The vulnerability of nuclear plants during military conflict

Lessons from Fukushima Daiichi
Focus on Zaporizhzhia, Ukraine

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Briefing - Greenpeace International

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Ukraine has a complex and large-scale nuclear power infrastructure. It is a country with 15 operational nuclear reactors of which 9 were in operation on February 28th 2022. In addition, the Chornobyl[1] Nuclear Power Plant (NPP), with its unit 4 reactor that was destroyed in 1986, is in Ukraine. It is obvious that in a time of war, the operation of these systems are at risk of disruption with the potential for significant, even severe consequences.

Nuclear power plants are some of the most complex and sensitive industrial installations, which require a very complex set of resources in ready state at all times to keep them operational. This cannot be guaranteed in a war.

An operational nuclear power plant requires at all times electricity supply to power pumps and water supply to cool its nuclear fuel, both in the reactor and in the adjacent spent nuclear fuel pool. Even when the reactor is shut down, there is an enormous amount of residual heat in the fuel core which requires continuous cooling. Without cooling, the water in the reactor core (and spent fuel pool) begins to heat. In the case of an operational reactor the heating is rapid. The water reaches boiling point and begins to evaporate, and the hot nuclear reactor fuel assemblies are at risk of being exposed to air which then would lead to a thermal reaction of the nuclear fuel assembly cladding and reactor core fuel melt. In the case of nuclear fuel in the spent fuel pool, the highly exothermic chemical reaction is called a runaway zirconium oxidation reaction or autocatalytic ignition, with resultant release of a very large volume of radioactivity.

In March 2011, the magnitude 9.0 earthquake and tsunami in Japan led to the loss of site power at the Fukushima Daiichi nuclear plant – the site was no longer connected to the grid. The tsunami that then struck the plant flooded it, including Emergency Diesel Generators (EDGs) and their fuel supply, all needed to power the cooling pumps.[2] Even with some level of redundancy in case the EDGs would not be available such as batteries and turbine driven pumps[3], all three reactor cores that were in operation at the time of the earthquake and flooding

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[1] Formerly known by alternative spelling ‘Chernobyl’

[2] Diet of Japan, “The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission”, 2012, https://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/wp-content/uploads/2012/09/NAIIC_report_lo_res10.pdf

[3] IAEA, The Fukushima Daiichi Nuclear Accident. Technical Volume 1/5. 2015. https://www-pub.iaea.org/MTCD/Publications/PDF/AdditionalVolumes/P1710/Pub1710-TV1-Web.pdf

melted down. The spent fuel pond of reactor 4 came close to boiling out, which would have set off a nuclear disaster far worse than the meltdowns in reactors 1-3[4].

So, even without physical damage to the power plant, such as through an intentional or accidental hit by artillery or missiles, a nuclear power plant is very vulnerable to a disruption of the support systems. A nuclear power plant that is in operation requires active systems to remain functioning at all times. This includes many aspects, not only electricity but also cooling water and the continuous presence of qualified personnel to operate the plant. Even under normal functioning, hundreds of workers need to be able to reach the plant from their homes, which is evidently not feasible under war circumstances.

In a scenario where there would be a technical disruption, which could be for instance the electricity grid failing, or some of the diesel generators not starting up properly, you would need the ability to quickly mobilise vast amounts of equipment and additional personnel, such as fire brigades or crane operators. The example of Fukushima again demonstrated the need to be able to bring in heavy equipment such as massive cranes and specialised crane operators, fire brigades, heavy pumps etc[5]. Every technical disruption, for whatever reason, could require a major logistical operation at a nation-wide level which could be severely compromised through the war activities around the power plant. In the context of an armed conflict, it cannot be excluded that a power plant would be isolated from the grid for a longer period of time, which would require emergency diesel generators to remain reliable and have sufficient fuel supply till the grid connection is re-established.

Nuclear power plants present unique hazards in terms of the potential consequences resulting from a severe accident. Nuclear reactors and their associated high level spent fuel stores are vulnerable to natural disasters, as Fukushima Daiichi showed, but they are also vulnerable in times of conflict. This brief seeks to explain some of the hazards and potential consequences that exist today in Ukraine.

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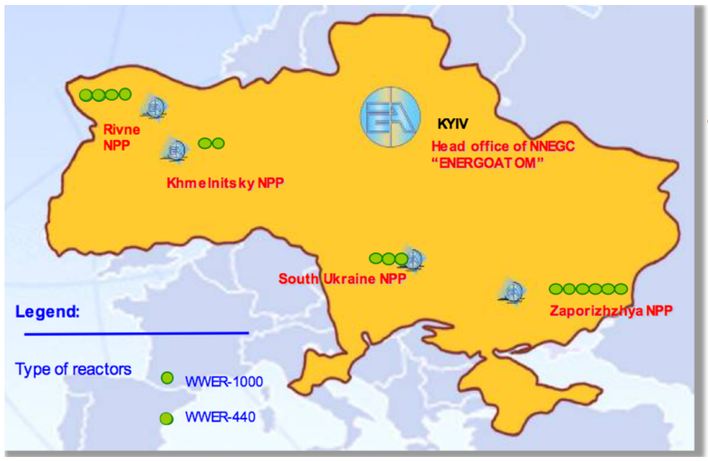
[4] Frank N. von Hippel and Michael Schoeppner, “Reducing the Danger from Fires in Spent Fuel Pools”, Program on Science and Global Security, Princeton University, Princeton, NJ, U.S.A., Science & Global Security, 2016, https://scienceandglobalsecurity.org/archive/sgs24vonhippel.pdf

[5] Op.cit. IAEA, 2015

Current status of nuclear power plant operation in Ukraine



There are 4 NPPs in operation in Ukraine, namely:
▪Zaporizhzhya NPP
▪South-Ukraine NPP
▪Rivne NPP
▪Khmelnitsky NPP

Source: IAEA https://nucleus.iaea.org/sites/INPRO/df17/VI.14-Ukraine_Leonid%20Benkovskyi.pdf

Ukraine's nuclear plant operator EnergoAtom reported[6] on 1 March that its Zaporizhzhia, Rivne, Khmelnytsky and South Ukraine nuclear plants were operating normally. Of the fifteen commercial power reactors in Ukraine, 9 of the 15 operational reactors are currently operating.

The six reactors not operating as of 28 February are:

- Rivne-1 – scheduled outage
- Khmelnitsky 2 – scheduled outage
- Zaporizhzhia – 5 & 6 – according to EnergoAtom, were disconnected from the grid and shutdown on 25 February for reasons of "operational safety" (remaining in cold reserve)
- Zaporizhzhia 1 - shutdown on 27 February according to EnergoAtom for "scheduled maintenance".
- South-Ukrainian - 3 shutdown on 26 February (remaining in cold reserve).

Zaporizhzhia

The recent confirmation of armed conflict in the region of the city of Energo and Zaporizhzhia raises the spectre of major risks to Europe's largest nuclear power plant at Zaporizhzhia.

There are six Russian VVER-1000/320 reactors (units 1-6) at the site, each with a capacity of generating 950 MWe. There is also a Dry Storage Facility at the plant for high level nuclear spent fuel (DSFSF). As of 2017 there were 2,204 tons of spent fuel in storage at the site – 855 tons inside the spent fuel pools, and 1,349 tons in the DSFSF.[7]

Risks

[6] EnergoAtom, "Zaporizhzhya NPP continues to operate normally", 1 March 2022, see https://www.npp.zp.ua/uk/node/5483

[7] IAEA, "Ukraine National Report: On Compliance with Obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management", 2017, see https://www.iaea.org/sites/default/files/national_report_of_ukraine_for_the_6th_review_meeting_-_english.pdf

There have been multiple safety issues with the Zaporizhzhia reactors over the decades not least that these reactors are ageing having been designed and built in the 1970's to the 1990s[8]. Of particular concern, but not exclusively, in the current conflict context, are:

1. Vulnerability to loss of electrical power
2. Spent fuel storage
3. Flood and dam burst risks

Zaporizhzhia nuclear plant https://www.npp.zp.ua/uk/press-center/gallery/plant-site

1. Emergency diesel generators

As noted above, loss of off-site electrical power requires the operation of emergency diesel generators. In 2020, the Ukrainian NGO EcoAction in Kyiv received information from nuclear industry whistleblowers about the functionality of the 20 AC-5600 emergency diesel generators at Zaporizhzhia . Produced by "Diesel Energo" in St. Petersburg, Russia (former Leningrad) their operation was considered not to be guaranteed, mainly due to a lack of spare parts. On 24

[8] For background and details on Zaporizhia see the archives of Bankwatch, https://bankwatch.org/tag/zaporizhye

September 2020, the Ukrainian nuclear regulator SNRIU published on its official Facebook page that one of the diesel generators had malfunctioned.[9] This incident was scaled as INES 1. In October 2020, in a response to an inquiry by Greenpeace International,[10] the State Nuclear Regulatory Inspectorate confirmed monthly testing and full functionality of the diesel generators. There remain however significant doubts about the reliability of Zaporizhzhia's diesel generators, including the current status of the completion of upgrades.

The Zaporizhzhia diesel generators should have been upgraded under the Complex Consolidated Safety Upgrade Programme (CCSUP) of Energoatom, financed by a Euratom (EIB) and EBRD loan of 600 Mln EUR. The EBRD is the lead in this programme. In this programme, the diesels should have received modern electronic controls. The final date of completion of the CCSUP has been put back from 2017 to 2023.

The on-site diesel generators at Zaporizhzhia are reported to have enough fuel for seven days.[11] In addition to the on-site emergency diesel generators, the Zaporizhzhia nuclear plant has installed mobile diesel generators. These have been installed as a consequence of the event at Fukushima Daiichi. In 2012 as part of Ukraine's post Fukushima stress test assessment, it is reported that there will be 16 mobile generators units at the Zaporizhzhia nuclear plant, which have diesel fuel to operate for 8 hours.[12] If the diesel fuel tank is continuously re-filled, the generators are reported to be able to operate "indefinitely." In 2013 it was reported that, "To ensure power supply in case of extreme events that may cause long-term station blackout, separate mobile 0.4 kV and 6.0 kV diesel generators will be used to feed at least one emergency power distribution panel."[13]

"In case of failure or impossibility to use regular Diesel Generators, there are measures to provide NPP sites with mobile pumping units and diesel generators. It is additionally planned to develop measures for their refueling if long-term performance is needed."[14] As noted in this briefing the operation of these safety systems, including securing additional fuel supply during armed conflict, is a major concern.

The reliability of the equipment installed at the Zaporizhzhia nuclear plant is certainly in question, with a Austrian government assessment of the safety risks at the Zaporizhzhia reactors concluding in 2017 that, "The documents provided and available lead to the conclusion

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[9] State Nuclear Regulatory Inspectorate of Ukraine, October 2020, https://www.facebook.com/permalink.php?story_fbid=3435209429874103&id=171734492888296

[10] Jan Haverkamp, "Functionality of diesel generators at the NPP Zaporizhzhia Request for access to information", Greenpeace International letter to Mr. Hryhorii Plachkov president of the State Nuclear Regulatory Inspectorate of Ukraine, 14 October 2020.

[11] ENSREG, "Peer review country report Stress tests performed on European nuclear power plants", 26 April 2012, see https://www.ensreg.eu/sites/default/files/Country%20Report%20UA%20Final.pdf
[12] Ibiden.
[13] ENSREG, "State Nuclear Regulatory Inspectorate of Ukraine ", Kyiv, 2013, see https://www.ensreg.eu/sites/default/files/National%20Action%20Plan%20%28Ukraine%29.pdf
[14] Ibiden.

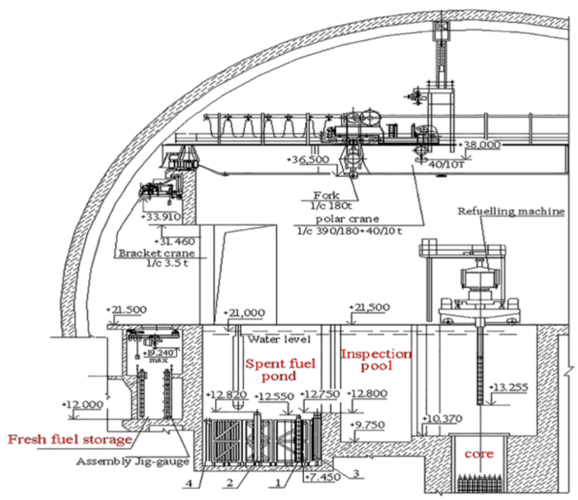
that a high probability exists for accident scenarios to develop into a severe accident that threatens the integrity of the containment and results in a large release."[15]

2. The vulnerability of spent nuclear fuel

2.1. Status of spent fuel at the Zaporizhzhia plant

For the storage of spent nuclear fuel, we need to distinguish between the smaller pool adjacent to the nuclear reactor and the larger longer term storage (dry storage) outside the containment.

The pools are in the case of the Zaporizhzhia reactors inside the reactor containment building (see image below), where the very hot spent fuel is cooled during about five years after being unloaded from the reactor building. After that, the fuel is transfered into concrete dry storage casks, which are stored in open air at the DSFSF storage at the power plant (see image below).



VVER-1000/320 reactor containment showing location of spent fuel pool (source[16])

At the Zaporizhzhia plant, there are six reactors, which each have such a deactivation or cooling pool at the reactor. Furthermore, there is a centralised dry storage area, where concrete dry storage containers are lined up (see below).

[15] Federal Ministry of the Environment, Austria, "NPP Zaporizhzhya Lifetime-Extension Environmental Impact Assessment Expert Statement", 2017, see https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0775.pdff

[16] VVER-1000/V446 spent fuel pool risk assessment and support through portable mitigating equipment N. Afshar a, A. Pirouzmand a,b,⇑, F. Faghihi, 2021, Annals of Nuclear Energy 156 (2021), see 108204, https://www.sciencedirect.com/science/article/pii/S0306454921000803

Dry Storage Facility (DSFSF) at the Zaporizhzhia site with concrete dry storage casks

The latest full data available are from 2017, when at the deactivation or cooling pools, the amount of spent fuel was between 132 and 157tHM.[17] There were in total 2,204 tons of spent fuel in storage at the site – 855 tons inside the spent fuel pools, and 1,349 tons in the DSFSF.[18] At the end of 2020, there were 163 casks at the DSFSF storage site, containing 3,912 fuel elements.

Annex 2. Inventory of Spent Fuel as of 1 July 2017

Material	Location	Number of SFAs	Weight of heavy metal, t
VVER-1000 SFAs	KhNPP Unit 1	433	184.75
VVER-1000 SFAs	KhNPP Unit 2	491	212.56
VVER-440 SFAs	RNPP Unit 1, 2	1217	146.47
VVER-1000 SFAs	RNPP Unit 3	508	212.45
VVER-1000 SFAs	RNPP Unit 4	421	177.79
VVER-1000 SFAs	SUNPP Unit 1	270	117.29
VVER-1000 SFAs	SUNPP Unit 2	252	111.09
VVER-1000 SFAs	SUNPP Unit 3	424	180.82
VVER-1000 SFAs	ZNPP Unit 1	326	141.32
VVER-1000 SFAs	ZNPP Unit 2	305	131.65
VVER-1000 SFAs	ZNPP Unit 3	356	153.82
VVER-1000 SFAs	ZNPP Unit 4	334	144.77
VVER-1000 SFAs	ZNPP Unit 5	363	157.25
VVER-1000 SFAs	ZNPP Unit 6	299	129.25
VVER-1000 SFAs	ZNPP DSFSF	3354	1349.87
RBMK-1000 SFAs	ChNPP ISF-1	21284	2396.111
Research reactor VVR-M SFAs	NRI	0	0
Research reactor IR-100 SFAs	SUNEI	0 *	0

The dry casks have a passive cooling, the heat of the 24 fuel elements inside the cask is estimated at less than 24kW, and can dissipate through the air circulation around the container without the fuel overheating. Such a container could be damaged through an explosion, e.g. an

[17] Op.Cit. IAEA, 2017.

[18] IAEA, "Ukraine National Report: On Compliance with Obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management", 2017, see https://www.iaea.org/sites/default/files/national_report_of_ukraine_for_the_6th_review_meeting_-_english.pdf

anti-tank grenade, but it would most likely not lead to a large-scale release comparable with a severe accident in a reactor or spent fuel pool. Therefore our attention focuses at this stage on the fuel pools.

2.2. The case of Fukushima Daiichi 4 spent fuel pool following the 11 March 2011 earthquake

To evaluate the risk of a spent fuel accident, we first look at what happened at the Fukushima Daiichi-4 spent fuel pool. This pool contained 2.4 cores of fuel, containing 900PBq of Cs-137[19].

For the pool of Fukushima-4, there was by design 7m of water above the top of the fuel. In a scenario where water vapor could escape, the 2MWt of heat would raise the temperature of the 1400m3 of water in the pool to near boiling in about three days.[20] After that, the rate of water loss to evaporation would be about 0.67m/day. The level of the water would have dropped, uncovering half of the fuel in about 16 days or on 27 March 2011. At that point, a runaway zirconium fire would have ignited, releasing most of the radioactive Cs-137 as well as other isotopes. Because the containment around the pool was already damaged after a hydrogen explosion four days after the tsunami hit the power plant, the radioactivity would have been able to escape more freely.

A 2014 USNRC study explained that:

> "*If cooling of the spent fuel were not reestablished, the fuel could heat up to temperatures on the order of 1,000°C. 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.*"[21]

This is not what happened.

A special crane succeeded to add more water to the pool, but also there was another unintentional source of water which saved the fuel from igniting. It can be considered as a "near-miss" because the water level reached on April 22nd a level only 1.5m above the top of the fuel elements[22].

In the graph below, the actual water level vs the calculated water level (including the added water) is presented. The dotted line shows that without the added water, the fuel would have been half exposed to the air around 27 March[23].

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[19] Frank N. von Hippel and Michael Schoeppner, "Reducing the Danger from Fires in Spent Fuel Pools", Program on Science and Global Security, Princeton University, Princeton, NJ, U.S.A., Science & Global Security, 2016, https://scienceandglobalsecurity.org/archive/sgs24vonhippel.pdf (p 143)
[20] Ibidem
[21] Ibdem
[22] Ibidem
[23] Ibidem

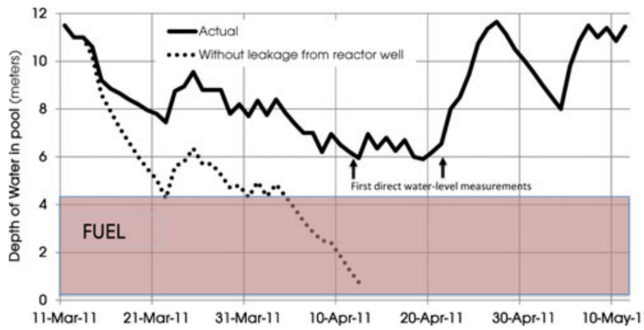

Figure 2. Solid line: TEPCO reconstruction of the history of the water level in pool 4 during the two months after the earthquake.[21] The arrows show the first actual measurements, the first of which was made on 12 April and the second on 22 April. The dotted line below shows an estimate in the National Academy of Sciences report of the amount of water that would have been in the pool in the absence of water leaking into the pool from the adjacent reactor well.[22]

2.3. Consequences of a large-scale release from a spent fuel pool

Extensive research has been conducted on the near-disaster at the spent fuel pool of Fukushima Daiichi-4. The simulation below compares on the left the actual release from the meltdowns of reactors 1-3. There, on average only 2% of the Cs-137 inventory was released. On the map in the middle, the simulation shows the deposition if the release had happened on 9 April and on the right map, and if the release happened on March 19 March with an open containment and the wind blowing towards Tokyo. The pool contained 2.4 cores and 900PBq.[24]

The maps below show in red the area above 1,000kBq/m2. On request of the then Japanese Prime Minister Naoto Kan, Shunsuke Kondo, the chairman of Japan's Atomic Energy Commission calculated that if the criteria used around Chornobyl for compulsory long-term evacuation would be applied, the area above 1,480kBq/m2 would need to be permanently evacuated, which would extend up to 170km from the power plant (thus not the entire red zone).

It is clear from the maps below, that a fuel pool accident, even if containing less spent fuel in storage as was the case in the Fukushima Daiichi-4 pool, the release of Cs-137 from a zirconium fire would be at an unprecedented scale. Due to the relatively short half life of Iodine-131 (eight days) there would be very low levels in the spent fuel pools, and then only for fuel discharged most recently.

[24] Ibidem

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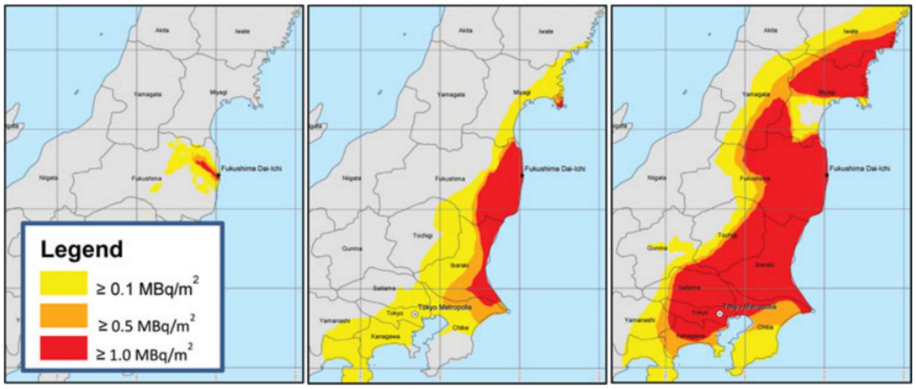

Figure 5. Left: Actual contamination levels after the Fukushima Daiichi accident.[33] Middle: Contamination levels after a hypothetical spent fuel fire in pool 4 starting, as per the scenario in Figure 4, on 9 April 2011 when the wind was blowing mostly to sea. Right: Contamination levels after a hypothetical spent fuel fire in pool 4 starting on 19 March 2011 when the wind was blowing toward Tokyo. This is a scenario that physically could only have occurred had there been a leak in pool 4. The maps show the levels of cesium-137 contamination with the red areas contaminated to above 1 MBq/m^2, which led to compulsory relocation for the actual accident. The orange areas are contaminated to between 0.5 and 1 MBq/m^2. The huge difference in the areas contaminated above 1 MBq/m^2 in the left and right figures is due to the fact that the destruction of the roof and walls surrounding pool 4 by a hydrogen explosion would have allowed the cesium-137 in the pool to be released directly into the atmosphere. In contrast, the primary containments of reactors 1–3 at Fukushima Daiichi released on average only about 2% of their core inventories of cesium-137.

2.4. Significance for Zaporizhzhia

The vulnerability of a spent fuel pool strongly depends on key parameters such as the burnup of the fuel and especially how densely the fuel is racked inside the spent pool, and how recently the latest batch was unloaded from the reactor into the pool. Burnup is a critical factor, and refers to the amount of energy generated with one tonne of nuclear fuel, which is equivalent with the amount of radioactivity in the fuel and its residual heat generation. This is one of the principle factors that determines the heat generation of the fuel and the radiological inventory. It is given as Gigawatt days per ton of heavy metal - GWd/tHM.

Comparing the Fukushima-Daiichi-4 pool inventory with the VVER-1000 pools and how fast the cooling water would evaporate in case of a long power outage, is complex, given the many variables, and beyond the scope of this briefing. So the analogy with the spent fuel at Fukushima Daiichi-4 is only a rough indication of the risks at the Ukrainian nuclear power plant.

The amount of spent fuel in each of the pools at the six Zaporizhzhia reactors ranges from 132 to 157 tons as of 2017, and in total 855 tons of spent fuel are in the six pools. This is the latest publicly available data we have access to. It is not possible without precise data to say what the radiological inventory is of this spent fuel, however, in our review of the scientific and technical literature of the past two decades it appears that the average fuel burn-up of the nuclear fuel used over the last 20 years at Zaporizhzhia is 44-49GWd/tHM[25]. This is comparable, and perhaps higher, than the nuclear fuel in the pools at Fukushima Daiichi.

[25] IAEA, International Conference on the Storage of Spent Fuel from Power Reactors. 2003, p.91

In the event of a loss of cooling and resultant fire in any of the spent fuel pools at Zaporizhzhia, the potential for a very large release of radioactivity would have a devastating effect not only on Ukraine but also its neighbouring countries, including Russia, and potentially, depending on the weather conditions and wind directions, on a large part of Europe. Again, it should be stressed that in the event of such a catastrophic incident, the entire power plant might have to be evacuated and a cascade of similar accidents at the other five pools as well as the six reactors might take place.

3. Flood risk and dam breach

The vast Dnipro river system is highly vulnerable to flooding. The reactors at Zaporizhzhia are located on the Kakhovka Reservoir, which is connected to the Dniproriver. There have been assessments on measures required to reduce flood risks for the Dnipro system, in particular during high spring floods.[26] In a flood situation, equipment able to guarantee the safety of nuclear reactors must remain operational, so the necessary protective devices must remain functional and engage, whenever necessary, to safeguard against the various unforeseen circumstances that could lead to flooding or to maintain essential functions whilst and should the plant become flooded. This protection is based on several lines of defence (embankments, walls, water drainage networks, etc.), including volumetric protection which encompasses the buildings containing equipment able to guarantee reactor safety.[27]

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[26] Anna Poludenko, "How to avoid a natural disaster?", 2012, https://day.kyiv.ua/uk/article/cuspilstvo/yak-uniknuti-prirodnoyi-katastrofi

[27] John Large, "Vulnerability Of French Nuclear Power Plants To Aircraft Crash", Greenpeace France, 2012, see https://www.sortirdunucleaire.org/docrestreint.api/19594/3ddda3a0406787005202fed39d1792fc1821afd3/pdf/largej-greenpeace-2016-04-26-vulnerability_of_french_npps_to_aircraft_crash.pdf; and NRC,

In addition to flood risk to the site, there is the risk if the dams on the Dnipro reservoir system are damaged. The cooling water for the Zaporizhzhia reactors is pumped from the reservoir and five other reservoirs are located upstream of the nuclear plant. Due to the power plant's reliance on the filled reservoirs, any breaches of their dams could have an adverse effect on the reactor's cooling water supply,[28] which would have potential severe consequences for the reactors.

"Screening Analysis Report for the Proposed Generic Issue on Flooding of Nuclear Power Plant Sites Following Upstream Dam Failures", 2011, Richard H. Perkins, P.E. Michelle T. Bensi, Ph.D. Jacob Philip, P.E. Selim Sancaktar, Ph.D, see https://www.nrc.gov/docs/ML1218/ML12188A239.pdf

[28] Oko Institute, "Nuclear safety in crisis regions", April 2017, see https://www.oeko.de/fileadmin/oekodoc/Nuclear-safety-in-crisis-regions.pdf