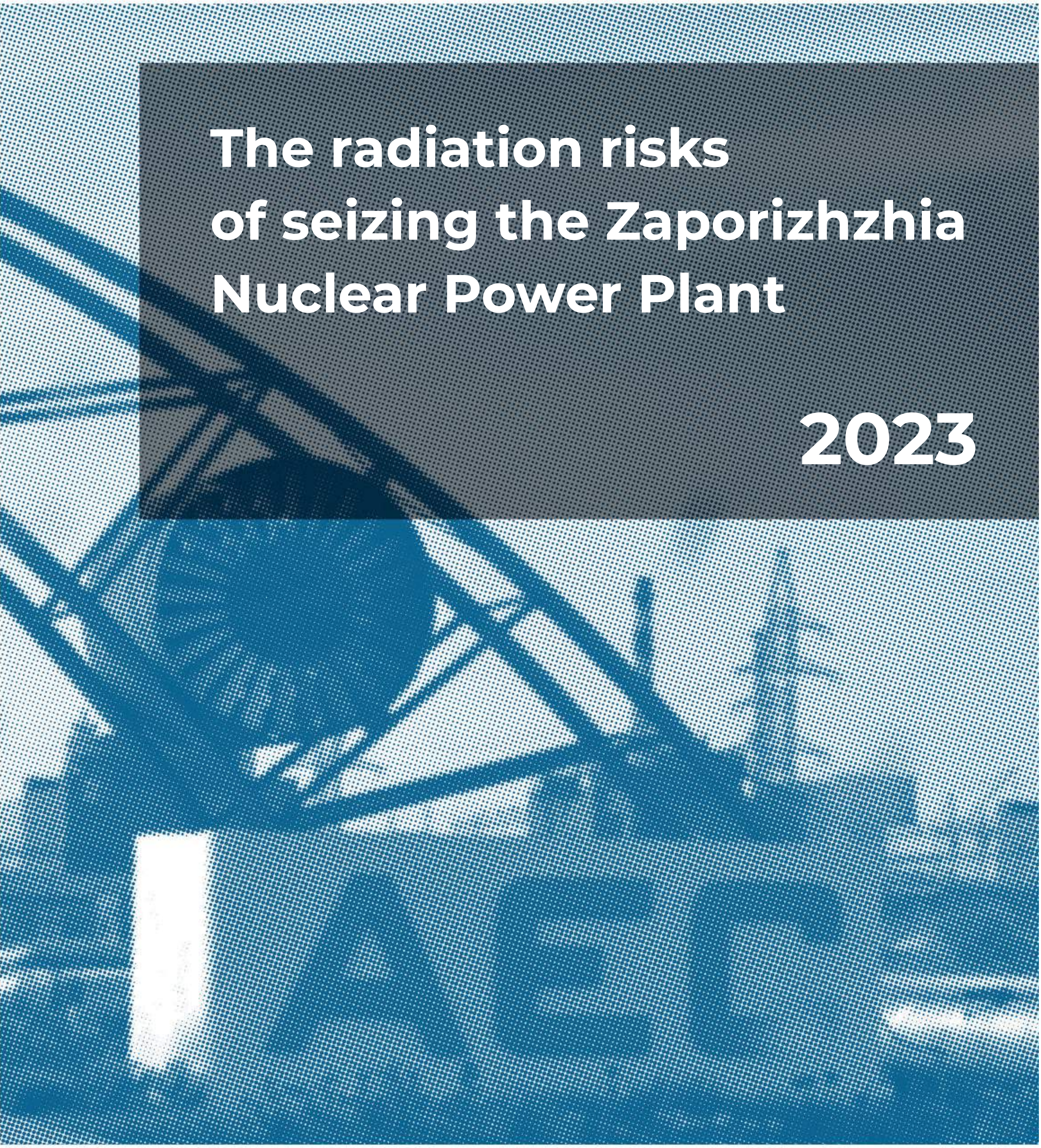
BELLONA



The radiation risks of seizing the Zaporizhzhia Nuclear Power Plant

2023

Working paper, 2023

**THE RADIATION RISKS OF SEIZING
THE ZAPORIZHZHIA NUCLEAR POWER PLANT**

Author: Dmitry Gorchakov

Translated by: Charles Digges

Published by: The Bellona Foundation, Vilnius

http://bellona.org

transparency@bellona.org

About Bellona:
The Bellona Foundation is an international environmental NGO working on the major climate and environmental problems. Founded in 1986 as a direct action protest group, Bellona has become a recognised technology and solution-oriented organization with offices in Oslo, Brussels, Berlin, and Vilnius, and representatives in USA and several EU Member States.

TABLE OF CONTENTS

The radiation risks of seizing the Zaporizhzhia Nuclear Power Plant An analysis of possible nuclear accidents at the nuclear plant Russia has occupied	3
The Zaporizhzhia NPP's features and VVER-1000 reactors	4
Differences between the VVER-1000 and Chernobyl's RBMK-1000	5
POSSIBLE RISKS	9
1. Destruction of a reactor unit operating at power	9
2. Release of Iodine 131	11
3. Release of Cesium 137	12
4. Destruction of power unit while the reactor was shut down	16
5. Explosion at a dry storage for spent nuclear fuel	17
6. Power cut-off — the Fukushima scenario	18
7. Dam break in the Dnieper cascade and the Kakhovka reservoir	24
8. The intolerable circumstances for plant personnel	25
CONCLUSIONS	26

The radiation risks of seizing the Zaporizhzhia Nuclear Power Plant

An analysis of possible nuclear accidents at the nuclear plant Russia has occupied

The Zaporizhzhia Nuclear Power Plant (ZNPP) in Ukraine has been occupied by Russian troops for 15 months. Since the end of summer of 2022, both the station itself and the territory around it have been regularly shelled and the nuclear power plant has repeatedly lost contact with external power grids. Russia and Ukraine accuse each other of nuclear terrorism and the situation around the plant is regularly discussed at the UN Security Council. Since September, inspectors from the International Atomic Energy Agency (IAEA) have been present at the station, and its head has been trying to negotiate the creation of a demilitarized zone around the station, meeting with both Vladimir Zelensky and Vladimir Putin.

With the outbreak of the war, Bellona ceased its work inside Russia, but continues to closely follow developments in the field of nuclear and radiation safety during this war. Undoubtedly, the first ever capture of an operating nuclear power plant during a military conflict remains one of the most dangerous events of this war.

This report is devoted to describing possible emergency scenarios at the plant that could be caused by hostilities and analyzing what their consequences might be. Consistently, it gives a general description of the plant and its features, describes emergency scenarios associated with direct shelling of reactor facilities and the possible consequences of damage depending on what modes of operation the reactors are in. It also considers the possible consequences of shelling spent nuclear fuel storage facilities at the plant, and assessed the risks of the Fukushima scenario, which could arise should cooling be lost due to the plant being disconnected from external power. It also presents an overview of the risks of a dam break at the Dnieper cascade of hydraulic structures and explores the risk of staffing shortages at the plant.

At the end of this report, we provide a description of important factors that should be closely monitored in the near future and make recommendations for reducing nuclear and radiation risks. They are as follows:

— While the plant is under occupation and the risk of shelling and disconnection from external power remains, it is important that all six reactors remain in a subcritical state;

— It is crucial while the risk of hostilities remains and the plant remains short-staffed that no efforts to unload, pack and transport fuel be undertaken.

— On the background of an expected Ukrainian counteroffensive, it is important that there be no clashes on the territory of the station itself, especially those involving heavy weapons, and that while Russian troops potential withdraw that equipment critical for nuclear safety not be damaged.

— Should troops withdraw from the plant or hostiles in the area cease altogether, a technical analysis of the state of the plant must be undertaken before it is put back into commission. The international community must provide Ukraine with all possible assistance in carrying out these efforts, from expert and technical assistance as well as financial aid.

— Plant staff will need to be rehabilitated and shift personnel needed for operational assistance following a potential withdrawal of Russian troops and Rosatom specialists must be prepared

— It will be necessary to investigate the crimes committed during the occupation of the station, as well as the unauthorized actions or inaction of various officials and organizations.

— The unprecedented history of the occupation of the largest nuclear power plant in Europe itself should be analyzed, studied and discussed with the participation of a wide international expert community in order to develop recommendations for preventing similar events at nuclear facilities in the future. The world nuclear community must develop responses of a technical, organizational and legal nature.

INTRODUCTION

On March 4, 2022, Russian troops entered the territory of the Zaporizhzhia NPP. During a night clash involving heavy equipment, a fire broke out in the building of the station’s training center and several people died. In July of 2022, Ukraine targeted Russian troops stationed at the plant with drones. Russia placed military vehicles, trucks and equipment inside the plant’s machine rooms, and the plant’s fortified command post was occupied by the Russian military and representatives of Rosatom.

In August of 2022, shelling of the station site and the area around it began, with Russia and Ukraine blaming each other for the attacks. Since then, the station has been repeatedly fired upon by large-caliber artillery and rockets. From August 2022 to March 2023, the station was disconnected from the external power grid at least six times and was forced to operate safety systems using backup diesel generators. At the same time, the power units were abnormally stopped. In September, the station was visited for the first time by an IAEA mission led by Director General Rafael Grossi.

As a result of that visit, the IAEA issued a report on the state of the plant. Since then, at least two IAEA inspectors are constantly present at the station with the aim of informing the agency and the world community about what is happening within it. By April 2023, there have already been 8 rotations of these experts to the plant. During the war, Grossi, has repeatedly met with representatives of both Russia and Ukraine, including the presidents of each country in an effort to create a security zone around the station, but these negotiations have yet to produce a result.

Since September, all six of Zaporizhzhia’s reactors have been shut down. Four of them were transferred to the cold stop mode. Units 5 and 6 were operated in the semi-hot shutdown mode in winter to provide the station and the neighboring city of Energodar with heat.

In October 2022, President Putin signed a decree declaring the plant to be Russian property, after which Ukrainian personnel began to be persuaded to sign contracts with the Russian company operating the station. In the same month, an unsuccessful attempt by Ukraine to land troops and free Energodar and the Zaporizhzhia nuclear power plant were undertaken.

During the occupation of the nuclear power plant, Russia has gradually turned it into a fortified military facility, mining the perimeter, organizing firing points on the territory and even on the roofs of power units, placing military equipment and soldiers on the territory of the plant and inside the turbine rooms of reactor units. In addition, Russia has placed additional mobile diesel boilers at the plant, providing fuel for emergency diesel generators. Russia has also strengthened the open nuclear fuel storage area, has erected an additional fence and mesh covering against drone attacks, and is also trying to ensure the repair of power lines for possible connection of the station to a network in Russian-controlled territory. Due to a shortage of personnel at the plant, Russia also sent specialists from Russian nuclear power plants to the Zaporizhzhia NPP.

In May 2023, the occupying authorities began a partial evacuation of personnel and residents of Energodar to Russia or to Russian controlled territories of Ukraine. Apparently, a large-scale counter-offensive of Ukraine is expected in late May and early summer. This could affect the area where the plant is located. Therefore, despite almost 15 months of occupation of the station, many dangerous events may occur around it in the coming months.

Bellona is closely following developments related to nuclear and radiation safety in Ukraine during the war, and is devoting special attention to what is happening around the Zaporizhzhia plant. Since the beginning of 2023, we have been releasing monthly nuclear digests[1] with reviews of these events, including our own brief analysis, and we are also planning a number of reports and deeper publications on the topic.

---

[1] Bellona’s nuclear digest for March, 2023
https://bellona.org/news/nuclear-issues/2023-04-bellonas-russian-nuclear-digest-for-march-2023

The Zaporizhzhia NPP's features and VVER-1000 reactors

The Zaporizhzhia NPP is the largest nuclear power plant not only in Ukraine, but in Europe as well. It has six power units with a total capacity of 6 GW, which is about 43% of all nuclear power in Ukraine and is comparable to the capacity of three other Ukrainian nuclear power plants — the Khmelnytsky, South-Ukrainian and Rivne plants — combined. Before the war, Ukraine's nuclear energy sector provided more than 50% of the country's total electricity, and the contribution of the Zaporizhzhia NPP to the energy balance of Ukraine was about 20%. In addition, the Zaporizhzhia NPP provided heat to the neighboring city of Enerhodar, where plant workers and their families lived with a pre-war population of about 50 thousand people.

There are six power units with VVER-1000 reactor units operating at the Zaporizhzhia NPP. This is a Soviet-designed power reactor of the pressurized water-cooled type.

Such reactors are the most common type of power reactor in the world and is known in its Western classification as a PWR, or pressurized water reactor. A total of 37 VVER-1000 reactors with various modifications have been built since 1980 in Russia, Ukraine, Bulgaria, the Czech Republic, India and China, all of which are still in operation.

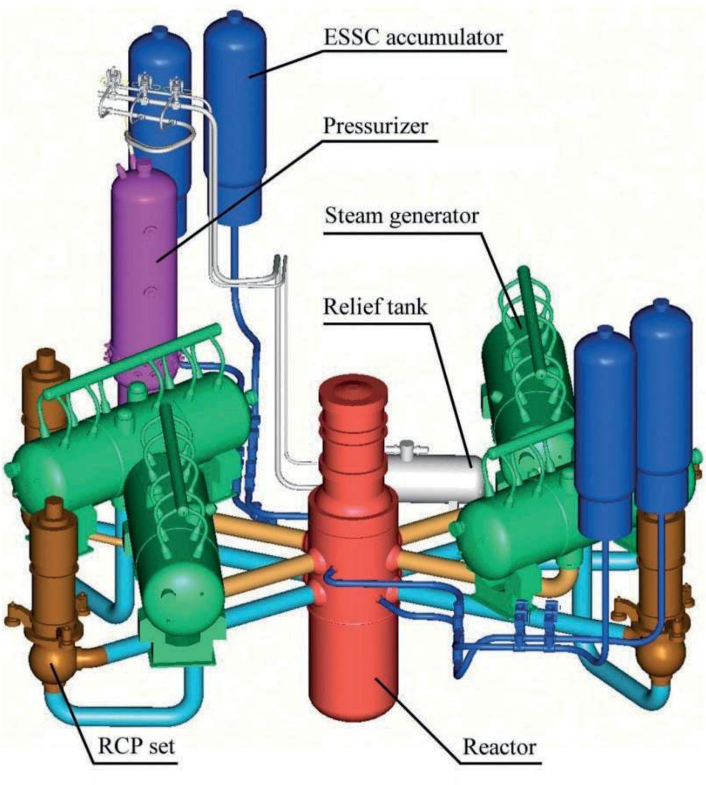
Specifically there are six VVER-1000s of the V-320 modification at the Zaporizhzhia nuclear plant. This is the most common modification of the VVER-1000 of which 25 were built, and all are still in operation. Ten VVER-1000/V-320s are operating in Russia at the Balakovo, Kalinin and Rostov nuclear plants. Eleven V-320s are operating in Ukraine at all four of its nuclear power plants — the Zaporizhzhia, the South Ukraine, the Rivne and the Khmelnitsky. An addition two such units operate in Bulgaria and the Czech Republic at the Kozloduy and Temelin nuclear plants, respectively.

This reactor emerged in the late 1970s and early 1980s, and those built at the Zaporizhzhia plant were among the first of the V-320 modification to be built. The six units there were put into operation between 1985 and 1996. The sixth unit has not yet reached the end of its 30 year designed life expectancy. At Units 1 to 5, work was carried out to extend the lifetimes from 2016 through 2021, and licences to extend their service lives to 40 years were issued.

Differences between the VVER-1000 and Chernobyl's RBMK-1000

Since the capture of the Zaporizhzhia nuclear power plant in early March 2022, the press has often compared a possible accident at this plant with the 1986 Chernobyl disaster. Sometimes it has even been erroneously suggested that the same reactors were installed at Zaporizhzhia. This is not true. And it is important to understand this difference since it is directly related to the issue of the functioning of safety systems and the possible scale of the accident.

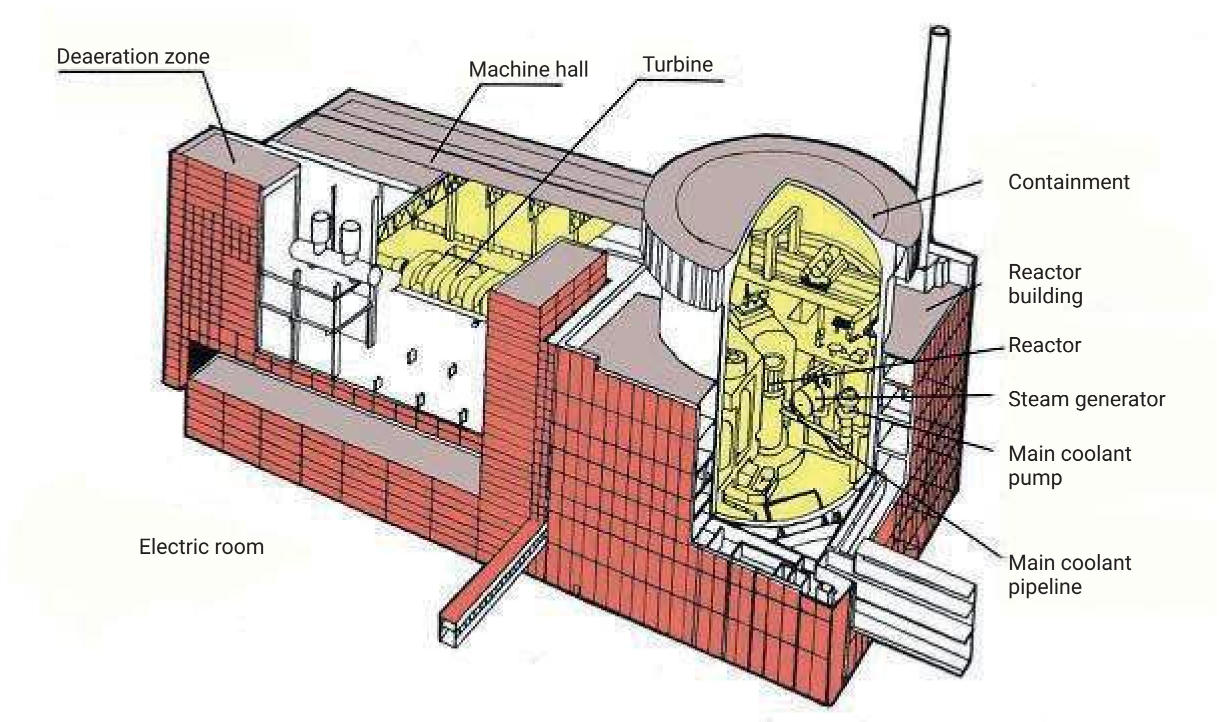
The Chernobyl nuclear power plant operated RBMK-1000 channel graphite reactors. At the Zaporizhzhia NPP, there are VVER-1000 reactors of the same capacity, but of a different type and design. Unlike Chernobyl, VVER-1000 reactors are more compact and protected.



Layout of the VVER-1000 reactor's primary circuit. It is enclosed inside the reactor compartment. A radioactive coolant (water with a weak admixture of boric acid) circulates through it in a volume of about 370 m^3. Photo: *OKB Gidropress*

Unlike RBMKs, VVERs are double-circuit — that is, radioactive coolant does not leave the protected reactor compartment. They do not contain graphite, as the RBMK does, where there are about 2000 tons of it, and which, due to partial combustion, could have increased the release of radioactive substances during the Chernobyl accident.

The VVER reactor itself is much more compact. Its body diameter is about 4.5 meters, while the RBMK has an active zone with a diameter of about 11 meters. The mass of nuclear fuel inside the VVER-1000 is about 80 tons, while in the RBMK it is about 200 tons.

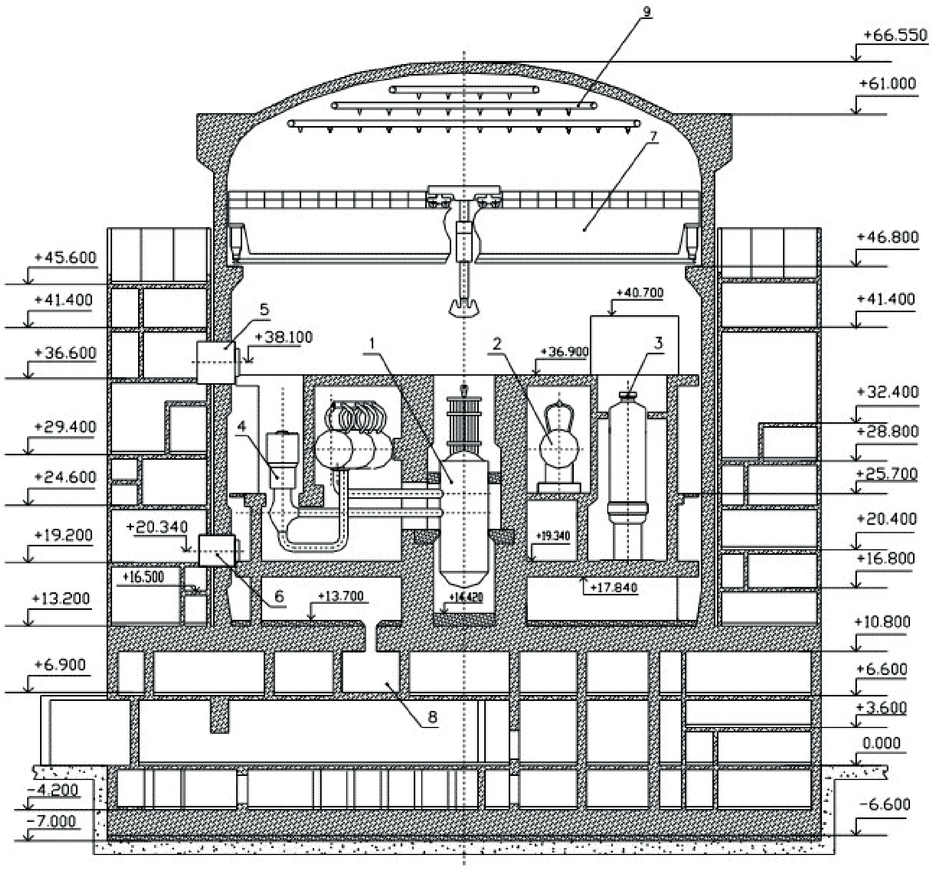


Layout of the VVER-1000/V-320. Photo: *Studfile.net*

The VVER is not a channel, but a vessel reactor. Its durable steel case has a wall with a thickness of about 20 cm, as it is designed for a huge working pressure of more than 150 atmospheres.

The most potentially dangerous places in the Zaporizhzhia plant in the nuclear and radiation sense are the reactor compartments. They contain nuclear reactors and the first radioactive circuit of power units, as well as nuclear fuel. And not only the fuel inside the reactors themselves, but also the spent fuel in the spent fuel pools. But it is precisely because of the potential danger that the reactor compartments at the plant are the most protected.

One of the main differences between power units with VVER-1000 reactors and power units with RBMK reactors is that their reactor compartments are hermetically sealed from all sides by a single concrete protective shell called a containment. It was at the VVER-1000 power units in the early 1980s that such containments began to be installed at scale. Previous designs of Soviet reactors did not have full-sized containments.



1. Reactor
2. Steam generator
3. Pressurizer
4. Reactor coolant pump
5. Personnel airlock
6. Emergency airlock
7. Polar crane
8. Sump tank
9. Sprinkler system

A section of the VVER-1000 with dimensions. Photo: *Rosenergoatom*

The walls of the prestressed concrete containment are 120 cm thick. Its diameter is about 45 meters and its height is about 60 m. The main task of the containment is to prevent the release of radiation to the outside in the event of an accident at the reactor itself. Inside the first circuit of the power unit and inside the VVER-1000 reactor, water circulates under a pressure of more than 150 atmospheres. In the event of a depressurization of the circuit, the water will turn into steam, but all the released radioactive steam needs to be kept inside the containment — and the containment is designed for this.

Photo taken during the construction of the containment for the Balakovo NPP, which is similar in design to the Zaporizhzhia plant. The massive scale of the object is obvious — this is the perimeter of the dome. The end of rebar cables for concrete prestressing are visible. To comprehend the scale, note the people at the bottom of the photo.
Photo: *The Centre of the Public Information Balakovo NPP*

In addition to localizing the consequences of internal accidents, the containment is also designed to protect against external influences, both weather and man-made — including the blow of a crashing light aircraft weighing up to 6 tons. Of course, this is not enough to withstand the blow from a modern military or passenger aircraft, to say nothing of a cruise missile strike. But we must remember, firstly, that this is a design from the 1980s. And secondly, that the Chernobyl RBMK reactor had no containment at all.

Possible risks

1. Destruction of a reactor unit operating at power

However, not a single nuclear power plant is designed for military hostilities and the threats that accompany them. This is a peaceful civilian facility, not a bunker. Therefore, shelling, in the worst case, can lead to damage to the containment, the formation of a crack or even holes. Most likely, a VVER-1000 reactor would not crumble entirely, as it is a domed reinforced concrete structure.

The destruction of the containment itself would not cause a nuclear accident. If the reactor is not damaged, then theoretically it can function without its containment. Only if the concrete containment itself is pierced, and the reactor itself or the primary circuit equipment suffers a blow from shelling, then its depressurization and the release of radioactive steam are possible. In the worst case, if there is a strike in the reactor itself, then a release is possible along with fragments of nuclear fuel.

However, considering the design of the VVER-100, this would be possible only as a result of a targeted and/or prolonged shelling of the containment, or as a result of the use of special ammunition. It is unlikely to occur as the result of a random projectile or bomb. There must be a combination of several factors. Because, having broken through the containment, you still need to hit the reactor, hidden deep inside the building in a relatively narrow pool.

And the other equipment of the primary circuit is also under the floors, which must be broken through. Theoretically, this is possible, but the probability of damage to the reactor itself because of an accidental hit by a projectile or missile is relatively small. The probability of simultaneous damage resulting from shelling of several power units is even less.

The reactor hall of the VVER-1200 (similar to the VVER-1000).
The reactor vessel is pictured at bottom center. Photo: *Rosatom*

What are the threats if a projectile hits the nuclear reactor itself? Contrary to popular belief, this will not cause a nuclear explosion. The reactor is not an atomic bomb, even if at the time of the accident it is operating at full capacity. There was no nuclear explosion either at Chernobyl or at Fukushima.

Even if a strike on a reactor operating at power should damage the control rods (which in the VVER-1000 are located in the upper part of the reactor, which would most likely suffer in the event of an impact) and somehow cause a reactor runaway, then it would sooner fall apart and depressurize than it would release a large amount of energy as the result of an uncontrolled chain reaction. Most likely it would simply depressurize with a release of water, steam and possibly the fuel itself, and the nuclear reaction would be extinguished on its own.

The consequences of such an accident would greatly depend on many factors, including the state of the reactor itself and weather conditions. In the worst case, if the reactor was operating at power at the time of the accident, then a rather strong steam explosion is possible because of its depressurization. If the containment were damaged, then the radioactive vapor, volatile elements from the damaged fuel, and the fuel fragments themselves would be partially released into the environment.

2. Release of Iodine 131

In such an accident iodine-131 would pose the primary danger since it can spread over large distances. Its half-life is only about 8 days meaning the element would only pose a threat for several weeks. Because of its impact on the human body, it would be the main threat to those living in areas around the nuclear power plant. Not coincidentally, the Ukrainian authorities have already organized the distribution of stable iodine preparations in the form of potassium iodide tablets to residents of nearby regions for iodine prophylaxis.

This is because iodine accumulates in the thyroid gland. Before a possible release of radioactive iodine (isotope iodine-131) into the atmosphere, iodine prophylaxis with stable iodine is recommended. This guards the thyroid gland against the absorption of radioactive iodine.

There are various recommendations for the correct methods of iodine prophylaxis published by numerous government[2] health ministries and agencies. To summarize, the recommended dosage is 125 milligrams a day for adults five days from the beginning of possible exposure. Children's dosages are a multiple less. But such dosages are found only in special preparations. Ordinary tablets of potassium iodide or other iodine preparations — which can be bought in ordinary pharmacies and which are used for purposes other than iodine prophylaxis — contain dosage thousands of times smaller, measured in micrograms.

Importantly, a loading dose of the potassium drug used for iodine prophylaxis can be dangerous for older people and for those who have heart problems. Therefore, these drugs should only be ingested after official notifications are given about radioactive releases and the need for iodine prophylaxis.

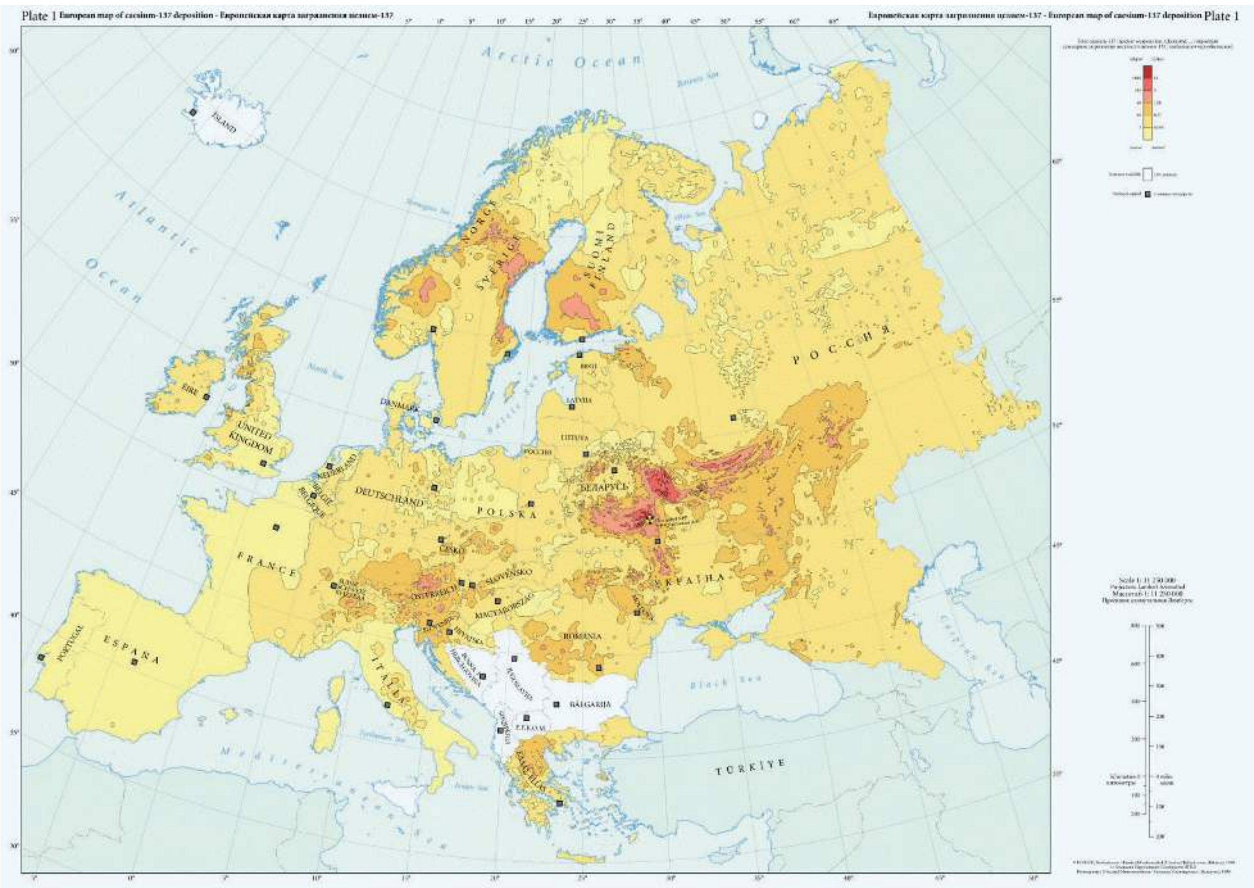
---

[2] Iodine thyroid blocking: Guidelines for use in planning and responding to radiological and nuclear emergencies. WHO Technical document
https://www.who.int/publications/i/item/9789241550185

3. Release of Cesium 137

The second dangerous factor of a possible radiation release in the event of reactor damage is airborne cesium-137 isotope, with its half-life of 30 years. After Chernobyl, it was, to a greater extent, this isotope that constituted the main contamination of the territory resulting from the radioactive release.

However, how far and in what quantity cesium-137 can spread because of an accident can cause a wide range of consequence which depend on many factors, including the accident scenario itself, the scale and nature of the accident and the release, as well as weather factors, among other things.



Map of Europe's cesium-137 contamination as a result of the Chernobyl accident and global fallout.
Photo: *Yu. A. Izrael Institute of Global Climate And Ecology*
European map of cesium-137 deposition. (1998).
EC/IGCE, Roshydromet (Russia)/Minchernobyl (Ukraine)/Belhydromet (Belarus).
http://www.etomesto.ru/img_map.php?id=2037

For example, the map shows that background levels (the two lightest shades covering all of Europe) are <2 kBq/m^2 and <10 kBq/m^2. This is a conditional background level of pollution in Europe. Most of the pollution in these territories was formed even before Chernobyl due to global fallout from nuclear weapons tests in the 1960s. The conditional level of pollution from global fallout in Europe is about 2-4 kBq/m^2 (see the Atlas of Caesium Deposition After the Chernobyl Accident[3]).

What was dispersed over more than a few dozen of kilometers from the place of release most often no longer poses a serious threat to human health due to large dispersion. However, the fallout is usually uneven and often patchy due to being washed out by precipitation (see the map above), or it can form a long narrow plume (as in the Kyshtym accident[4] of 1957) if there is a steady strong wind blowing in one direction.

The contamination zone will also depend on the duration of the release.
At Chernobyl, for instance, the release lasted more than a week until the fuel masses cooled down, such that a change in the wind during this time sent emissions through the destroyed block in different directions. But in the case of the Zaporizhzhia NPP, if there is a release, it would most likely be a short, one-time burst.

Several simulations of a release from a hypothetical accident give only qualitative estimates. For example, forecasts by the Ukrainian Hydrometeorological Institute show that the main fallout from a release from the Zaporizhzhia NPP would fall within a radius of 50-100 km from the plant.

When discussing outlier modeling, references to the Austrian research project FlexRISK[5] often appear. This resource gives estimates of possible emissions from accidents at various nuclear power plants in Europe, including the Zaporizhzhia NPP. FlexRISK itself does not provide explanations about the nature of the accident included in their release model, however, the air release of the Cs-137 isotope in the amount of 50 PBq suggests that a possible at the Zaporizhzhia NPP is comparable to the Chernobyl accident in terms of the release level (a release of about 85-100 PBq of Cs-137) and would even exceed Fukushima (about 16 PBq Cs-137)[6].

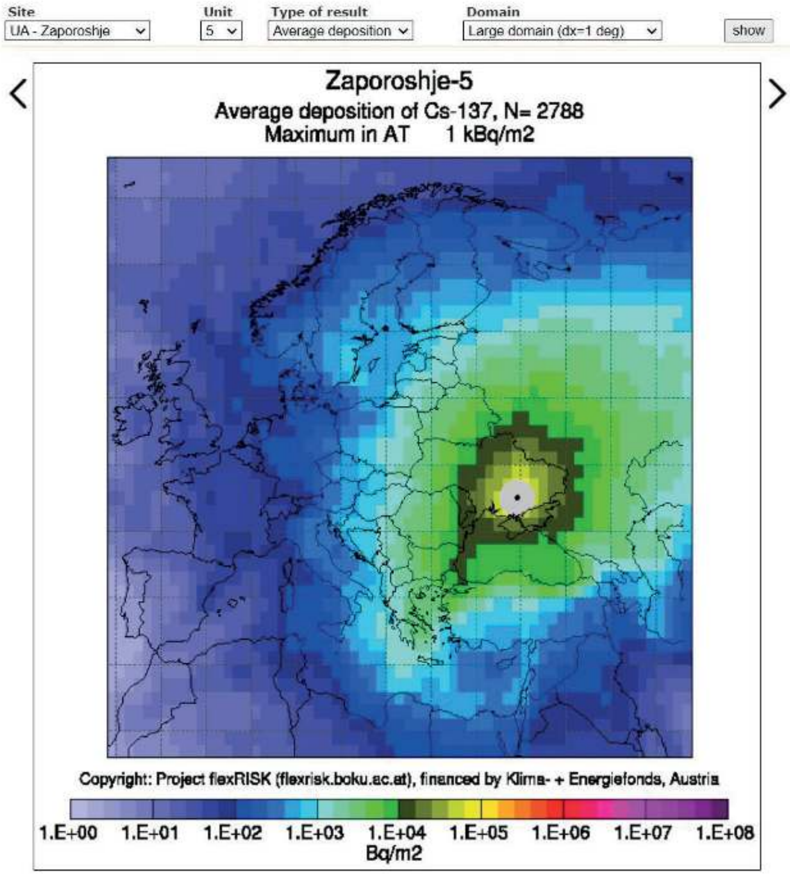
---

[3] Atlas of cesium deposition after the Chernobyl accident. (1998). Office for official publications of the European Communities. *https://op.europa.eu/en/publication-detail/-/publication/3dda49b2-ea5b-11e9-9c4e-01aa75ed71a1/language-en/format-PDF/source-search*

[4] Digges C., The worst nuclear disaster you've never heard of celebrates its 60th birthday. (2017, October 2). Bellona.

[5] Results of the project flexRISK. (2012, August 21). The climate and energy fund, Austria. *http://flexrisk.boku.ac.at/en/results.html*

[6] Steinhauser G. and others, Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts. (2014) Science of The Total Environment. *https://www.sciencedirect.com/science/article/abs/pii/S004896971301173X*



Modeling of the average fallout of cesium-137 in Europe resulting from a serious accident at the Zaporizhzhia NPP.
Photo: *Flexrisk*

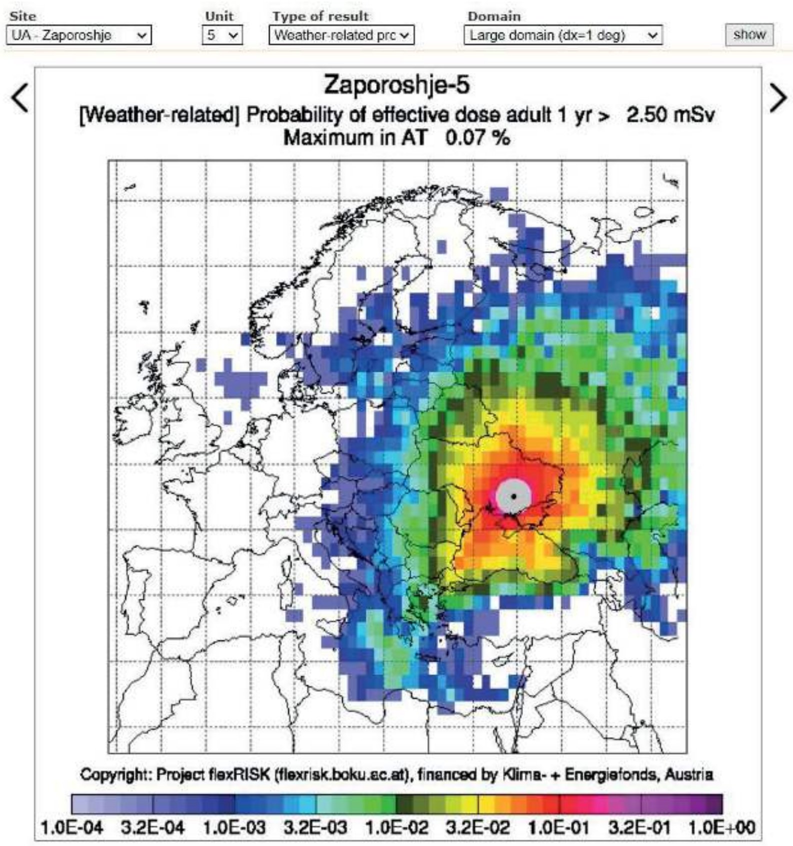
However, because of the design differences in the Zaporizhzhia NPP's VVER-1000 reactors described above, this is unlikely. Thus, the scale of the consequences from FlexRISK can be considered a conservative overestimate.

The FlexRISK maps show definitively how a radiation release could cover the whole of Europe. However, a close reading of these maps shows the level of pollution to be below 10 kBq/m^2 (see the map of Chernobyl fallout above) — this is the green area and further towards blue. Roughly speaking, in the direction of Europe outside of Ukraine, the level of fallout would be approximately similar to what has already existed there for several decades due to fallout from the Chernobyl accident and other global fallout (see, for example, the pollution map of Austria[7]). This confirms

[7] Cesium-137 soil pollution as of May 1, 2021. (2021). The Federal Environment Agency of Austria. *https://www.umweltbundesamt.at/fileadmin/site/themen/energie/caesiumkarte_2021.pdf*

the qualitative forecast of the Ukrainian Hydrometeorological Institute that the main fallout will be within tens and hundreds of kilometers from the station.

You can also see the estimated doses received by the population from these fallouts. Below is a model dose map for the same conditions. More precisely, the probabilities for an adult to receive a dose of more than 2.5 mSv in the first year after the accident. Note that 2.5 mSv is about half what each of us receives on average per year from natural sources of radiation. Thus, judging by the modeling and the map, outside the southeastern part of Ukraine, the probability of receiving a dose of more than 2.5 mSv is below 0.1 — and on the border of neighboring states, it is already lower by an order of magnitude.



Model distribution of the probability of receiving a dose of more than 2.5 mSv in the first year after the accident. Photo: *Flexrisk*

Model distribution of the probability of receiving a dose of more than 2.5 mSv in the first year after the accident. Photo: Flexrisk

However, these are all simulation maps modelled to average weather conditions. The actual nature of pollution will strongly depend on what the weather is actually doing that day. Contamination can be highly patchy, or, in the case of sustained winds, an elongated plume with high levels of contamination forming over hundreds of kilometers.

Such high levels of contamination could prompt evacuations and the resettlement of several populated areas located within a radius of a few dozen kilometers from the station, as was the case after the Chernobyl accident. The contamination could also limit the use of land, primarily farmland, for many years. In the event of a major accident, in addition to the territory of Ukraine itself, it is likely that neighboring countries such as Moldova, Romania, Poland, Belarus, Russia and even Turkey, as well as the Black and Azov Seas, may suffer. In the case of a large release, traces of contamination could also be found in other countries of the region, but most likely their level will be relatively small.

4. Destruction of power unit while the reactor is shut down

The scenarios described above concern the most dangerous — but less likely — scenario of a projectile striking an operating reactor through a destroyed containment, followed by its destruction and a steam explosion with an atmospheric release of numerous of radioactive substances.

However, if the reactor struck had already been shut down for some time, especially weeks and months, then it will not contain the iodine-131 that is most dangerous to humans because with a half-life of only about eight days, it will already have decayed. If the reactor is in a state of cold shutdown (the reactor is shut down, the pressure in the primary circuit is close to atmospheric pressure), then there will be neither the high temperature nor pressure that could enhance the energy of the release. All of this reduces the probability of an accident and the scale of its consequences[8].

[8] Attila Aszódi. A nuclear safety expert's view on the crisis at the Zaporizhzhia nuclear power plant. Bulletin of the Atomic Scientists. September 2, 2022. https://thebulletin.org/2022/09/a-nuclear-safety-experts-view-on-the-crisis-at-the-zaporizhzhia-nuclear-power-plant/#post-heading

Thus, a long period of cold shutdown during the current conflict is much safer, as it reduces the risks and extent of a possible accident[9].

As of the beginning of May 2023, all six NPP units have been shut down. Four of them have been in a state of cold shutdown for many months. Some of them have been so since the very beginning of the war, meaning that the iodine-131 within them has already practically decayed. On September 10, the last two power units — Unit 5 and Unit 6 — were shut down. Between September and May, the content of iodine-131 in their fuel has decreased by at least a million times, meaning that this element is also practically absent.

Thus from the point of view of nuclear and radiation safety, as long as there are risks of shelling and damage to the plant, the reactors of the Zaporizhzhia nuclear power plant must be kept in a shutdown state.

However, by the end of 2022 Units 5 and 6 where put into so-called semi-hot shutdown mode in order to supply heat to the plant's complex and provide at least some heating to Enerhodar in the midst of winter conditions.

Semi-hot shutdown is a condition in which the reactors remain shut down — that is, they still do not produce new isotopes — and the temperature of the water in the primary circuit increases to about 200 degrees due to the operation of circulation pumps, a heating element in the pressure compensator and decay heat from nuclear fuel.

This mode of operation is possible only if there is a connection to an external power grid. The state of a semi-hot shutdown increases the risks associated with depressurization of the primary circuit and the risk of equipment wear in the event of an emergency shutdown of the unit. But in circumstances where it is necessary to supply the plant's complex with heat, this is a an unavoidable measure. On April 21, 2023, with the onset of the warm season, the ZNPP's Unit 6 reactor was also put into cold shutdown mode[10]. At the beginning of May 2023, only the Unit 6 reactor remains in a semi-hot shutdown.

---

[9] Aszodi A. A nuclear safety expert's view on the crisis at the Zaporizhzhia nuclear power plant. (2022, September 2). Bulletin of the Atomic Scientists. *https://thebulletin.org/2022/09/a-nuclear-safety-experts-view-on-the-crisis-at-the-zaporizhzhia-nuclear-power-plant/#post-heading*

[10] *https://www.iaea.org/newscenter/pressreleases/update-155-iaea-director-general-statement-on-situation-in-ukraine*

5. Explosion at a dry storage for spent nuclear fuel

Besides the reactor compartments at the Zaporizhzhia NPP, there is another site where nuclear fuel is located. This is a dry storage facility for spent nuclear fuel (SNF). Previously, SNF from all operating plants was exported to Russia for storage and processing, but for about 20 years, fuel from the Zaporizhzhia NPP has not been exported.

Since 2001[11], Ukraine has been using technology that is widespread in the US and many other countries. After unloading from the reactor and several years of storage in the holding pools in the reactor compartments, fuel is placed in special thick-walled concrete containers of 24 assemblies and stored on an open concrete platform. The dry storage facility is designed to store 380 casks containing about 9,000 spent fuel assemblies. At present there are just over 170 casks containing up to 2,000 tons of SNF at the site. This is the fuel accumulated at the station for about 15 years.

Dry spent nuclear fuel storage. Photo: *Energoatom*

[11] https://www.uatom.org/ru/ekspluatatsyya-shoyat-na-zaporozhskoj-aes

The containers are quite strong and resistant to external influences. They are a multi-layer structure made of steel and concrete, the thickness of which is about 70 cm. But, of course, they are also not designed to withstand shelling and bombardment.

There have already been shell hits and damage to auxiliary sensors near the dry storage site, so the possibility of damage to the containers themselves cannot be ruled out. Most likely, in the event of a direct hit on the site by a rocket or projectile, one or more of them would be damaged. However, inside the containers there are no combustible materials, no high-pressure liquids, no short-lived volatile elements that have decayed over many years. So the most probable consequences of container destruction are the dispersion of solid and heavy fuel fragments and local contamination of the storage site and the area near the NPP industrial site.

6. Power cut-off – the Fukushima scenario

Let's turn out attention to the most probable and dangerous accident scenario, which has already partially begun to be realized. A nuclear power plant is a huge building — and the Zaporizhzhia NPP is especially so. It occupies an area of several square kilometers, and in addition to reactor compartments and storage facilities, hundreds of buildings and structures are located within it. These are much easier to destroy accidentally or on purpose since they are not protected. Most of these structures do not contain any radioactive materials, and their destruction would not directly lead to a radiation accident. However, many systems are important for the normal operation of a nuclear power plant and its safety systems.

Some facilities and structures at the Zaporizhzhia NPP site.
Author's diagram on Google Earth satellite image.

In this case, the most likely and dangerous outcome the complete cutting of power to the nuclear power plant. This is the Fukushima scenario. Even after a reactor is shutdown, the fuel inside needs to be cooled. The chain reaction and fission of uranium and plutonium in it cease, but the decay of radioactive elements continues. The energy release of this process is less than with a working reactor, but quite significant. A few hours after the shutdown of a reactor, the energy release of the fuel remains at a level of about 1% of the nominal value and then decreases further approximately exponentially. To remove this heat, the operation of pumps is needed, and for them electricity is needed.

The most reliable way to supply this power is to take it from the grid. The worst power outage circumstances arise when that grid power is cut off. Because of shelling and fires around the station, such blackouts have already happened. The first complete blackout of the Zaporizhzhia NPP happened on August 25, 2022, when all 4 power lines running into the station from the Ukrainian grid were switched off for a short time. This was the first time in the plant's 40-year history that it had been entirely disconnected from the grid. The running units were stopped automatically.

Their cooling was carried out with standby diesel generators. There are 20 such generators at the station, and the fuel supply is usually available for 7-10 days, although since fall of 2022 it has been increased to 15 days.

The plant had been severed from the grid at least six more times since August 2022. As of early May, the last such outage due to shelling occurred on March 9, 2023[12]. Each such shutdown is the beginning of an emergency scenario. Unfortunately, this situation is not isolated to the Zaporizhzhia NPP. With the start of Russia's massive strikes on Ukraine's energy infrastructure this autumn, shutdowns of other nuclear power plants have become regular. So, on November 2, due to a strike on substations, one of the 750 kV lines connecting the South Ukrainian NPP to the power grid was lost, forcing one of its units to reduce power by 50%[13]. And on November 15, due to shelling of substations, power lines to the Khmelnitsky nuclear power plant were cut off, as a result of which both of its power units were stopped[14]. At the Rovno NPP, one block had to be stopped and the power reduced at another. Thus, due to Russian strikes, all nuclear power plants in Ukraine, without exception, are already exposed to risks.

Why is this dangerous? If it is not possible to quickly restore power lines, and diesel generators do not work or they run out of fuel, then nuclear fuel in reactors and spent fuel pools will heat up, break down and eventually melt, which will lead to a radiation accident. This is exactly what happened at the Fukushima nuclear power plant in Japan in 2011, where an earthquake and tsunami caused both external lines to break and diesel engines to flood.

With heating of the fuel in the reactors of the Fukushima NPP, hydrogen evolution began as a result of the steam-zirconium reaction of the interaction of fuel element claddings with water vapor. The resulting explosive mixture led to the explosions of three reactor compartments and the release of a cloud of volatile isotopes.

---

12 *https://www.iaea.org/newscenter/pressreleases/update-150-iaea-director-general-statement-on-situation-in-ukraine*

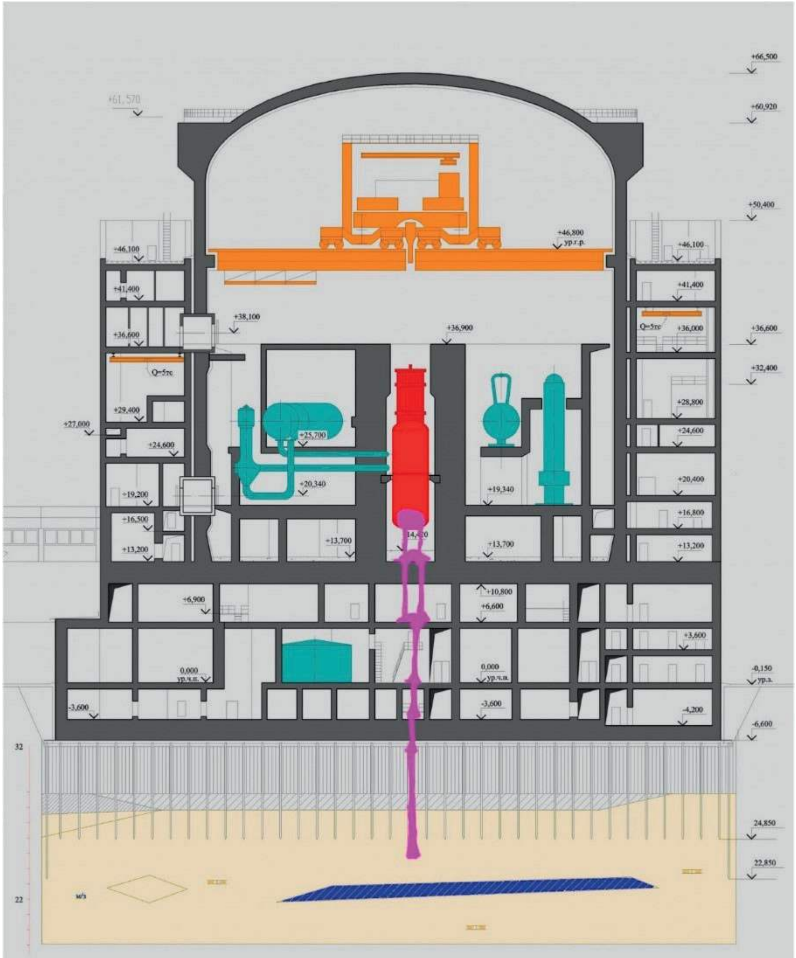
13 *https://www.iaea.org/newscenter/pressreleases/update-123-iaea-director-general-statement-on-situation-in-ukraine*

14 *https://www.iaea.org/newscenter/pressreleases/update-127-iaea-director-general-statement-on-situation-in-ukraine*

Explosion of a hydrogen mixture at one of the reactors at the Fukushima nuclear power plant. Photo: *TV screenshot*

Fortunately, hydrogen recombiners have been installed at the Zaporizhzhia NPP during the post-Fukushima modernization. Recombiners do not need electricity to operate, they chemically convert excess hydrogen back into water and prevent it from accumulating in a dangerous concentration in the reactor compartment. Thus there should be no explosions and air release like in Fukushima at the Zaporizhzhia nuclear power plant even in case of fuel overheating.

However, as the temperature rises, the fuel will break down and melt, which can lead to the melting of the reactor vessel and the escape of the resulting mixture into the under-reactor space. At modern nuclear power plants there are special melt traps that must hold and cool this melt. But there are none on VVER-1000/V-320, just as there were none on Fukushima and Chernobyl.

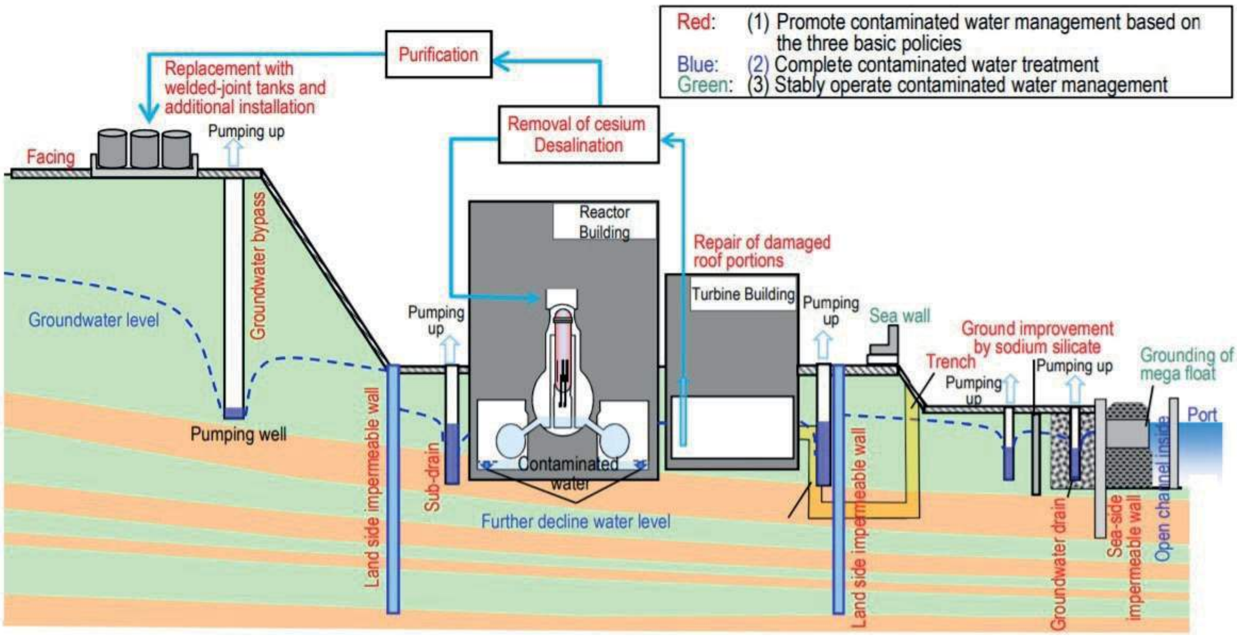


Schematic of possible egress of the fuel melt outside a reactor containment during a severe accident at a VVER-1000.
Photo: *Bellona, Andrey Ozharovsky*

Departure of the fuel melt threatens depressurization of the containment, contamination of ground and surface waters. It was the contamination of water, which accidentally or deliberately entered the leaky Fukushima reactors, that created serious problems in Japan.

Now, about a million tons of polluted water have been accumulated at the Fukushima nuclear power plant site, which they were able to collect and partially clean. But the rest has flowed into the ocean.

A similar accident at the Zaporizhzhia NPP, could contaminate the Kakhovka reservoir, the Dnieper River and the Black Sea. But everything would depend on the scale of the accident and contamination.



Schematic of the movement of surface water along the water table through the afflicted reactors at the Fukushima nuclear power plant towards the ocean. Photo: *TEPCO*

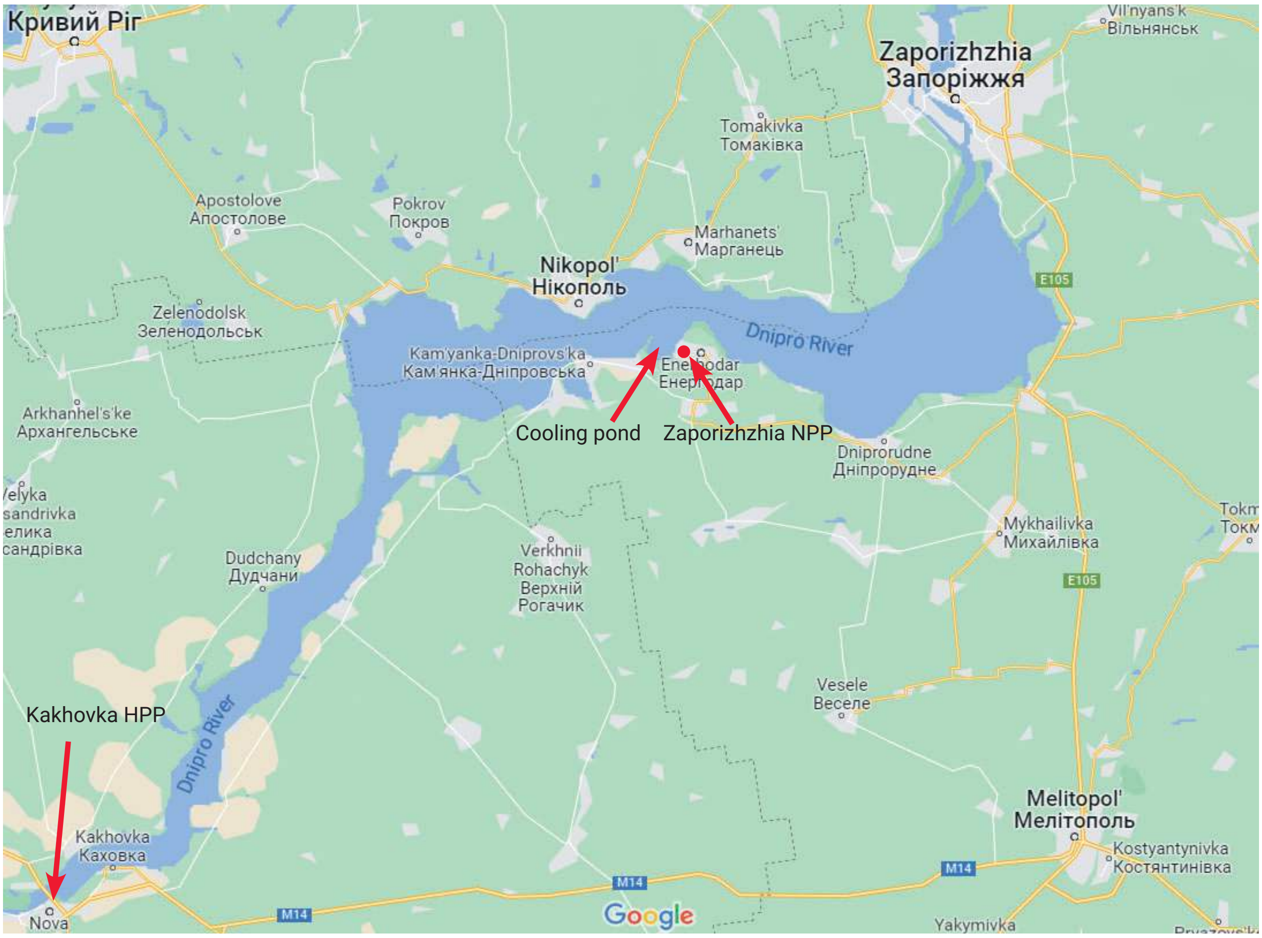
Such a scenario is possible. But such an accident would develop into the worst case over several hours if the reactors were still operating, versus several days if they had been put into shutdown mode. Overheating does not happen all at once, and in this situation, the staff, if they are helped, not hindered, will have time to react and prevent the worst scenario. In the current situation, when power units have been in a state of cold or even half-hot shutdown for months, the risks are much less than in the case of reactors operating at power.

7. Dam break in the Dnieper cascade and the Kakhovka reservoir

Considering the military situation as it has developed over the last six months in the regions of Ukraine adjecent to where the ZNPP is located, and the ongoing attacks on the infrastructure of Ukraine, including hydroelectric power plants, there are risks associated with the possible destruction of the dams of the Dnieper cascade of hydroelectric power plants and the Kakhovka reservoir, on which the Zaporizhzhia nuclear power plant is located.

The first scenario concerns the rupture of the dams on the Dnieper cascade above the Kakhovka reservoir, with flood risks at the site of the Zaporizhzhia NPP. The 2011 National Report of the State Inspectorate for Nuclear Regulation of Ukraine on stress— tests at Ukrainian NPPs analyzes a similar scenario. The report[15] noted that the normal retaining level of the Kakhovka reservoir is 16 m, and the Zaporizhzhia NPP site is located at around 22 m. Despite certain disruptions in the operation of the cooling elements and flooding from any breakthrough waves, the document says no serious threats to the safety of the station are expected.

The second scenario is associated with the rupture in the dam of the Kakhovka Hydroelectric Power Plant and the release of water from the Kakhovka reservoir.



Locations of the Kakhovska hydroelectric power station and the Zaporizhzhia nuclear power plant.
Author's diagram on Google Earth satellite image.

[15] National report of Ukraine. Stress test results. (2011). State Nuclear Regulatory Inspectorate of Ukraine. *https://snriu.gov.ua/storage/app/sites/1/docs/Stress-tests/National%20Report%20of%20Ukraine.pdf*

Here it is worth clarifying that for cooling the nuclear power plant, water is not taken directly from the reservoir. Instead a special cooling pond is used, which is divided from the Kakhovka reservoir by a bulk dam. It is refilled from the reservoir through a system of locks, but in general it is an isolated hydraulic structure.

According to the stress test report, in the event of a dam failure at the Kakhovka HPP, located about 120 km downstream of the Dnieper from the Zaporizhzhia NPP, the water level in the Kakhovka reservoir at the NPP site is expected to drop from 16 to 10 m. At the same time, the water level in the cooling pond will remain the same, and a 6 m level difference, according to the report, the dam of the cooling pond is able to withstand such a rupture without destruction. Descent of water is possible only as a result of the destruction of the sluice of the cooling pond.

However, the question remains about the completeness and accuracy of such studies and their applicability to the current situation of hostilities, with all of its new risks. On November 6, the State Inspectorate for Nuclear Regulation of Ukraine urgently instructed Energoatom, the operator of Ukrainian nuclear power plants, to analyze the safety risks of operating the power units of the Zaporizhzhia nuclear power plant in the event of a drop in the level in the Kakhovka reservoir[16]. However, as of the end of 2022, the results of this analysis were not publicly available.

8. Intolerable circumstances for plant personnel

An important aspect for nuclear safety is the question of the state of the plant's personnel. Ukrainian personnel have been working at the station throughout its occupation under physical and psychological pressure from Russian forces. As in other Russian-occupied territories during this war, hundreds of employees of the Zaporizhzhia NPP and other residents of its company city of Enerhodar have been subjected to interrogations, abductions, and torture, including deaths, as Russian troops attempt to ferret out supposed saboteurs and partisans[17].

---

[16] *https://www.epravda.com.ua/rus/news/2022/11/6/693513/*

[17] Parkinson J. and Hinshaw D. 'The Hole': Gruesome accounts of Russian occupation emerge from Ukrainian nuclear plant. (2022, November 18). The Wall Street Journal. *https://www.wsj.com/articles/russian-occupation-of-nuclear-plant-turns-brutal-with-accusations-of-torture-andbeatings-11668786893*

The number of personnel at the station has dropped critically due to the departure of many workers and their families from the war zone. By November 2022, according to the plant's operator, Energoatom, only about 3,000 plant workers remained at the site, compared to some 11,000 who worked there before the war. Several thousand more remain[18] in the city of Energodar, prevented from leaving the city by Russian occupiers while at the same time forbidden from working at the plant over their refusal to sign contracts with the Russian company running the plant and suspicions of disloyalty.

After the creation in early October of the Russian operating organization, a subsidiary of Rosatom, the pressure on personnel to sign on to work contracts with the new Rosatom-driven structure increased. At the same time, the uncertainties and risks associated with the lack of a clear management of nuclear power plants and the violation of regulations and work protocols have grown. In the most difficult conditions of frequent emergencies, shelling and pressure[19], the remaining specialists continue to work to ensure the safe operation of the largest nuclear power plant in Europe.

---

[18] *https://forbes.ua/ru/company/torturi-eksperimenti-riziki-yadernoi-katastrofi-shcho-rozpovidayut-spivrobitniki-okupovanoi-zaporizkoi-aes-yakim-vdalos-vtekti-23022023-11876*

[19] *https://www.iaea.org/sites/default/files/22/11/gov2022-71_rus.pdf?fbclid=IwAR0Ng8LhOllq6urTvIT2Moo4P_teAkG7p7EDmtGPXOhVCAdMxzntuE3X5lg*

CONCLUSIONS

It is important to emphasize that this report is devoted to technical issues related to the safety of the Zaporizhzhya NPP. Never in history has a nuclear plant been captured in the course of hostilities. As we see now, the international community, both represented by the UN Security Council and by specialized organizations such as the IAEA, does not have effective mechanisms to sufficiently respond to such an incident. The organization of a permanent IAEA mission to the station and negotiations on the creation of a demilitarized zone around the nuclear power plant are important and useful steps in the current situation, but in essence they are an impromptu and diplomatic initiative of IAEA head Rafael Grossi.

We can say that the risks of major nuclear incidents remain at the Zaporizhzhia NPP. These risks are associated with both possible accidental or deliberate damage to the reactors units themselves as a result of shelling, as well as with power blackouts at the complex. It is also important to note that blackout risks since fall of 2022 are likewise arising periodically at the three other Ukrainian nuclear power plants due to the full-scale Russian strikes on Ukraine's energy infrastructure.

The current state of the Zaporizhzhia NPP, with all its reactors in a state of shut down for at least several months, significantly reduces the scale of possible consequences in the event of an accident, as well as the threat to the population from the volatile isotope of iodine-131. Nevertheless, the risks of contamination of large areas with medium— and long-lived radionuclides — primarily cesium-137 — remain as a result of shelling or because of a possible Fukushima-type scenario.

Alerting the population and arranging for its evacuation and protection in the event of a nuclear or radiation threat or accident at the plant is, in the heat of war, difficult if not impossible, according to some emergency response scenarios. This should be taken up not just by the Ukrainian side, but also the international community, primarily the IAEA. This is the question of the presence or absence of appropriate «international protocols of action», to which we have already alluded.

Important factors for reducing nuclear and radiation risks, which Bellona proposes receive special attention in the nearest future:

— in the current circumstances of the plant's occupation and possible clashes and ongoing shelling of its territory, it is important that all six reactors remain in a subcritical state, despite other difficulties that may arise, such as the loss of a large electricity source for both sides of the conflict, in addition to a heat source for the city of Enerhodar and the site itself. Providing heat and steam to the plant's industrial site for its normal operation is possible even without starting the reactors — but is possible only with a stable connection with the external power system. Any attempts to launch units, both by Russia or Ukraine, will lead in the current circumstances to increased risk for nuclear accidents and incidents.

— in the context of a shortage of qualified personnel, risks of shelling and lack of reliable communication with regulatory authorities, it is important that, until these problems are eliminated, the plant does not carry out operations to unload fuel from reactors, as well as any operations to pack it into shipping containers and place them in an open area storage.

— in the context of the expected Ukrainian counter-offensive in the spring-summer of 2023 and the future abandonment of the station Russian troops, it is important that there be no clashes on the territory of the station itself, especially those using heavy weapons, and that there be no provocations and accidental or intentional damage to equipment during the withdrawal of Russian troops from the plant, especially that equipment that is critical to nuclear safety.

— After the withdrawal of Russian troops from the plant, it will be important to conduct a technical analysis of the condition of facilities and equipment, to carry out operations to clear the facility, to ensure reliable connections of the facility with the external power grid, and to take measures to reduce the risks of future shelling of the facility before the plant can begin to carry out the necessary routine maintenance work for equipment and put the plant into operation in the power mode. The international community will have to provide Ukraine with all possible assistance in carrying out these efforts, and provide expert, technical and financial assistance.

— Ukraine and Energoatom, the operator of the Zaporizhzhia NPP, must be ready not only for the restoration of the plant, but also for the rehabilitation of personnel. They must also prepare replacement personnel that will be needed for operational assistance at the nuclear power plant after the withdrawal of Russian troops and Russian and other specialists who collaborated with Rosatom and worked during the occupation of the station.

— Crimes committed during the occupation of the station, illegal actions or inaction of various officials and organizations of both Russia and Ukraine should be investigated, and the unprecedented history of the occupation of the largest nuclear power plant in Europe should be analyzed, studied and discussed with the participation of a wide international expert community in order to develop recommendations aimed at preventing similar events at nuclear facilities in the future. The world nuclear community must develop responses of a technical, organizational and legal nature. It is possible that the experience of capturing a nuclear facility would not lead to a reorganization of structures and additions to the response protocols of various international institutions, such as the IAEA, as well as to the norms of international law in the field of nuclear regulation and nuclear terrorism.

BELLONA

The radiation risks of seizing
the Zaporizhzhia Nuclear Power Plant

2023