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ANALYSIS

Nuclear Power in Wartime: Zaporizhzhia NPP as a Test Case for Nuclear Safety

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Abstract
Russia's war of aggression against Ukraine is the first interstate war in human history in which civilian nuclear facilities have been attacked. The article discusses the situation at Zaporizhzhia Nuclear Power Plant, Europe's largest NPP, which was occupied by Russia in March 2022. The six-unit plant is now a theatre of war and a test case for nuclear safety under wartime conditions. The safety issues analysed in this report are also representative for the operating nuclear reactors in Ukraine which are under Ukrainian control. Numerous abnormal operating situations have occurred at Zaporizhzhia as a result of the war. The staff have to ensure the safety of the plant under the terror of the occupying forces. So far, emergency situations have been managed without severe damage to the nuclear installations. However, there is concern that a major nuclear accident could occur in Zaporizhzhia. The fear of such an accident is also itself an instrument of hybrid warfare.

Introduction
Russia's war against Ukraine is the first interstate war in human history in which civilian nuclear facilities have been attacked. The facility in question, the Zaporizhzhia Nuclear Power Plant (NPP), was forcibly occupied by the attackers on March 4, 2022. It experienced abnormal operating states several times as a result of this act of war. By attacking an operating nuclear power plant, Russia broke international law: Article 56 of the Additional Protocol to the Geneva Convention "Relating to the Protection of Victims of International Armed Conflicts" prohibits attacks on objects such as dykes, dams and nuclear power plants if they may release forces dangerous to the civilian population.

The IAEA noted that the seven pillars on which nuclear safety is based had already been destroyed or had their stability threatened in Zaporizhzhia as a result of the attack. The prerequisites for nuclear safety are:

1) The physical integrity of the facilities;
2) The full functioning of safety and monitoring systems;
3) The operating crews must be able to work and make decisions without being bothered;
4) A safe external power supply must be ensured;
5) The supply with diesel fuel for emergency backup generators, spare parts, food etc. must be guaranteed;
6) Monitoring of the environment and emergency response measures must be guaranteed; and
7) Unimpeded communication of the plant with the operating organization and the nuclear regulatory authority is required.

Russia did not follow the IAEA's repeated demand for demilitarization of the power plant site as the basic prerequisite for safety. Observers speak of "nuclear piracy," which differs from nuclear terrorism in that here it is a state posing the threat to nuclear security (IAEA 2022a, Alkis/Goldblum 2023).

The Human Factor
In October 2022, the occupiers unlawfully transferred the plant into the possession of the Russian nuclear power company Rosenergoatom (Pavlysh 2022) and installed an occupation management (Slovo i Dilo 2022, Ukrinform 2022, SNRIU 2023, Enerhoatom 2023a). Many members of the plant staff who were employed in departments not directly necessary for maintaining operations fled or were evacuated to areas under Ukrainian control. The occupation station manager stated at the end of 2022 that about half of the prewar workforce of 11,000 had left, and that 2,500 employees continued working on the plant site every day. Of the once 80,000 inhabitants of the nuclear city of Enerhodar, only 15,000 people remained due to flight and forced evacuations, especially of children and young people, to Crimea, Russia and Belarus (RIA Novosti 2022; Leite 2022; City of Enerhodar 2023; Voloshko 2023).

The remaining power plant workforce has been subjected to downright terror since the beginning of the occupation. This includes violent assaults by the soldiers present on the plant premises, arrests, disappearances and systematic torture in now around 1,000 cases (Truth Hounds 2023; Leite 2022; Avdeenko 2022). Since the fall of 2022, employees have been forced to sign employment contracts with Rosenergoatom and take on Russian citizenship. Those who refuse are subjected to reprisals and locked out; unofficial sources suggest up to 3,000 employees have been affected in this way. A number of ZAES employees are passively resisting and risking their lives by giving information to the outside world. Much of the inside information communicated through the legitimate Ukrainian nuclear operator, Enerhoatom, comes from sources such as these (Enerhoatom 2023b). This terror is also a direct threat to nuclear safety, as intimidated, injured, overtired employees, much less those not allowed to work in the first place, cannot serve the needs of the plant in the necessary capacity.

The Plant

The six nuclear units in Zaporizhzhia contain pressurized water reactors of the Soviet type VVER-1000-V320 with a capacity of 1,000 megawatts (MW) each. This is the most advanced type of late Soviet reactor, similar in standard to those of Western plants of the same generation. This should be mentioned in view of the many misunderstandings about Ukrainian nuclear power plants circulating in the Western public. The VVER should not be confused with the RBMK reactor that suffered an accident in Chernobyl.[1] The basic concept of the VVER-1000 has many similarities with German nuclear power plants with pressurized water reactors: it is a monobloc unit with a "nuclear island" consisting of a reactor building with a four-loop primary circuit, an auxiliary building, and a turbine hall in which the non-nuclear parts of the steam generation system and the electrical machinery are located (BAES TsPP 2011; ENSREG 2012).

Nuclear Safety in Wartime

Despite the Russian attempts to reinterpret the occupation of Zaporizhzhia NPP into a normality clothed in formal legal forms, this "normality" is a mere illusion in view of the technical-military vicissitudes. During the summer of 2022 and the unceasing Russian artillery attacks on the Ukrainian power infrastructure in the fall and winter of 2022/23, regular operation of the plant could no longer be maintained. Therefore, on September 11, 2022, the last unit still in operation was shut down (Enerhoatom 2022a, Zaporiz'ka AES 2022). As of December 2023, Zaporizhzhia has since then provided no power to the Ukrainian grid.

After lengthy negotiations between Kiev, the IAEA headquarters in Vienna, and Moscow over safe travel routes, Russia agreed to allow an IAEA mission to enter the plant through Ukrainian-controlled territory. The IAEA Support and Assistance Mission to Zaporizhzhya (ISAMZ) consisted of several inspectors, two of whom remained at the plant as a permanent IAEA monitoring team. This was a clear security gain for the plant, and gave the Ukrainian side hope that any arbitrary or reckless Russian actions at the power plant site would now be observed and documented by a neutral party (IAEA 2022b).

With the attack on the Kakhovs'ka HES hydropower plant and its dam on June 6, 2023, the situation of Zaporizhzhia NPP was once again aggravated. In addition to the danger of a collapse of the external power supply constantly hovering over the plant, it experienced the loss of its ultimate heat sink, as the power plant's cooling pond was dependent on supplementary water from the reservoir. So far, the level of the cooling pond could be kept stable (Enerhoatom 2023c). The most recent episode of heightened tension was a communication war between Russia and Ukraine in early July 2023 over the alleged or actual mining of the plant, both sides accusing each other of preparing military actions against the NPP. Ultimately, it was indeed confirmed that Russian troops have laid minefields at the fence of the plant premises, though no further military actions are known to have taken place as of December 2023 (HUR MOU 2023, Enerhoatom 2023d, IAEA 2023a).

The Safety Concept of the Ukrainian Nuclear Power Plants

The safety challenges at Zaporizhzhia under wartime conditions are manifold. Statements about the safety systems and certain emergencies that have occurred or may occur during operation apply not only to Zaporizhzhia NPP, but also to the identical units at other Ukrainian sites: Rivne-3 and 4, Khmel'nytskyi-1 and 2, and South Ukraine-3. Units 1 and 2 at the South Ukraine plant are earlier VVER-1000 versions that may have slight variations.

The safety design of nuclear power plants is based on three overriding protection goals:

1) Subcriticality of the reactor in the event of an accident—i.e., the self-sustaining chain reaction in the reactor core must be reliably stoppable and must not revive automatically;
2) Heat transport from the reactor, i.e., the residual decay heat generated in the fuel assemblies even after the shutdown of the reactor, must be removed unhindered; and
3) Activity retention, i.e., there must be several barriers to prevent the release of radioactive fission products from the fuel assemblies.

These three protection goals are served by the safety equipment of a nuclear plant: various shutdown systems for subcriticality; operational and emergency cooling systems for heat transport; emergency power systems to maintain safety functions even in the event of a grid collapse; and specially sealed plant rooms, negative pressure maintenance, and hermetic reinforcements for reactor buildings (containment) for activity retention.

1 The RBMK-1000 reactor at Chernobyl NPP was a graphite-moderated pressure-tube boiling water reactor whose design features made the system unstable in certain operating conditions.

Most safety systems follow certain design principles to make them fail-safe: redundancy (providing multiple safety trains); diversity (using different operating principles to achieve a given protection goal); and spatial separation. These precautions are designed to prevent common-cause failures, in our particular case, from direct destruction and fire due to artillery attacks or other military action on the site.

The safety systems at Zaporizhzhia NPP are designed with triple redundancy, i.e., one train of the emergency cooling system or one of three emergency diesel generators per unit is sufficient to control the design basis accident.[2] Each redundancy has its own emergency power supply. The design of the safety systems is similar to that of German nuclear power plants, with high-pressure and low-pressure emergency cooling systems, passive emergency cooling via accumulators, high-pressure boron injection, an emergency feedwater system, and filtered venting in case of overpressure inside containment.[3]

A Nuclear Site at War

Military actions of any kind on the power plant site can cause damage that may be safety-relevant. Russia's troops have placed military equipment in the turbine halls and between the units, increasing the risk of explosions and fires (Enerhoatom 2022b). Therefore, of great interest is how robust Zaporizhzhia NPP's structures are.

The VVER-1000-V320 have reinforced concrete containments comparable to those of the French and most US plants (BAES TsPP 2011, 20–23). The primary circuit equipment and the spent fuel pool are situated beneath this 1.2-meter-thick containment, which also features an 8-millimeter steel liner. The emergency cooling systems are thus located behind a double barrier consisting of the walls of the auxiliary plant building and the reactor containment.[4]

The VVER-1000 containment is designed to withstand a pressure buildup of up to 5 bar overpressure due to a core meltdown accident, sufficient to withstand the maximum earthquake expected at the site, the impact of a small aircraft (10 tons at 720 km/h) and explosion pressure waves of 2 bar. Experts therefore expect that random hits from heavy weapons will not disintegrate a VVER-1000 containment, but targeted continuous fire would (BAES TsPP 2011, 21–23).

In addition to the six reactors and two large special buildings (in which radioactive materials and components are also handled), there is an open-air interim spent fuel storage facility at Zaporizhzhia NPP which is also subject to the effects of warfare and which must also be taken into account in risk analyses. This also applies to the pipeline bridges which, due to the spatial division of the radiation controlled area (RCA) between reactor buildings and special buildings, contain pipelines in which radioactively contaminated liquids are transported back and forth. Apart from the reactor buildings, none of these structures is structurally reinforced in such a way that radioactive releases in the event of bombardment can be ruled out. In addition, on the premises of the NPP, which covers more than 300 hectares, there are open-air facilities that are significant for residual heat removal from the reactors and the spent fuel pools, e.g. the spray ponds in which the essential service cooling water is cooled, as well as other buildings, pumping stations and containers for cooling water treatment and supply of demineralized water and nitrogen (Wikimedia Commons 2023, SNRIU 2023, BAES TsPP 2011, 15–20).

Power Supply at Risk

Of greatest concern is the infrastructure of the electrical transmission and distribution grids. In a worst-case scenario, hits on open-air switchgear or important transmission lines could cause the national grid of Ukraine, or at least that of large parts of the country, to collapse. Zaporizhzhia NPP has a total of seven national grid connections, plus reserve connections to the DniproHES and Kakhovka hydropower plants. At the NPP, there are three 5.6 MW emergency diesel gensets per unit, plus two mobile "common-unit" generators that can supply any two units (SNRIU 2023, 9–17). As early as mid-March 2022, three of the four 750 kilovolt (kV) and one of the three 330 kV grid connections collapsed for the first time, and for weeks the power plant was only connected to one 750 kV line (IAEA 2023b, WENRA 2022).

In the event of loss of offsite power (LOOP) while an NPP is operating, there are two possible scenarios, both of which having already occurred during wartime operations around Zaporizhzhia and other Ukrainian NPPs.

The first case is load shedding to station demand supply, meaning that a nuclear plant, due to grid collapse, cannot feed electricity to the grid anymore, but can produce for the demands of the plant itself. In this case, one unit at minimum load operation supplies the entire power plant with electricity. This case occurred

2 The "design basis accident" is the gravest accident which is expected to be managed by the safety systems. In the VVER-1000, the DBA is the maximum loss of coolant accident, a complete rupture of a 850mm pipe in a main cooling circuit.

3 The safety systems of the VVER-1000 V320 plants are designed according to the n+2 principle. "N" here denotes the number of systems necessary for accident control, "2" the additional two systems forming the reserve (BAES TsPP 2011, 139–141).

4 Own inspections of Rivne NPP during field work, Units 3 and 4 (identical in construction to Zaporizhzhia-1 to 6), 2015–2018.—Rivne NPP, Plan pomeshchenii Reaktornogo Otdeleniia, Kuznetsovsk.

at Zaporizhzhia-6 from September 9 to 11, 2022. But such operation is not a permanent solution, as the risk of a turbine and reactor trip due to vibrations and other unstable parameters is relatively high. In the meantime, this mode of operation is ruled out in Zaporizhzhia, as it can be used only when the station is producing power.

In the case of unit blackout, if the unit is at full load, it is automatically shut down and transferred to fast-track residual heat removal procedures. The power supply for the vital functions, first of all for emergency cooling systems, is provided by the emergency diesel generators. The large equipment needed for power operation, such as main coolant and feedwater pumps, consume too much power to be backed up by emergency power systems. This means that if the emergency situation persists, it is not possible to restart the plant until off-site power supply is restored (SNRIU 2023, 15–17). In Zaporizhzhia, unit blackouts have occurred eight times so far, the longest lasting over 40 hours. The Khmelnytskyi Nuclear Power Plant, which has two VVER-1000 units, also experienced a unit blackout on November 15, 2022 (UBO-List, see Appendix 1).

Only if the grid connection in Zaporizhzhia were to break down and all 20 emergency diesel generators failed would there be a so-called "station blackout" (SBO), a situation comparable to the accident at the Fukushima Daiichi plant in 2011. The VVER-1000 plants, with their horizontally installed steam generators, have relatively large reserves for heat transport compared to Western plants (ENSREG 2012, 20). In the SBO case, a meltdown could be delayed by a maximum of 16.5 hours with emergency measures. However, this is three times more time than was available in Fukushima.

This grace period in the case of a station blackout is currently most relevant to the operating plants in Right-bank Ukraine.[5] As Zaporizhzhia has been off-grid since the shutdown of Units 5 and 6 on September 11, 2022, the grace period has been extended to several days because much less decay heat needs to be removed from the fuel assemblies (Müllner/Hrdy 2023). This task is performed by the low-pressure residual heat removal systems as long as the reactor core is loaded, and by the pool cooling systems that cool the fuel assemblies in the spent fuel pool.

So far, the emergency power supply in Zaporizhzhia has proven to be very robust. The unit blackouts have lasted between a few hours and almost two days until the grid connections were repaired. There were no failures of the backup power supply for the residual heat removal systems during these periods. In the event of a prolonged emergency power outage, the plant must be replenished with diesel fuel after no more than nine days. However, under wartime conditions, both fuel supply and repair of the national grid could conceivably be hampered for significantly longer. So far, Zaporizhzhia NPP has been supplied with fuel by convoys of both Ukrainian operator Enerhoatom and Russia.

"Hot Shutdown" as a Safety Issue

At Zaporizhzhia NPP, one unit at a time is operated in the so-called "hot shutdown" mode, which serves to provide for the supply of process steam for the plant and for Enerhodar's district heating. In this operating mode, no nuclear chain reaction is maintained in the reactor core, but the system is kept at nominal temperature and pressure with waste heat from running the main coolant pumps and with the pressurizer heating.

The IAEA and the Ukrainian nuclear regulator argue that the steam supply should be provided by a temporary external boiler system because a cold, subcritical, unpressurized reactor state is the safest condition for the plant in light of the ongoing war. In the event of a station blackout with a cold reactor, emergency responders are given several days to take remedial action with a provisional emergency cooling system.

If the reactor is kept in hot shutdown, as it currently is, the time to core damage is reduced to a maximum of 24 hours due of the high temperature in the primary circuit (IAEA 2023c). Another problem is the occurrence of steam generator heating tube leakages, which are exacerbated by this mode of operation and lack of maintenance. In this current case of "hot shutdown," radioactive primary coolant leaks into the secondary circuit, which also means that the protection goal of activity retention is compromised (Enerhoatom 2023e, Zaporiz'ka AES 2023).

Water Supply at Risk

A nuclear power plant has manifold cooling requirements both during power operation and during shutdown, especially for residual heat removal, but also for the supply of other safety-relevant cooling tasks, e.g. for the emergency power diesel generators. These functions have been affected by military actions. Although the NPP has an autonomous cooling pond with reserves that last for months given the current lower cooling demand, replenishment of this cooling pond is in turn dependent on a feed from the Kakhovka reservoir. Since the destruction of the Kakhovka dam, the water level in the reservoir has dropped below the level at which the nuclear power plant's extraction pumps can still operate in order to feed the cooling pond. Consequently,

5 The figure refers to the "latest possibility for operator to intervene" to stop irreversible core damage. At the Zaporizhzhia plant, this period is 18 hours, after which the core is uncovered. (SNRIU 2023, 71–74; ENSREG 2012, 17+19).

the NPP has to use alternative water supplies to hold the water level in the cooling pond, including from deep wells and from the nearby cooling water channels of the neighboring coal-fired power plant. An alternative would be to lay temporary hose connections to the Dnipro River, whose water can be pumped by fire trucks.

Fortunately, the NPP cooling water requirements are much smaller than they would be during operation at full capacity. Since the fuel assemblies now emit only a fraction of the decay heat that occurs shortly after a reactor shutdown, less heat must be transported and less cooling water evaporates and needs to be replenished. By mid-November 2023, the NPP reported a stable water level in the cooling pond and the water supply channel.[6]

Conclusion and Outlook

The Russian-occupied Zaporizhzhia Nuclear Power Plant is a theater of war and a test case for nuclear safety under wartime conditions. It is representative of other Ukrainian nuclear power plants of the same design. Zaporizhzhia has experienced numerous abnormal operating situations as a result of wartime operations. So far, the plant has proven robust to emergency situations such as blackouts, shelling, and loss of the ultimative heat sink, but this resistance is fragile. Adding to this fragility, the remaining staff faces the challenge of having to ensure the safety of the plant under the terror of the occupiers.

The power plant is located directly on the current front line of the Russian-Ukrainian war. Disruptive events resulting from acts of war, e.g. in the event of Ukrainian reconquest of the region, could worsen the situation at the power plant from one day to the next. Therefore, the concern about an accident in Zaporizhzhia remains, even though, according to experts, it would not reach the severity of the Chernobyl or Fukushima disasters, as the relatively long response time leaves many more chances for coping with emergencies. For a detailed analysis of accident scenarios and risk assessments, see Wendland (2023).

The fear of an accident is also used in the psychological warfare of both sides. While the Russian attackers want to terrorize and paralyze the Ukrainian side with their threat communication, the defenders are referring to Zaporizhzhia as a global threat in order to appeal to the world community for help.[7] While this is a legitimate goal, Kyiv has put its credibility on the line with exaggerated portrayals of rather unlikely accident scenarios. This is another reason why the Zaporizhzhia Nuclear Power Plant remains a significant factor in the war effort—and why secure and accurate information about its condition is also a contribution to Ukraine's long-term resilience.

About the Author
Dr. habil. *Anna Veronika Wendland* is a researcher at the Herder Institute for Historical Research on East Central Europe. She is a specialist in science, technology, and society studies and Ukrainian studies. For her publications on the history of nuclear safety, she did field research at several NPPs in Eastern Europe and Germany.

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Appendix 1: List of Unit Blackouts (UBO) and Other Critical Events For the Power Supply at Zaporizhzhia NPP (ZNPP) and Other Ukrainian NPP

25 August 2022	Reactor trip due to disconnection from the national grid, but no UBO, ZNPP units 5 and 6, i.e. for the first time since commissioning, all units shut down simultaneously, Enerhoatom via Telegram, 25 August 2022, https://t.me/energoatom_ua/9183
01 September 2022	UBO1 ZNPP-2 due to reserve transformer trip 330 kV/6kV; reactor trip Zaporizhzhia-5 (without UBO), Enerhoatom via Telegram 01 September 2022, https://t.me/energoatom_ua/9334
01 September 2022	Reactor trip at ZNPP-5, Enerhoatom via Telegram, 01 September 2022, https://t.me/energoatom_ua/9334
08/09 October 2022	UBO2, ZNPP, all units, 40h, Enerhoatom, 09 October 2022, www.energoatom.com.ua/o-0910221.html
12 October 2022	UBO3, ZNPP, all units, Enerhoatom, 12 October 2022, www.energoatom.com.ua/o-1210222.html
02 November 2022	UBO4, ZNPP, all units, Enerhoatom, 03 November 2022, www.energoatom.com.ua/o-0311221.html
15 November 2022	UBO, Khmelnytskyi NPP, units 1 and 2, due to bombing of a switchyard, IAEA Update 127, 16 November 2022, www.iaea.org/newscenter/pressreleases/update-127-iaea-director-general-statement-on-situation-in-ukraine
23 November 2022	UBO5, ZNPP, all units, Enerhoatom, 23 November 2022, www.energoatom.com.ua/o-2311222.html.—After Russian missile attacks on the same day, 23 November 2022, all running units of NPPs Rivne, Khmelnytskyi, Pivdennoukraiinsk went off the grid with reactor trips.
09 March 2023	UBO6, ZNPP, all units, Enerhoatom, 09 March 2023, www.energoatom.com.ua/o-0903231.html
22 May 2023	UBO7, ZNPP, all units, Enerhoatom via Telegram, 22 May 2023, https://t.me/energoatom_ua/13192
02 December 2023	UBO8, ZNPP, all units, Enerhoatom via Telegram, 03 December 2023, https://t.me/energoatom_ua/15943

See overleaf for a map of Zaporizhzhia NPP (ZNPP) and Environs.

Appendix 2: Map of Zaporizhzhia NPP (ZNPP) and Environs