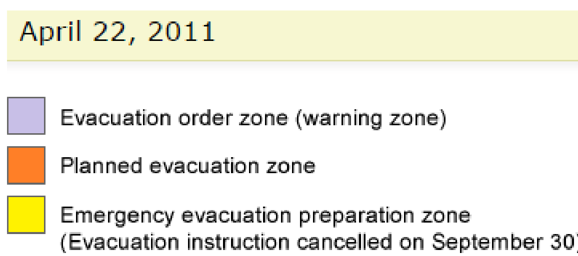
- More than 100,000 residents evacuated.
- Area of radiation control zone was 10,000 km^2 contaminated to levels greater than 0.5 MBq/m^2 of Cs-137

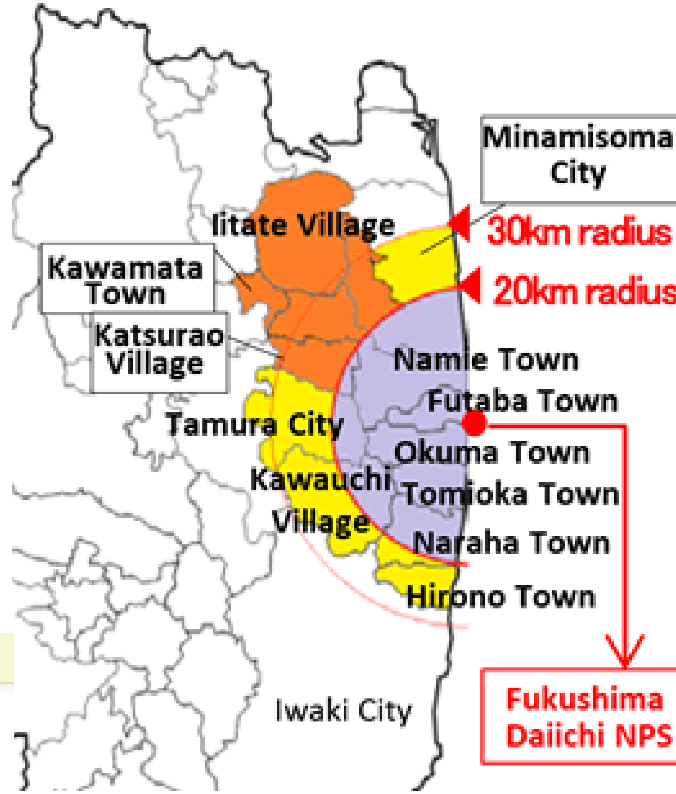
(Ref: Robert Alvarez et al., "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," Science and Global Security, 11:1–51, 2003)

Voluntary relocation: the area where the surface contamination concentration of Cs-137 exceeds 0.5 MBq/m^2
Compulsory relocation: the area where the surface contamination concentration of Cs-137 exceeds 1.5 MBq/m^2

March 2011 Fukushima Accident

(Ref: What Went Wrong: Fukushima Nuclear Disaster (http://www.popularmechanics.com/science/energy/a6721/fukushima-nuclear-disaster-what-went-wrong-5508927/))





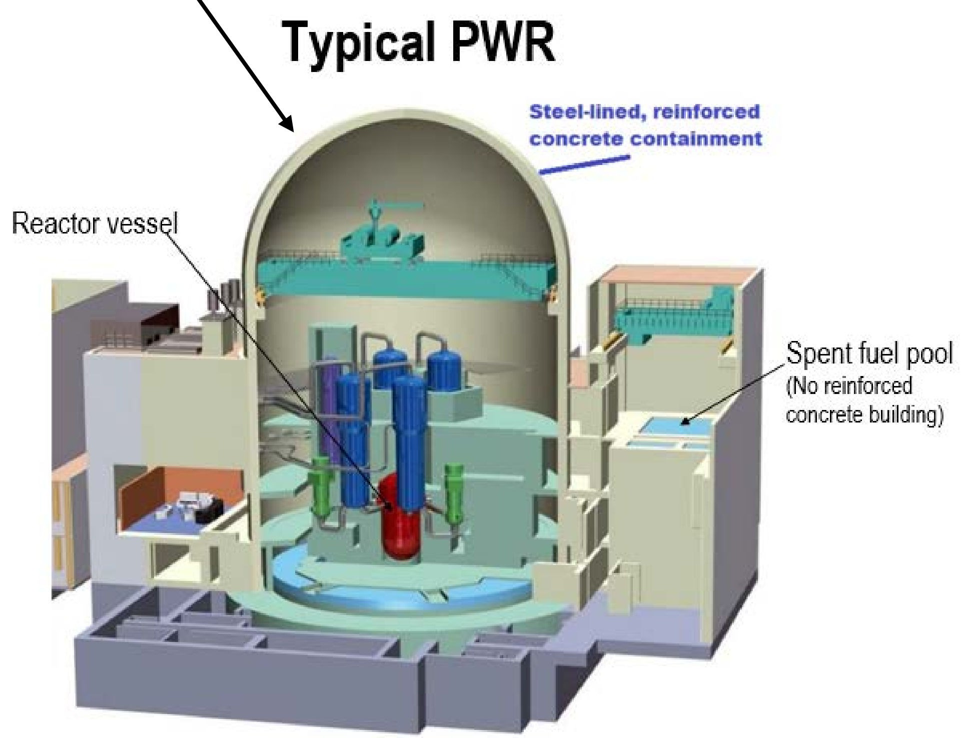
(Ref: Masa Takubo, "Fukushima disaster today," Busan, Korea, 27 February 2017)

- More than 160,000 residents evacuated to areas of lower contamination less than 1 MBq/m^2 of Cs-137.
- The mean total activity of Cs-137 was around 7–20 PBq.
    - Most of the releases were dispersed over the North Pacific Ocean.

(Ref: IAEA, "The Fukushima Daiichi Accident: Report by the Director General," 2015, p.107.)

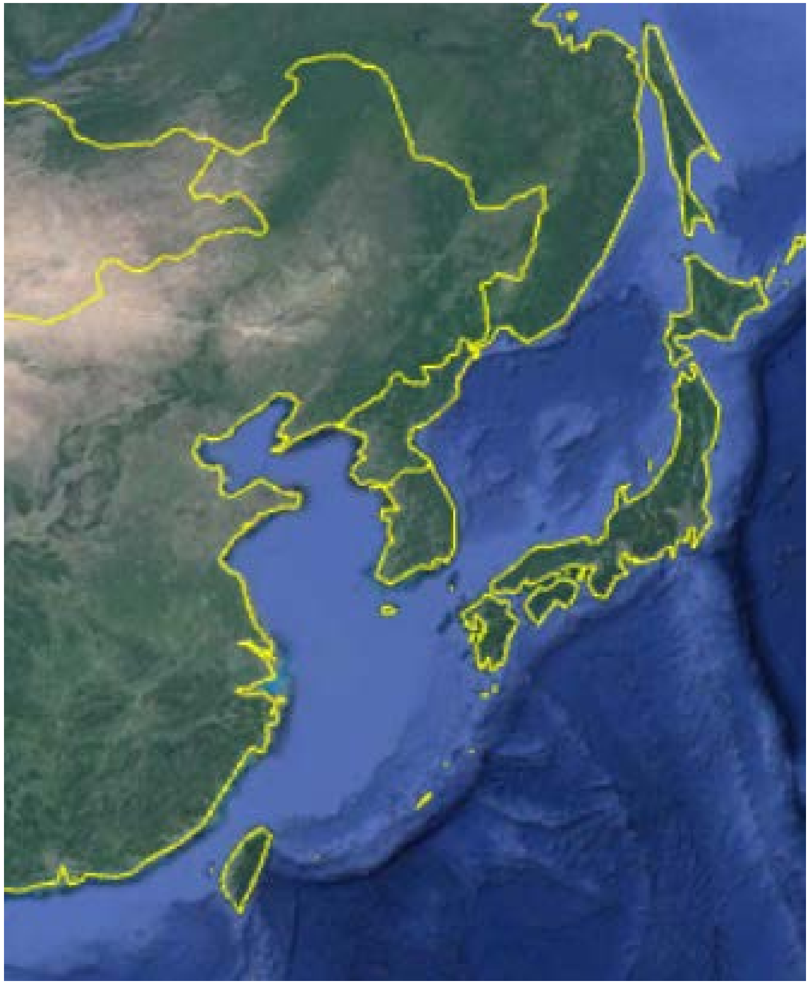
What if a nuclear power plant had been the target of missile attack?

(Ref: https://abcnews.go.com/International/north-korean-missile-test-year/story?id=46592733)



(Ref: https://allthingsnuclear.org/dlochbaum/nuclear-plant-containment-failure-overpressure)

In this study, I perform technical analysis if a nuclear power plant had been the target of missile attack, focusing on nuclear reactors and spent fuel pools in Northeast Asia



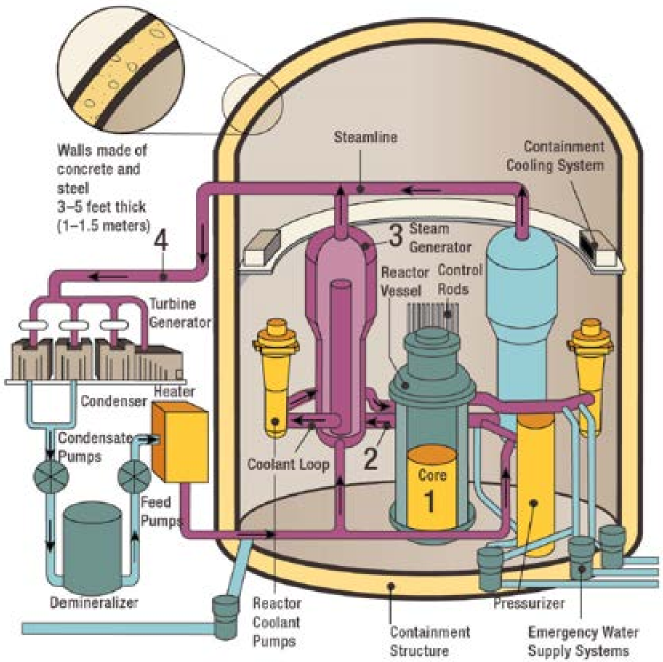
(Ref: Google Earth Pro, 6 May 2020.)

Vulnerability of Nuclear Power Plant

- The missile attack could damage on
  - Containment building
    - punctured or cracked partly or largely
    - lose its confinement capability to contain the escape of radioactive gas
  - Cooling systems
    - pumps and/or the main coolant piping breaks and thus the pumps cannot circulate coolant through the core that could lead to the core meltdown
    - results in a loss of cooling of spent fuel pool that could lead to the spent fuel pool fire
  - Power systems
    - cut off offsite power and get onsite emergency diesel generators to be malfunctioned
    - results in a loss of reactor coolant that could lead to the core meltdown
    - results in a loss of cooling of spent fuel pool that could lead to the spent fuel pool fire

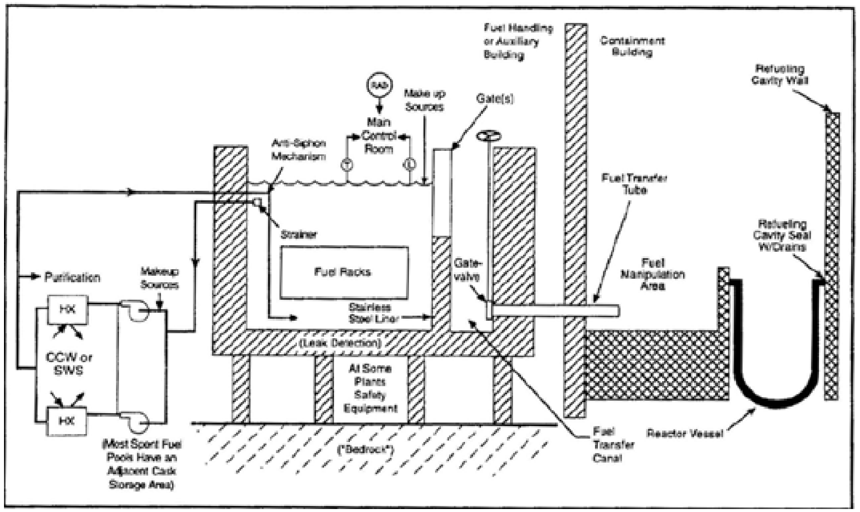
Vulnerability of Nuclear Power Plant (cont)

PWR Cooling System



(Ref: https://www.nrc.gov/reactors/pwrs.html)

Generic Spent Fuel Pool Design for PWRs



(Ref: Ibarra, J.G., et al., Operating experience feedback report: Assessment of spent fuel cooling, 1997, Report NUREG-1275, U.S. Nuclear Regulatory Commission, Washington, DC, USA.)

Cs-137, a dominant radioactive isotope released from the nuclear accidents of core meltdown or spent fuel pool fire

- Cs-137 (30-year half-life) is relatively volatile and is a potent land contaminant because 95% of its decays are to an excited state of Ba-137, which de-excites by emitting a penetrating (0.66-MeV) gamma ray.
- The release of Cs-137 from the Chernobyl accident was about 85 PBq (petabecquerel, 10^{15} Bq).
- The release of Cs-137 from the Fukushima accident was around 7–20 PBq.

- About 4 PBq of Cs-137 is contained in the 1 tHM of 10-year cooled PWR spent fuel with burnup of 40 MWd/kgHM. About 80 PBq of Cs-137 is contained in 20 tHM of PWR spent fuel which is annually discharged from the 1GWe PWR.

Zirconium Fire of Spent Nuclear Fuel

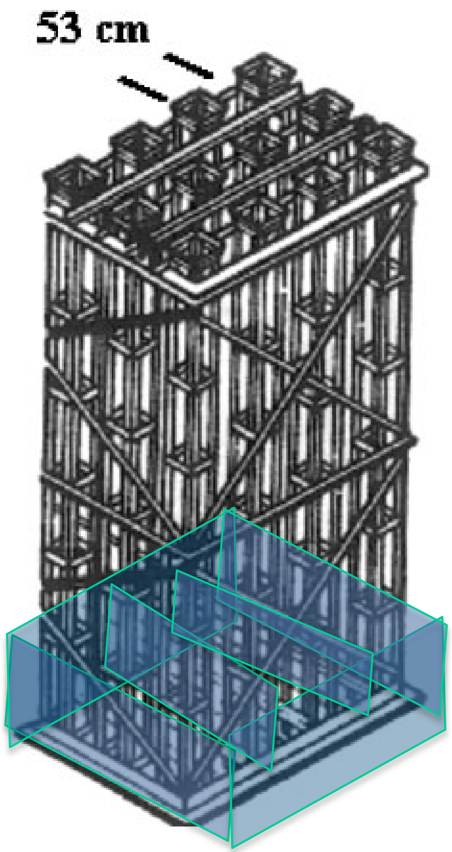
- Zirconium fire
  - “If cooling of the spent fuel were not reestablished, the fuel could heat up to temperatures on the order of 1,000℃. At this temperature, the spent fuel’s zirconium cladding would begin to react with air in a highly exothermic chemical reaction called a runaway zirconium oxidation 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.”
- Hydrogen production
  - Hydrogen is produced by reaction of water vapor with hot zirconium cladding of spent fuel:

$$H_2O\text{ (vapor)} + Zr \rightarrow H_2 + ZrO$$

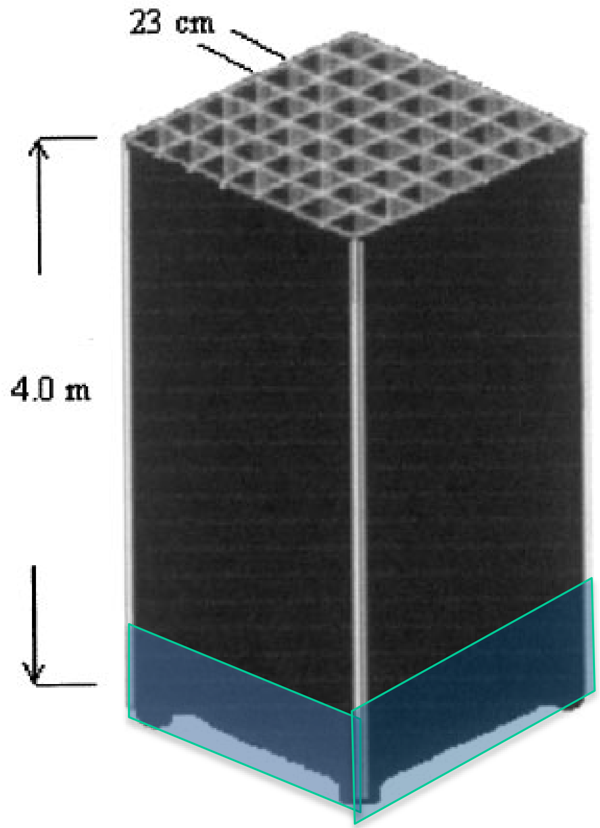
  - US NRC found less hydrogen with low-density pool storage and much less likelihood of an explosion.

(Ref: US NRC, "Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel," NUREG-2157 Vol.1, September 2013, p.F-1.; Frank von Hippel, "Proposals for Reducing the Danger from Spent Fuel Pool Fires," Busan, South Korea, 27 February 2017)

Low Density vs. High Density Spent Fuel Pool



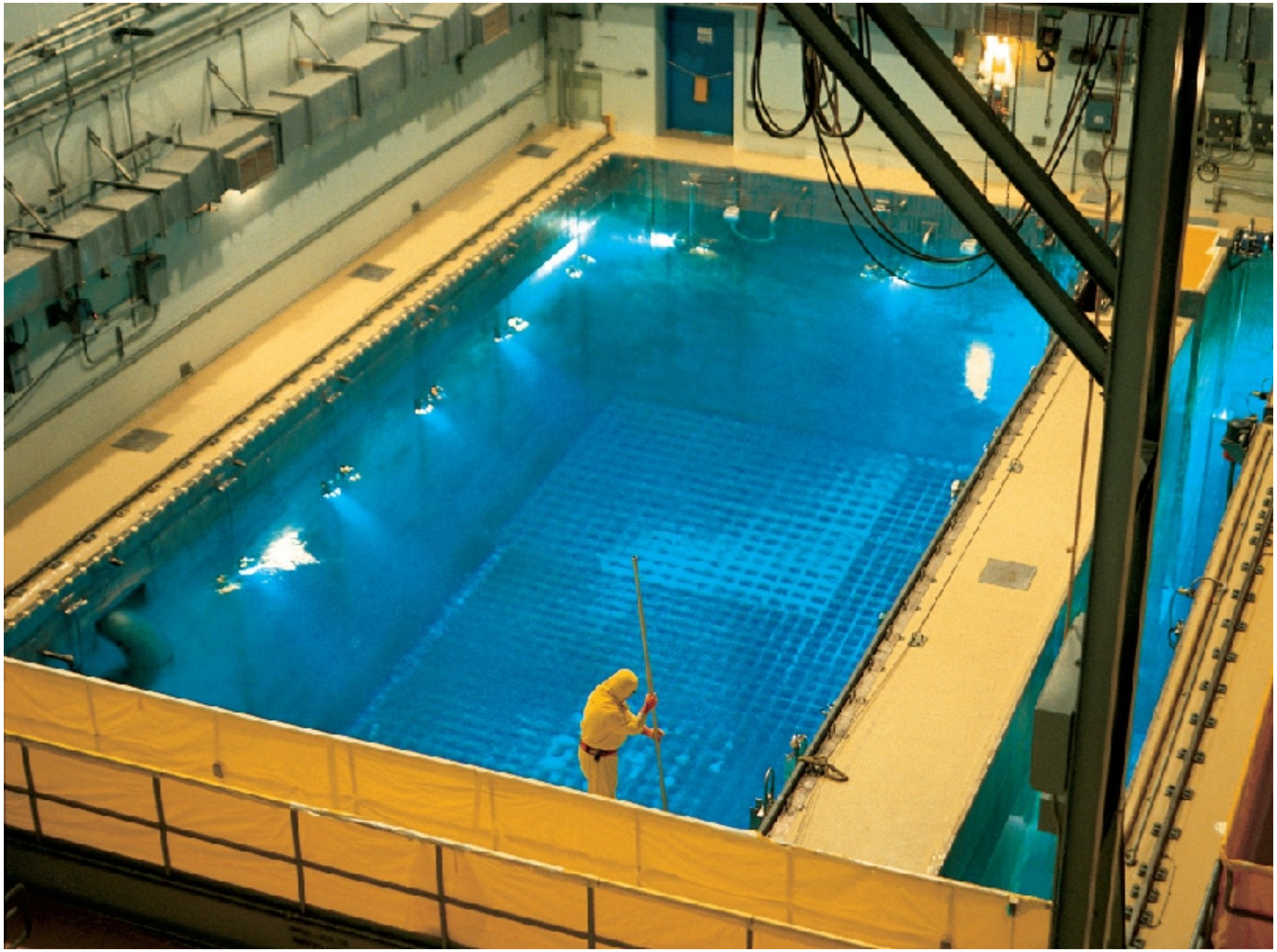
Low density,
air-cooling possible



High density,
air-cooling not possible – especially if partial drainage and bottom of racks covered with water.

(Ref: Frank von Hippel, "Proposals for Reducing the Danger from Spent Fuel Pool Fires," Busan, South Korea, 27 February 2017)

A Dense-Racked Spent Fuel Pool



(Ref: Frank von Hippel, "Proposals for Reducing the Danger from Spent Fuel Pool Fires," Busan, South Korea, 27 February 2017)

Cs-137 Inventory Release from SFPF

SFP loading	Low case	Base case	High case
High-density	10%	75%	90%
Low-density	0.5%	3%	5%

(Ref: USNRC, "COMSECY-13-0030 - Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel," November 25, 2013)

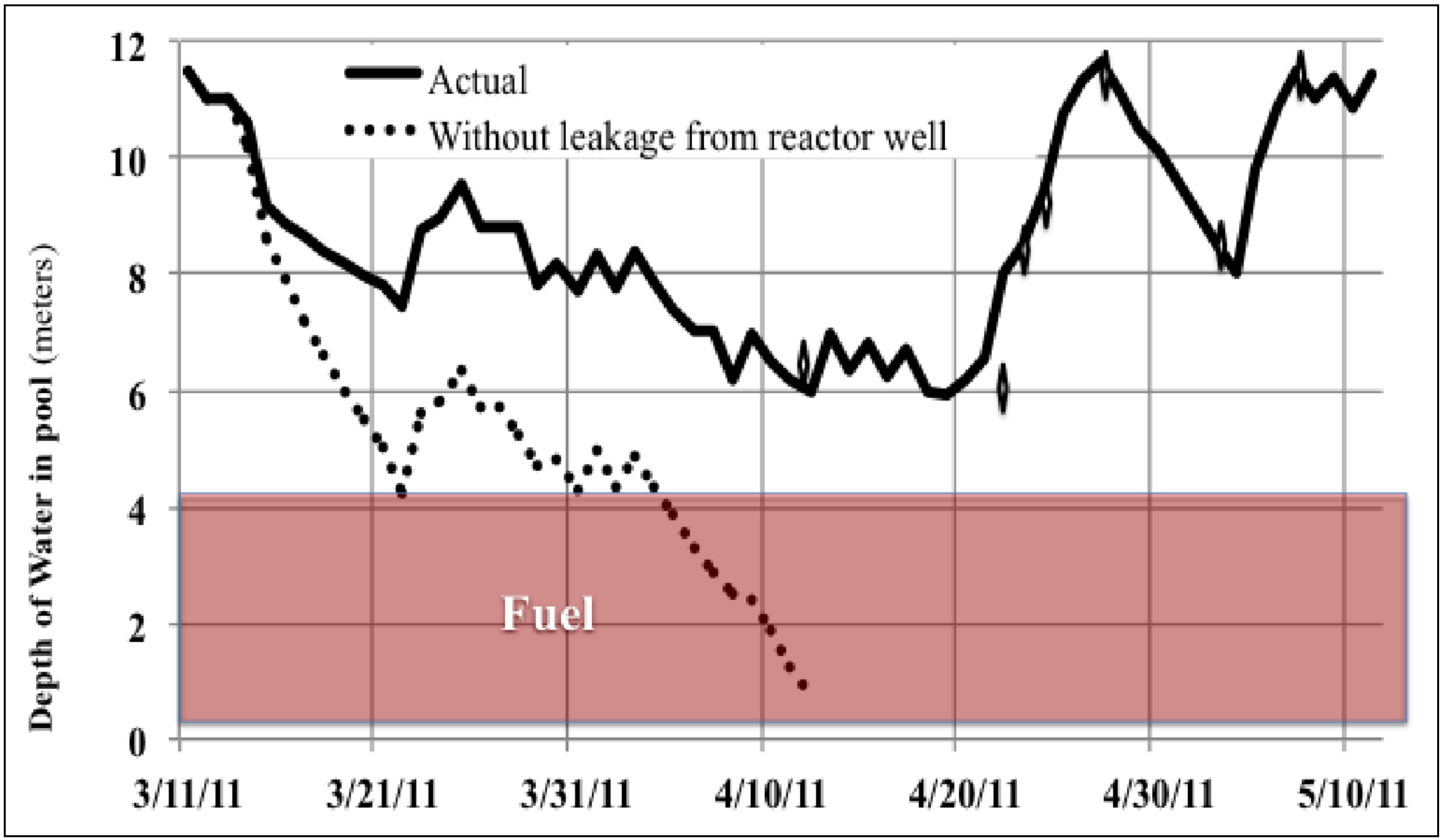
Devil's Scenario of Fukushima Spent Fuel Pool #4

- *Science* journal
  - "Japan's chief cabinet secretary called it "the devil's scenario." Two weeks after the 11 March 2011 earthquake and tsunami devastated the Fukushima Daiichi Nuclear Power Plant, causing three nuclear reactors to melt down and release radioactive plumes, officials were bracing for even worse. They feared that spent fuel stored in pools in the reactor halls would catch fire and send radioactive smoke across a much wider swath of eastern Japan, including Tokyo. Thanks to a lucky break detailed in a report released last week by the U.S. National Academies of Sciences, Engineering, and Medicine, Japan dodged that bullet."

(Ref: Richard Stone, "Near miss at Fukushima is a warning for U.S.: Panel says spent reactor fuel in a storage pool could have boiled dry and caught on fire," Science 27 May 2016, Vol. 352, Issue 6289, pp. 1039-1040)

Devil's Scenario of Fukushima Spent Fuel Pool #4 (cont)

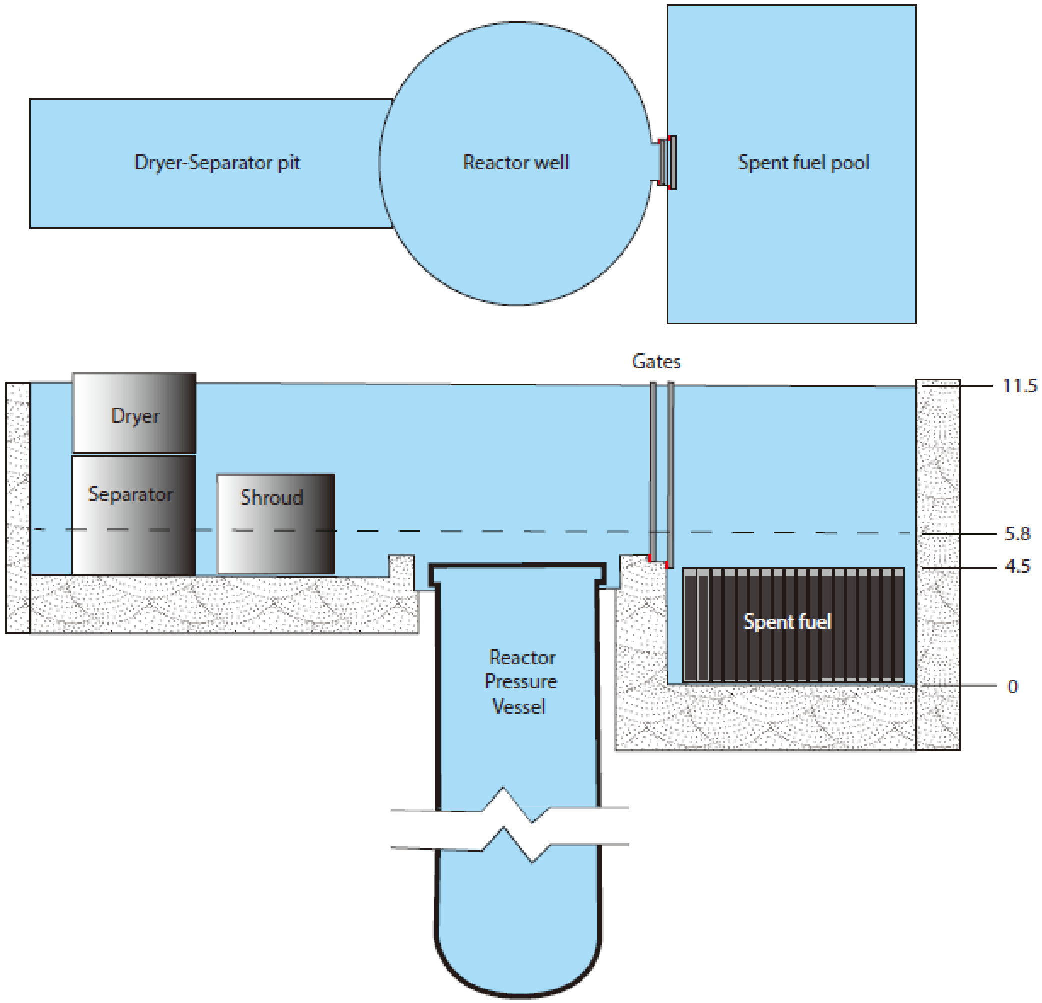
Leakage into the pool from the adjacent reactor pit saved Fukushima Spent Fuel Pool #4 from dryout



(Ref: Frank von Hippel, "Proposals for Reducing the Danger from Spent Fuel Pool Fires," Busan, South Korea, 27 February 2017)

Devil's Scenario of Fukushima Spent Fuel Pool #4 (cont)

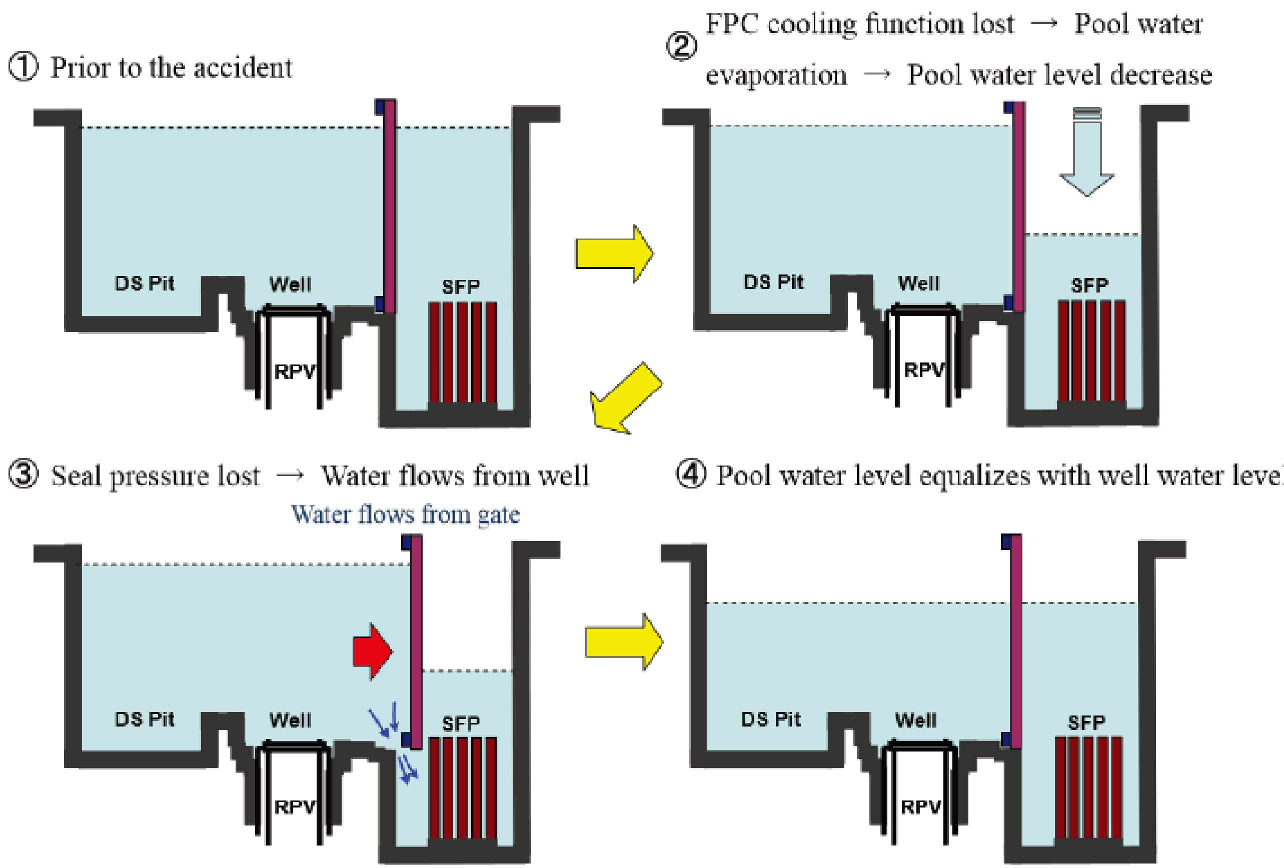
Source of water that kept the spent fuel in pool #4 covered



(Ref: "Lessons Learned from the Fukushima Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2," National Academy of Sciences, 2016, p.23)

Devil's Scenario of Fukushima Spent Fuel Pool #4 (cont)

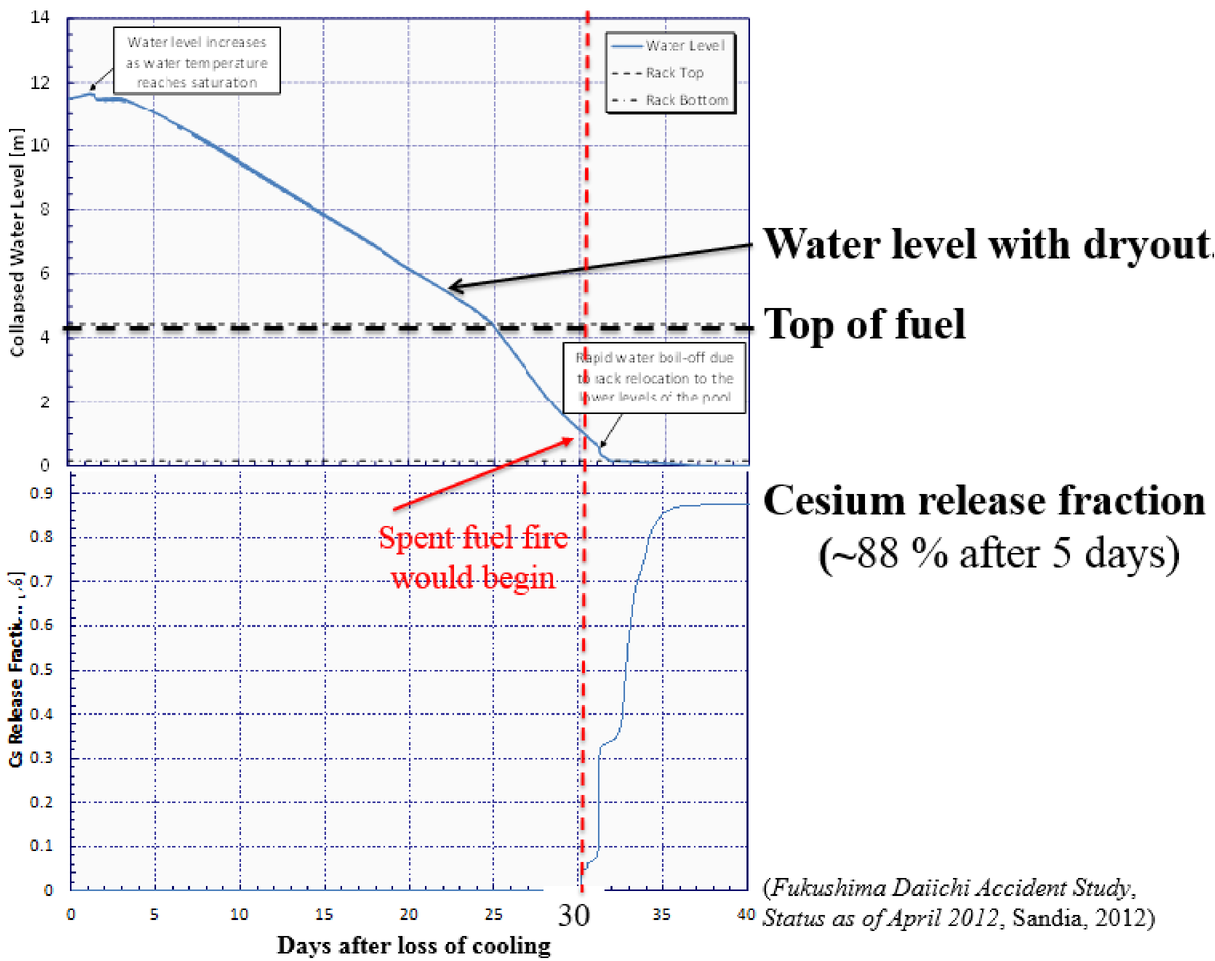
Sequence of events postulated by TEPCO for water inflow to the spent fuel pool from the reactor well. (DS Pit = dryer-separator pit; RPV = reactor pressure vessel; SFP = spent fuel pool; FPC = fuel pool cooling and cleanup)



(Ref: "Lessons Learned from the Fukushima Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2," National Academy of Sciences, 2016, p.45)

Devil’s Scenario of Fukushima Spent Fuel Pool #4 (cont)

If no water added, would have had fire in 30 days. If pool leaked, much sooner.



(*Fukushima Daiichi Accident Study*, *Status as of April 2012*, Sandia, 2012)

(Ref: Frank von Hippel, "Proposals for Reducing the Danger from Spent Fuel Pool Fires," Busan, South Korea, 27 February 2017)

Fukushima population relocated where Cs-137 contamination ≥ 1.5 MBq/m^2 (orange)

Hypothetical **fire in spent fuel pool #4**
historical weather**, HYSPLIT calculations,**

Actual Fukushima accident (3/15/2011)

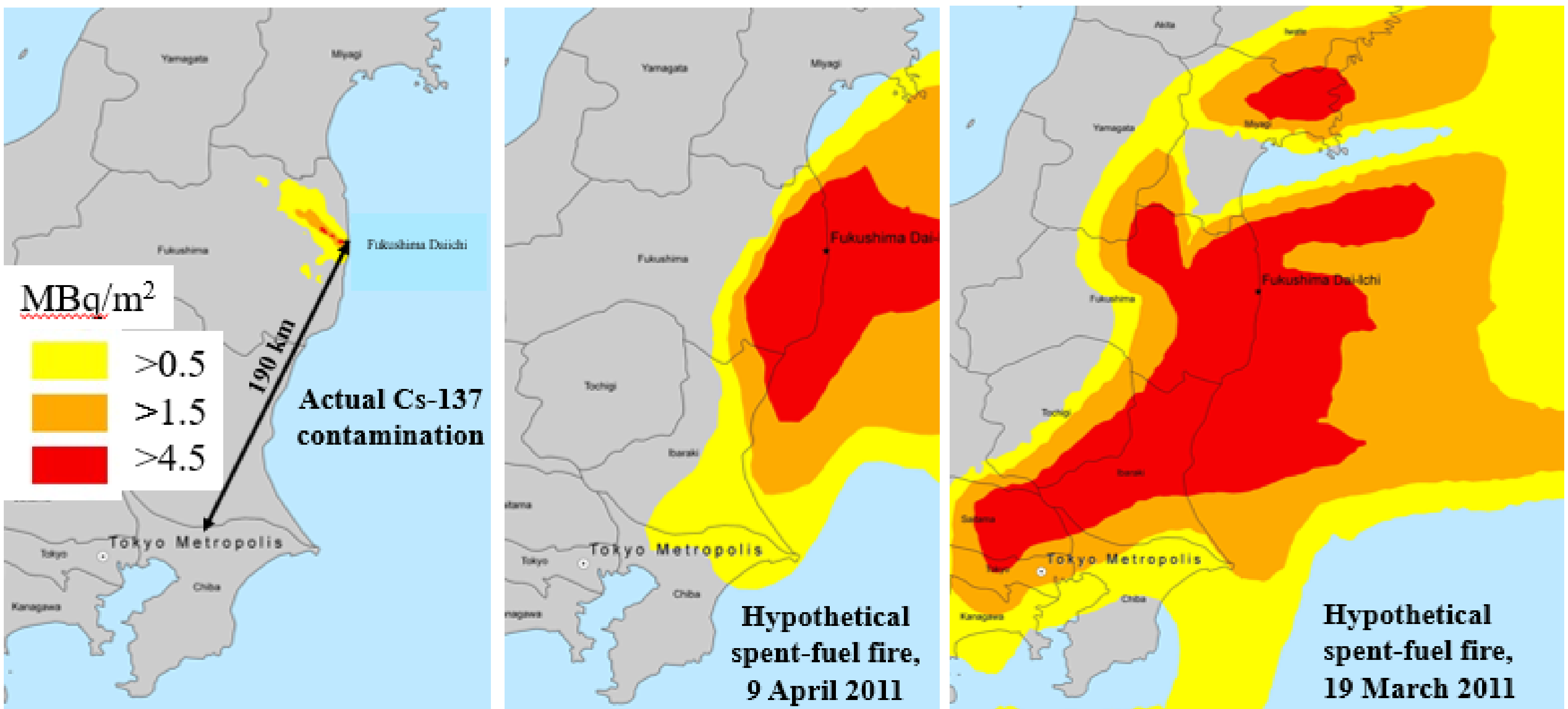
Relocated: 88,000
from 1,100 km^2

Wind toward ocean
(4/9/2011)

Relocated: 800,000
from 2,600 km^2

Wind toward Tokyo
(3/19/2011)

Relocated: 29,000,000
from 25,000 km^2



(Ref: (Ref: Frank von Hippel, Msafumi Takubo, Jungmin Kang "Plutonium: How Nuclear Power's Dream Fuel Became a Nightmare," Springer Nature, 2019))

Assumptions of this study

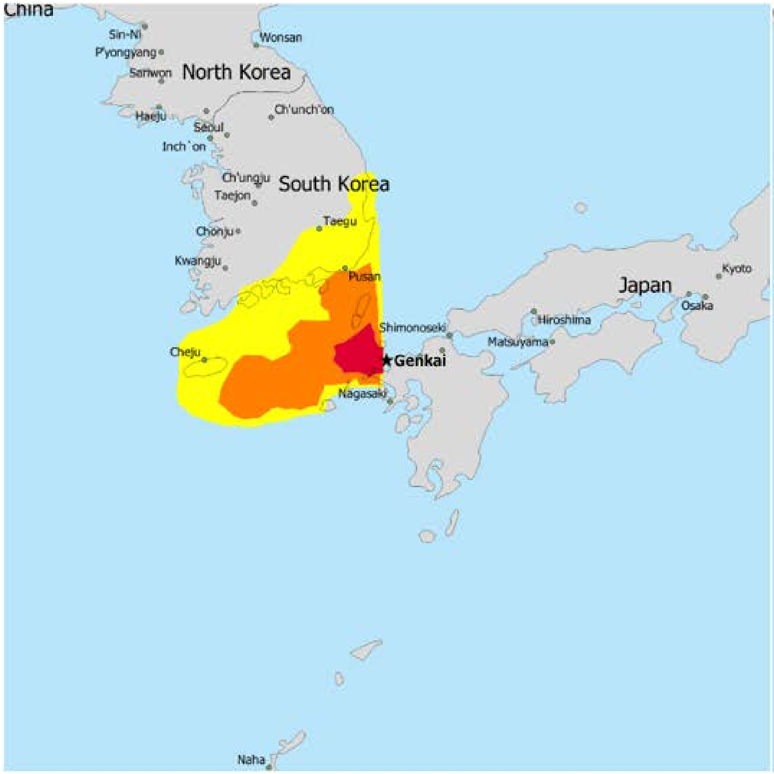
- The radioactivity of the Cs-137 release from the nuclear accident of core meltdown of 1GWe NPP is assumed about 258 PBq which is 75% of core inventory of Cs-137. The containment building is assumed to be punctured or cracked largely from the missile attack.
- For a fire in the Kori-3 pool, that would correspond to a release of about 2,240 PBq while about 6,470 PBq for a fire in the Rokkasho reprocessing plant’s spent fuel pool. Kori-3 pool is dense-packed with about 910 tons of spent fuel. The Rokkasho reprocessing plant’s pool contains 2,968 tons of spent fuel as of January 31, 2019.

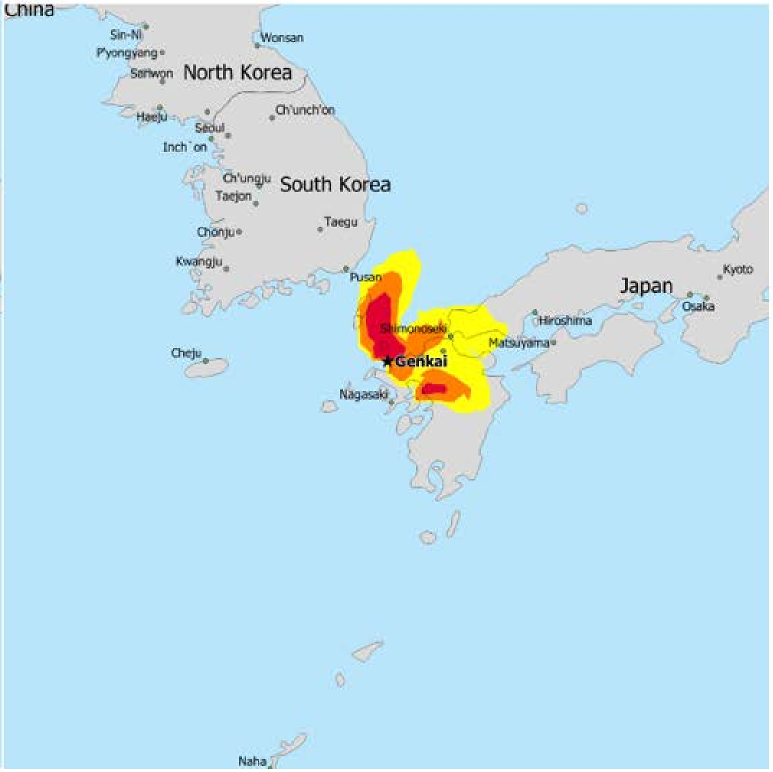
Assumptions of this study (Cont)

- Atmospheric transport simulations of hypothetical radiological release were conducted to assess the impact on population and land area
  - Using Hysplit model by NOAA with GDAS meteorological data (3-hour and 1-degree resolution) and population database (NASA)
  - 12 simulations were conducted for each scenario, one for the first day of each month in 2019 to cover seasonal variations.
  - Release was assumed to last 32 hours from a vertical line source of 0-300m.
  - Plume and fallout were simulated for one week, including dry and wet deposition.
- Output is the average and maximum number of affected people and land area according to the following thresholds
  - The contamination levels for compulsory evacuation are shown in orange and red and those for voluntary evacuation in yellow. The yellow area is great than 0.5 MBq/m^2 less than 1.5 MBq/m^2. The orange area is great than 1.5 MBq/m^2 less than 4.5 MBq/m^2. The red area is great than 4.5 MBq/m^2
- [The Hysplit calculations were done by Dr. Michael Schoeppner, Independent Consultant]

Hypothetical nuclear accident at the Genkai 3 reactor in Japan

Relocation areas for hypothetical nuclear accident at the Genkai 3 reactor on 1 October and 1 December 2019
(258 PBq of Cs-137 release)





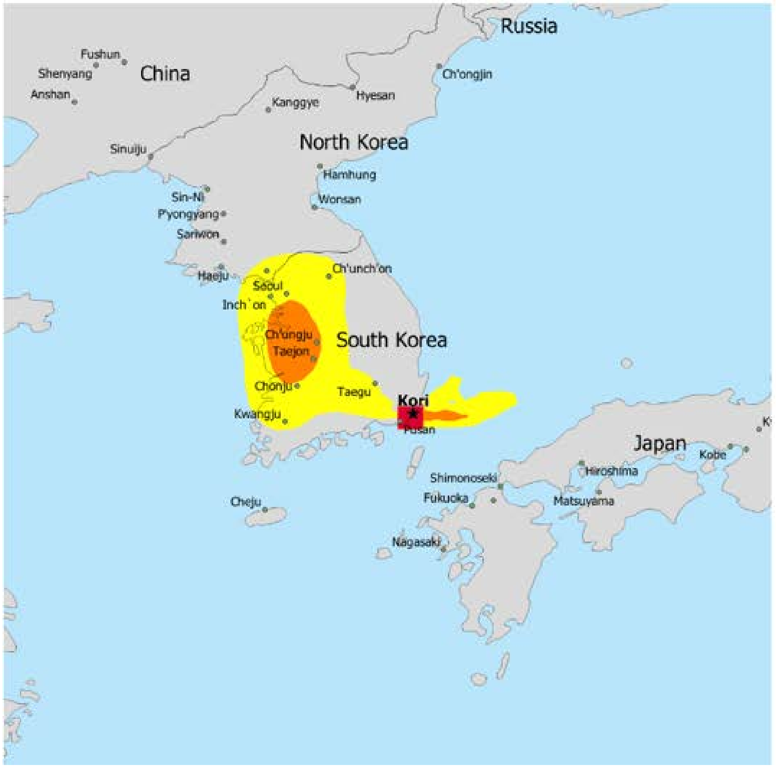
Hypothetical nuclear accident at the Genkai 3 reactor in Japan (cont)

Country	Relocated populations		Interdicted areas (km^2)	
	Average	Maximum	Average	Maximum
Japan	1.3 million (2.6 million)	9.5 million (12.4 million)	5,800 (14,300)	18,400 (40,500)
South Korea	400 (0.7 million)	5,000 (8.6 million)	50 (14,300)	600 (40,500)
China	(500)	(6,000)	(50)	(600)
Taiwan	(71,000)	(0.8 million)	(1,500)	(18,400)

(The numbers of the parenthesis are total numbers when the voluntary evacuation is added.)

Hypothetical nuclear accident at the Kori 3 reactor in South Korea

Relocation areas for hypothetical nuclear accident at the Kori 3 reactor on 1 August and 1 December 2019
(258 PBq of Cs-137 release)



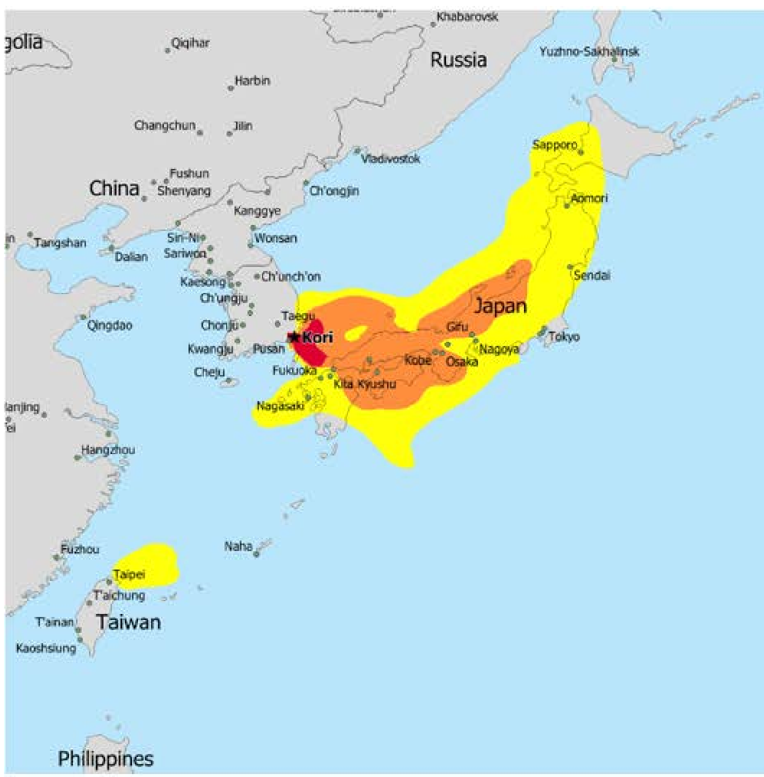
Hypothetical nuclear accident at the Kori 3 reactor in South Korea (cont)

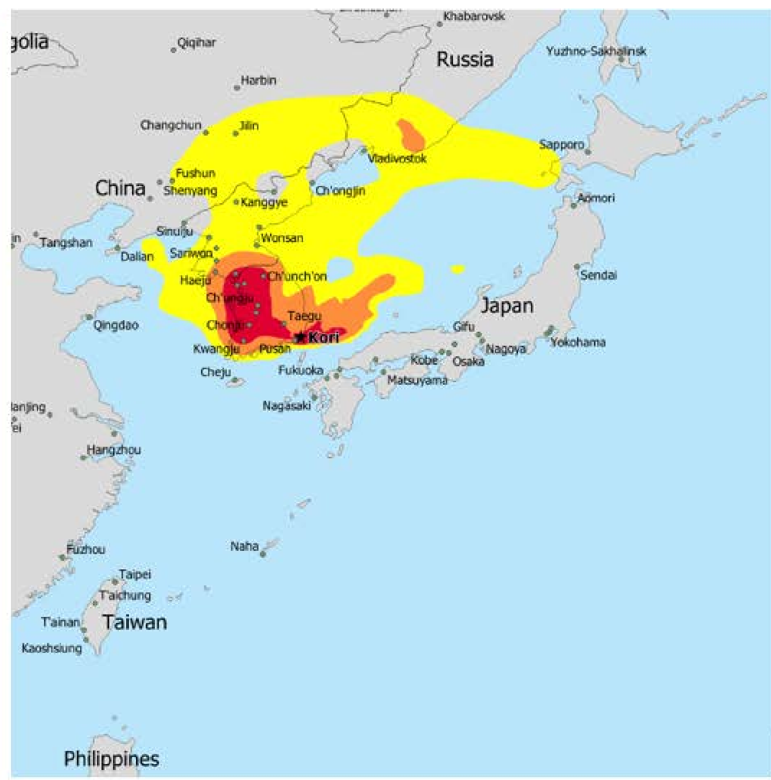
Country	Relocated populations		Interdicted areas (km^2)	
	Average	Maximum	Average	Maximum
South Korea	2.3 million (6.3 million)	12.9 million (46.6 million)	4,500 (14,900)	20,300 (72,200)
North Korea	(28,000)	(0.3 million)	(50)	(600)
Japan	47,000 (0.5 million)	459,000 (3.0 million)	400 (4,900)	2,500 (20,900)
Taiwan	(43,000)	(0.5 million)	(200)	(2,500)

(The numbers of the parenthesis are total numbers when the voluntary evacuation is added.)

Hypothetical nuclear accident at the Kori 3 spent fuel pool in South Korea

Relocation areas for hypothetical nuclear accident at the Kori 3 spent fuel pool on 1 May and 1 August 2019
(2,240 PBq of Cs-137 release)



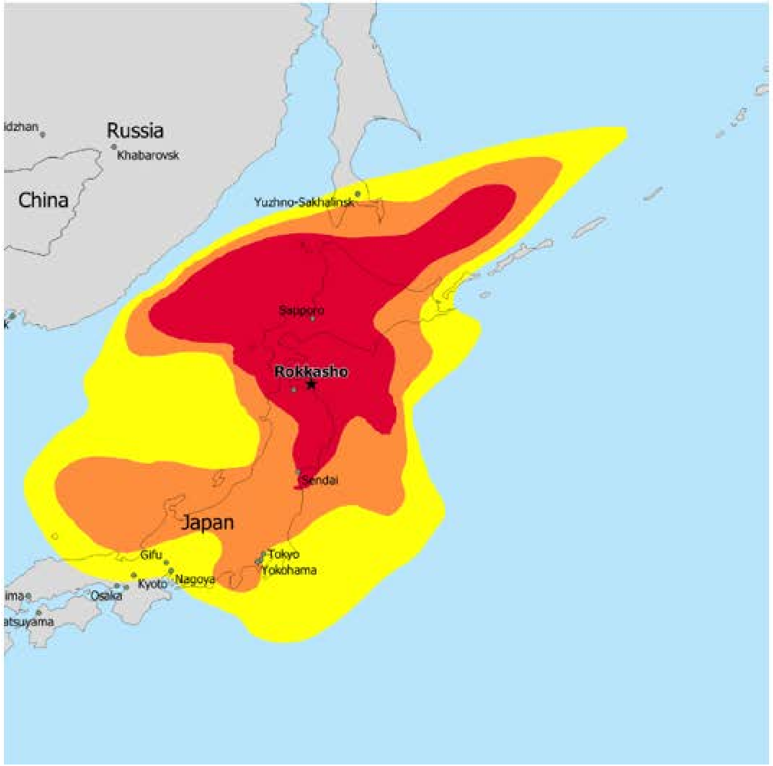


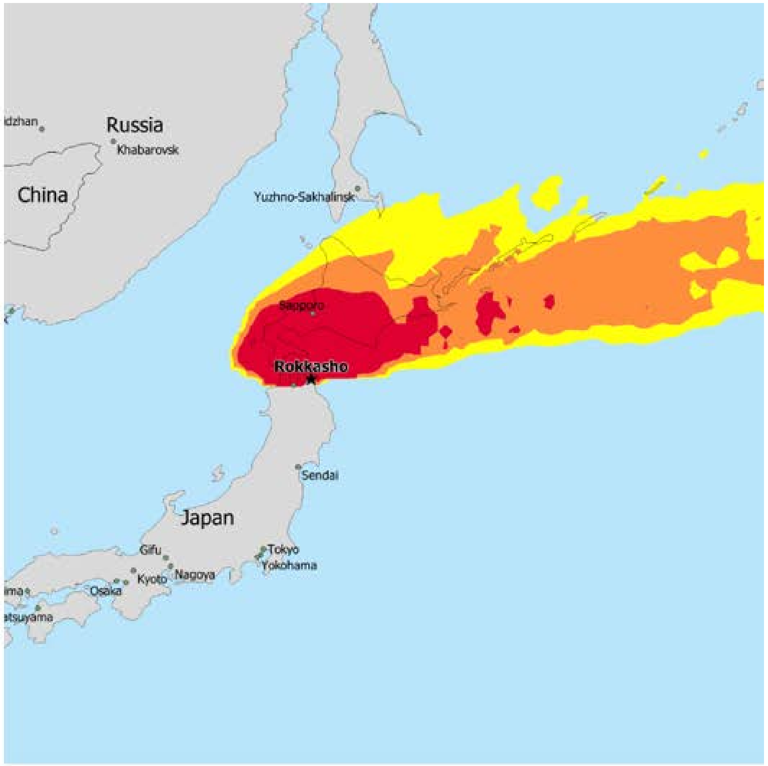
Hypothetical nuclear accident at the Kori 3 spent fuel pool in South Korea (cont)

Country	Relocated populations		Interdicted areas (km^2)	
	Average	Maximum	Average	Maximum
South Korea	8.5 million (10.0 million)	50.0 million (52.0 million)	26,700 (34,800)	117,100 (100,200)
North Korea	0.2 million (2.0 million)	2.6 million (21.5 million)	1,400 (12,900)	16,500 (124,100)
Japan	5.1 million (17.5 million)	40.0 million (118.6 million)	36,700 (111,100)	201,900 (467,200)
China	(2.0 million)	(17.4 million)	(19,000)	(199,400)
Russia	1,000 (0.1 million)	17,000 (1.1 million)	700 (10,400)	8,900 (91,800)
Taiwan	0.9 million (1.7 million)	11.0 million (20.1 million)	2,100 (3,900)	24,700 (44,300)
Philippine	(38,000)	(0.4 million)	(1,700)	(12,000)

Hypothetical nuclear accident at the Rokkasho reprocessing plant's spent fuel pool in Japan

Relocation areas for hypothetical nuclear accident at the Rokkasho reprocessing plant's spent fuel pool on 1 October and 1 December 2019 (6,470 PBq of Cs-137 release)





Hypothetical nuclear accident at the Rokkasho reprocessing plant's spent fuel pool in Japan (cont)

Country	Relocated populations		Interdicted areas (km^2)	
	Average	Maximum	Average	Maximum
Japan	6.4 million (8.9 million)	62.1 million (89.2 million)	51,700 (65,900)	312,700 (391,800)
Russia	5,000 (20,000)	31,000 (0.2 million)	12,100 (24,300)	70,300 (151,300)

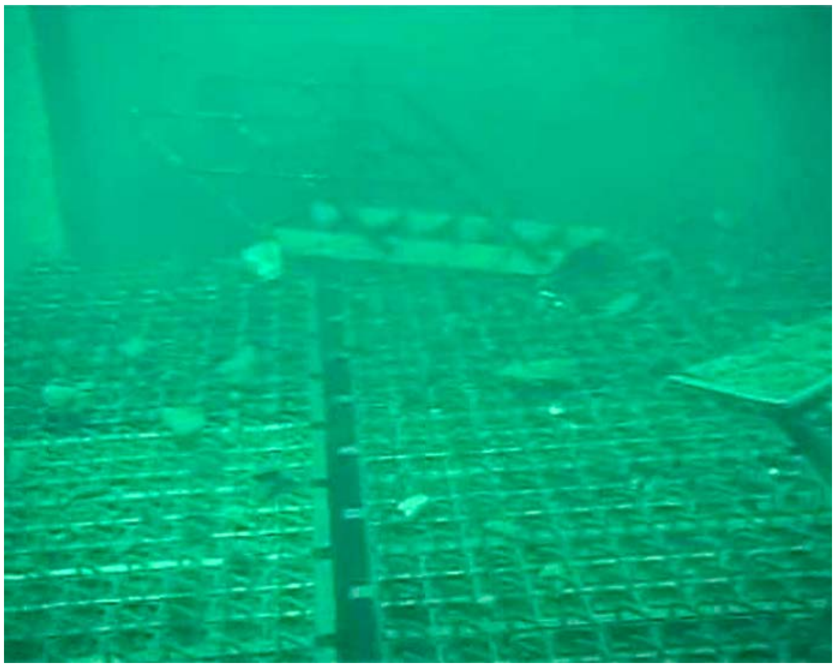
(The numbers of the parenthesis are total numbers when the voluntary evacuation is added.)

Conclusions

- The nuclear power plants are vulnerable from military attack, including missile attacks in war conditions.
- The missile attack could make containment building punctured or cracked to lose its confinement capability to contain the escape of radioactive gas. The missile attack also could damage on cooling systems/power systems that could lead to the core meltdown and/or the spent fuel pool fire.
- The hypothetical reactor core meltdown and/or spent fuel pool fire occurred by the missile attack could have major impacts in adjoining countries.
- Although it may not be possible to prevent these attacks, their consequences can be mitigated to some extent by moving spent fuel from the pools after five years of cooling into dry cask storage.

Pool Storage vs. Dry Cask Storage

Debris on top of fuel racks in Unit 4 pool



(Ref: "Lessons Learned from the Fukushima Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2," National Academy of Sciences, 2016, p.23)

Spent fuel storage casks at Fukashima after the tsunami

(Ref: http://cryptome.org/eyeball/daiichi090911/daiichi090911.htm)