Risk of the Missile Attack on Nuclear Facilities

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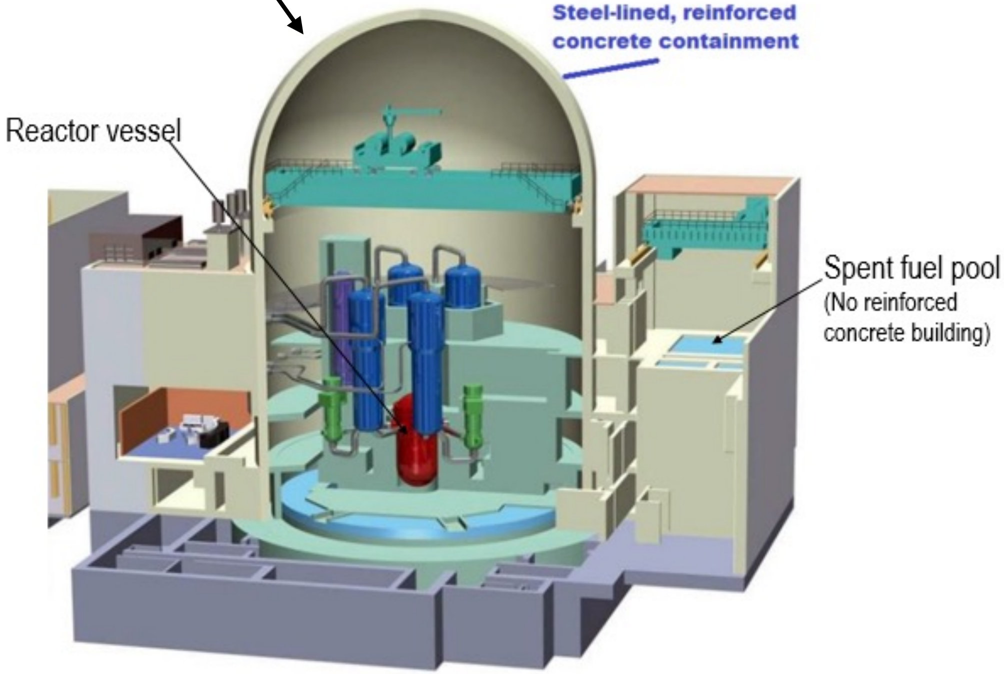
What if a nuclear power plant had been the target of missile attack?

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

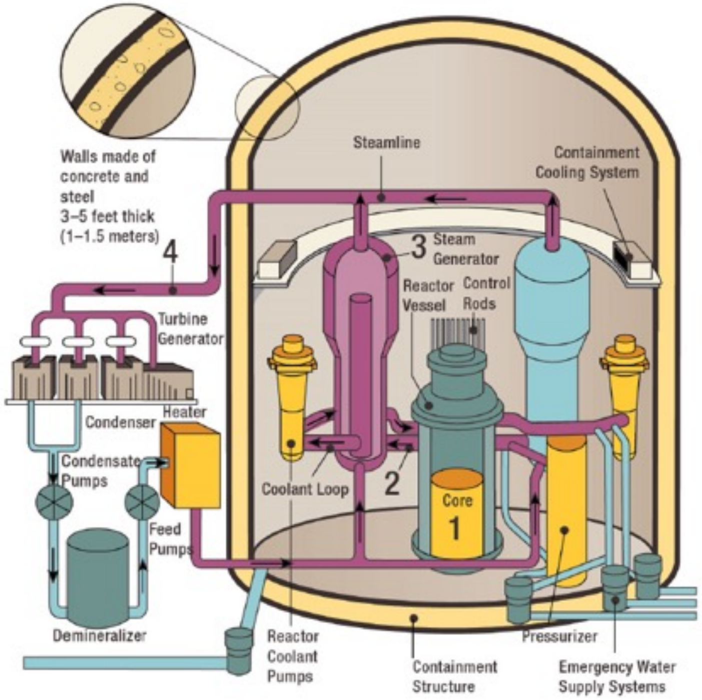
Typical PWR



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

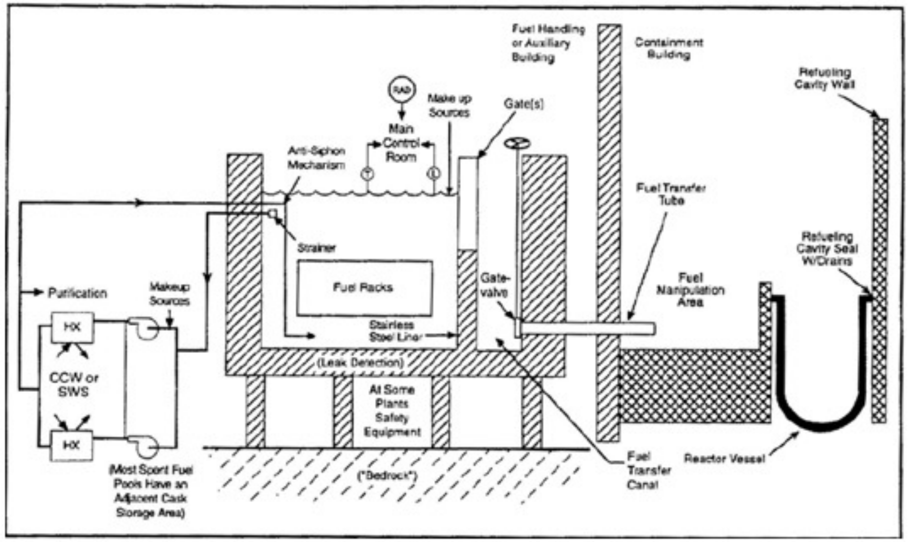
Vulnerability of Nuclear Power Plant

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.)

Vulnerability of Nuclear Power Plant (cont)

- 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

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.

Spent Fuel Pool Zirconium Fire

- 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)

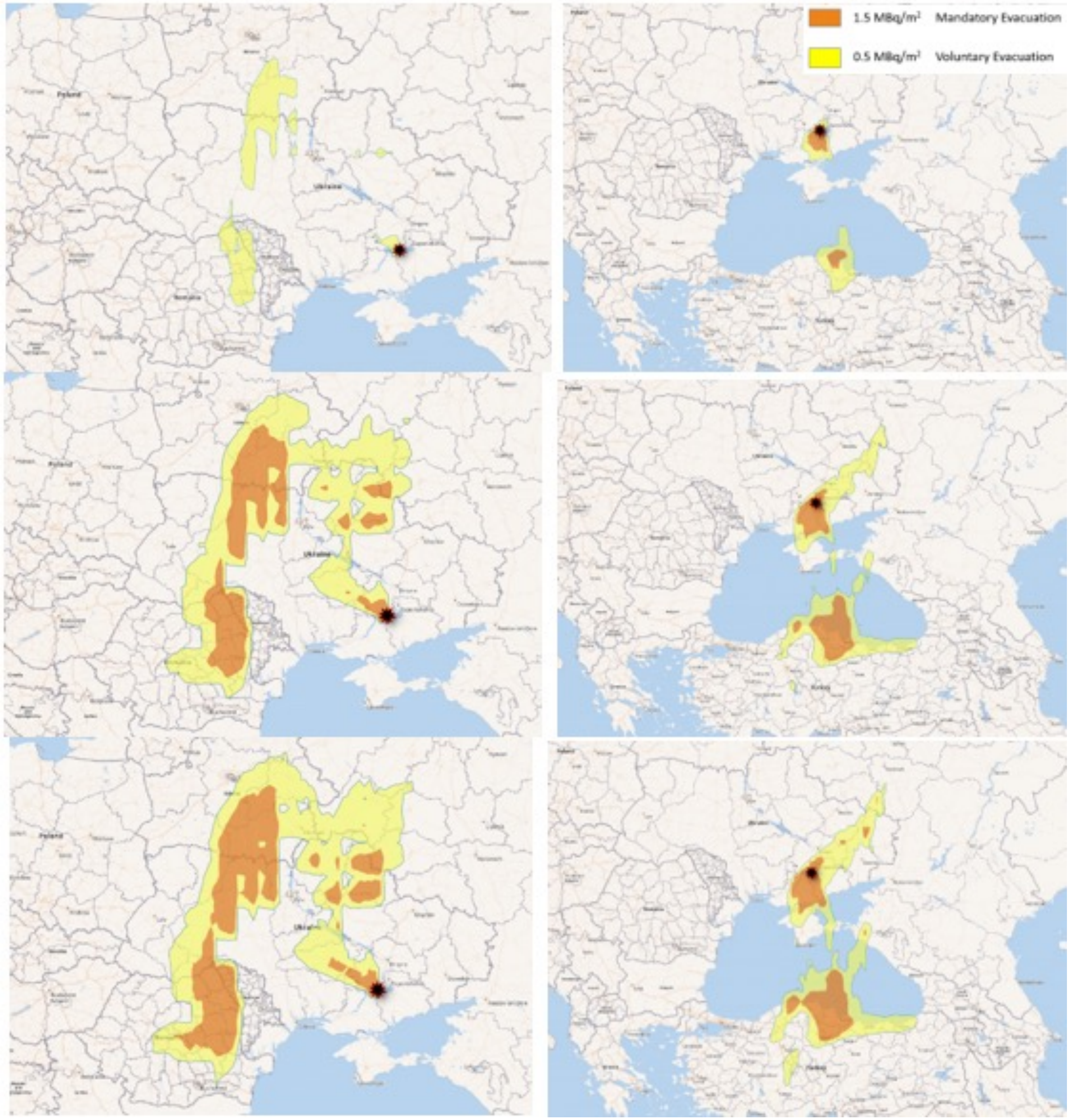
Some assumptions

- Zaporizhzhya 1 is a pressurized water reactor with an electric power capacity of 950 MWe; it has been operated since 1984. I assumed a Cs-137 release of 157 PBq due to a nuclear core meltdown of the reactor, which is 50% of the Cs-137 core inventory. For a spent fuel pool fire occurring in the Zaporizhzhya Unit 1 spent fuel pool, I assumed a Cs-137 release of 590 PBq, which is 75 percent of the pool inventory of Cs-137.
- 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.

Some assumptions (Cont)

- The atmospheric dispersion following the releases was simulated
  - Using the Hysplit model provided by the NOAA and a population database provided by the NASA.
  - The simulations ingested meteorological data from the GDAS and were conducted as if the radiation release and spread happened in the third and fourth weeks of March 2021 for Zaporizhzhya 1 case while on the first day of each month in 2019 for the cases of Kori-3 pool and Rokkasho reprocessing plant's pool.
- On the maps in Figures, 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
  - For Zaporizhzhya 1 case, the orange area is great than 1.5 MBq/m^2.
- The atmospheric dispersion calculations were done by Eva Lisowski for Zaporizhzhya 1 case and Dr. Michael Schoeppner for other cases.

Hypothetical nuclear accidents at Zaporizhzhya 1 in Ukraine



Contamination levels for hypothetical nuclear accidents at Zaporizhzhya 1 in the third (left) and fourth (right) week of March 2021. Severe Core Meltdown (top), Spent Fuel Pool Fire (middle), and both simultaneously (bottom)

[Ref: Jungmin Kang, Eva Lisowski, "Could an attack on Ukrainian nuclear facilities cause a disaster greater than Chernobyl? Possibly, simulations show." Bulletin of the Atomic Scientists, March 23, 2022]

Hypothetical nuclear accidents at Zaporizhzhya 1 in Ukraine (cont)

Table 1: Relocated populations for hypothetical nuclear accident at Zaporizhzhya 1

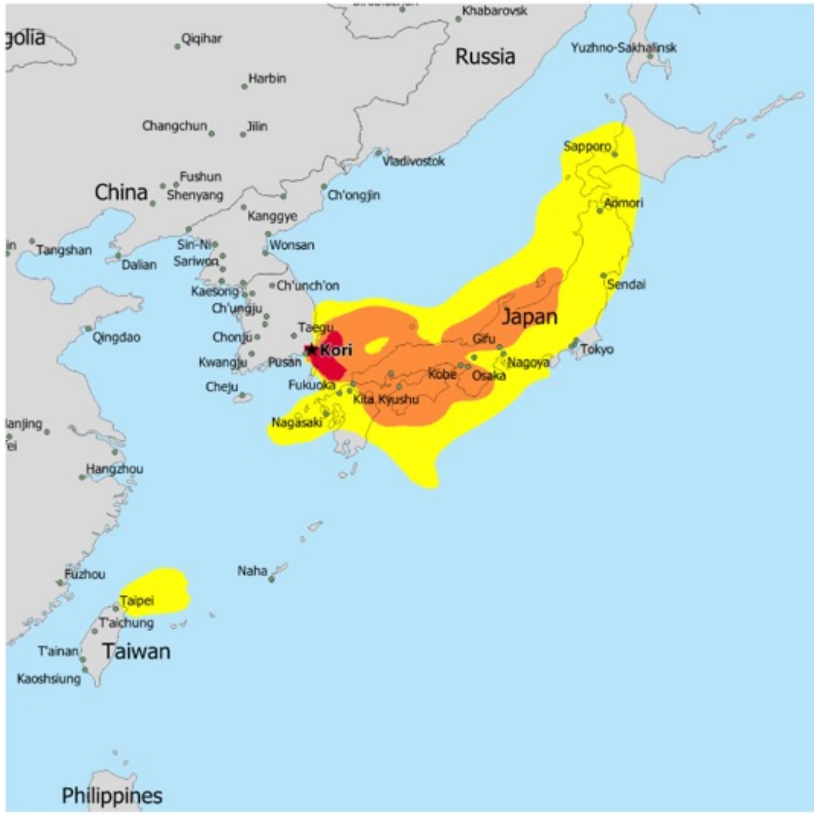
Country	Relocated populations (Week 3)	
	Compulsory	Voluntary
Ukraine	34,000 – 3.6 million	960,000 – 6.7 million
Russia	0 – 60,000	600 – 1.4 million
Romania	0 – 2.1 million	1.1–1.5 million
Moldova	0 – 420,000	260,000 – 450,000
Belarus	0 – 880,000	320,000 – 1.9 million

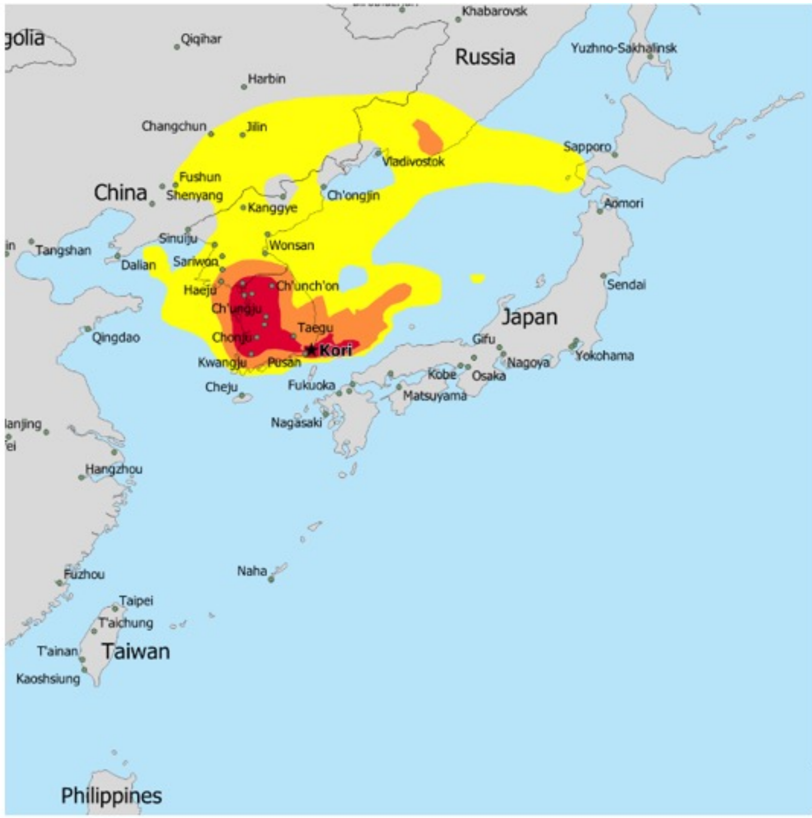
Country	Relocated populations (Week 4)	
	Compulsory	Voluntary
Ukraine	362,000 – 1.6 million	280,000 – 2.4 million
Turkey	69,000 – 2.2 million	1.7–3.2 million
Russia	0 – 28,000	0 – 770,000

[Ref: Jungmin Kang, Eva Lisowski, "Could an attack on Ukrainian nuclear facilities cause a disaster greater than Chernobyl? Possibly, simulations show." Bulletin of the Atomic Scientists, March 23, 2022]

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)





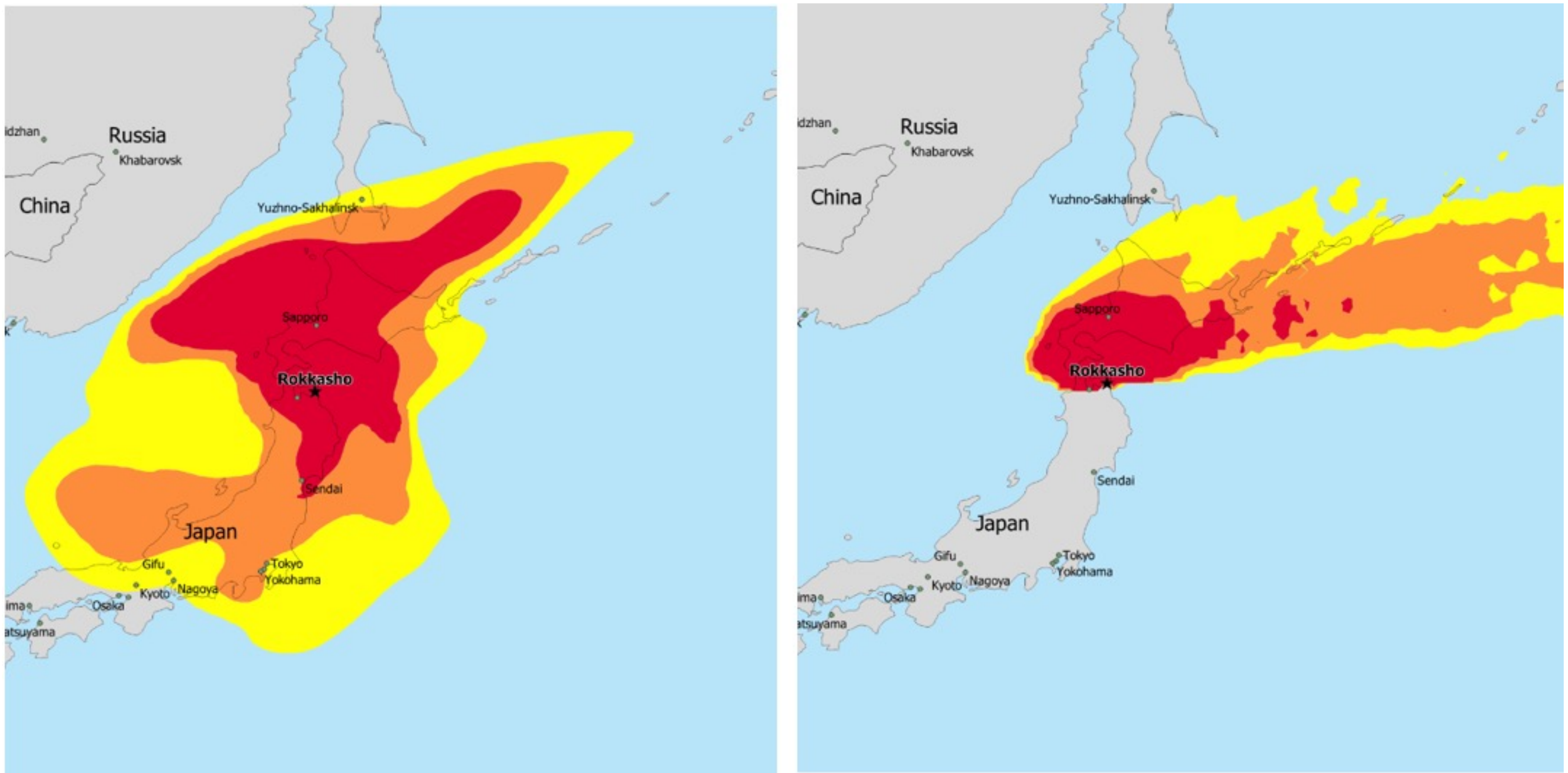
Hypothetical nuclear accident at the Kori 3 spent fuel pool in South Korea (cont)

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)

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

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 missile attack could make containment building of the nuclear power plants punctured or cracked to lose its confinement capability to contain the escape of radioactive gas.
- The missile attack 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 environmental impacts in adjoining countries.
- Although it may not be possible to prevent these attacks, their consequences can be mitigated significantly by moving spent fuel from the pools after five years of cooling into dry cask storage and maintaining low-density storage racks for spent fuel while still in the pools.