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Dangerous Targets: Civilian Nuclear Infrastructure and the War in Ukraine

Preliminary Lessons for Safety and Security in War Zones

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Contents

Executive Summary

RUSSIA'S FULL-SCALE INVASION of Ukraine on 24 February 2022 saw the immediate capture by Russian forces of Ukraine's Chornobyl Nuclear Power Plant (ChNPP). A few days later, Russian forces attacked the Zaporizhzhia Nuclear Power Plant (ZNPP) – the first instance of an operational nuclear power plant (NPP) directly targeted as part of a military operation. Over the past year, Russia's military activity in Ukraine has resulted in serious threats to the safety and security of Ukraine's nuclear infrastructure, and there is good reason to believe that Russia has violated the protections granted to NPPs in international humanitarian law (IHL). Given the significant projected global increase in the number of nuclear reactors over the coming decades, it is likely that this will not be the last time NPPs are in the midst of military conflict. This report seeks to assess the risks the ongoing war poses to NPPs in Ukraine and to draw preliminary conclusions from these events to improve the safety and security of NPPs in conflict.

The greatest threat to Ukraine's NPPs is unlikely to be from a direct strike on a reactor and an ensuing large-scale radiological incident similar to the 1986 Chornobyl disaster, but rather the failure of key systems – namely, water and energy supply – or human error, potentially resulting in an incident not unlike what occurred at Fukushima Daiichi NPP in 2011. The threat of direct strike is more of a concern when it comes to the pool-type spent nuclear fuel storage or the sarcophagus containing the remnants of the destroyed Unit 4 at the ChNPP, which are not designed to be as robust as the containment structures over the operating reactors. There is also a risk that Ukraine may run out of available storage for its used nuclear fuel as it cannot currently transport spent fuel safely. Finally, the possibility that Russia may manufacture a radiological incident at the ZNPP or another facility to spoil a Ukrainian offensive should not be disregarded.

This report makes three sets of recommendations. The first relates to mitigating the immediate risks posed to nuclear infrastructure in Ukraine. The second relates to strengthening regulations, standards and other considerations to mitigate against potential threats to nuclear safety and security in conflict. The third relates to the conduct of military operations around NPPs.

To improve nuclear safety and security in Ukraine, the international community should:

- Ensure the personal safety and welfare of staff at NPPs, including sufficient staffing levels.
- Ensure sufficient licensed Ukrainian staff are ready to resume operations at the ZNPP following Russian withdrawal from the facility.
- Facilitate the safe transport of spent nuclear fuel to dry storage facilities, where appropriate.
- Assess availability of highly radioactive waste storage facilities and certify additional storage if needed.

- Provide chemical, biological, radiological and nuclear, emergency response and other necessary equipment, training and support to the Ukrainian military, emergency services and NPP operators.
- Provide regular updates on the supply of fuel for emergency generators at Ukrainian nuclear facilities, as well as the water levels in the Kakhovka Reservoir.
- Ensure the safe supply of diesel fuel, maintenance parts and services, and other materials necessary for the safe operation of Ukraine's NPPs.
- Penalise Rosatom staff operating at the ZNPP for participating in Russia's occupation of Ukraine.
- Establish deterrence against a deliberately manufactured radiological incident by making clear to Russia that any such incident would be followed by a massive response to mitigate damage and expanded support for Ukraine's war effort.

To mitigate against potential threats to nuclear safety and security in future conflict, the international community should:

- Consider, and adopt the necessary prevention and mitigation measures for, state-level military conflict and occupation of nuclear facilities by an invading force as part of national threat assessments, design-basis threats and wider national defence and security planning.
- Include considerations on military attack and occupation of nuclear facilities in the International Atomic Energy Agency's nuclear safety and security standards.
- Harden physical protections in the design of new NPPs.
- Harden existing NPPs.

To ensure the safety and security of NPPs in areas of active operations, the international community should:

- Establish a 1-km demilitarised zone around NPPs.
- Grant special protected status to critical NPP safety, security and emergency response systems.
- Define an obligation for the establishment of deconfliction lines by militaries operating around NPPs, as well as the nuclear regulators or other responsible authorities in the concerned states.
- Establish regulations relating to effects of cyber and electromagnetic activities applied in the vicinity of NPPs.

Introduction

RUSSIA'S FULL-SCALE INVASION of Ukraine on 24 February 2022 led to widespread fears over the safety and security of nuclear power plants (NPPs) after Russian forces occupied two of Ukraine's five NPPs,[1] struck a nuclear research reactor in Kharkiv and severed power to a research reactor in Kyiv. Russia's invasion of Ukraine is the first time that operational NPPs have been the direct objectives of military operations. There are strong reasons to believe that similar challenges are likely to feature in future conflicts. The number of NPPs is expanding globally, and this may accelerate as countries seek to generate power while reducing their carbon emissions. As NPPs become a more prevalent source of energy production, and as energy itself becomes ever-more critical to the wider functioning of societies, warring states will likely seek to exert control over them. It is therefore important to consider how the international community should maximise the safety of NPPs in a conflict context.

This report aims to consolidate three interrelated discussions. First, it seeks to provide an overview of the safety risks extant in Russia's invasion of Ukraine, what the Ukrainian state has learned from its experiences and what measures may improve the safety of its NPPs during the ongoing conflict. Second, the report seeks to summarise civilian and military actors' existing obligations and approaches towards NPPs and identify conflicting imperatives that could expose NPPs to risk in future conflicts. Third, the report makes recommendations as to how states can improve the safety and security of their NPPs and how militaries should think about operating around these objects.

Methodology and Definitions

The methodology for this report involves four strands. First, the authors interviewed staff from Ukraine's NPPs, officials involved in Ukraine's energy infrastructure and governance, security officials responsible for assessing threats to Ukraine's NPPs, National Guard personnel responsible for the physical protection of the NPPs, and military personnel conducting operations in the vicinity of Ukraine's NPPs. The authors carried out many of these interviews in Ukraine in March 2023. Second, the report draws on physical inspection of Ukrainian nuclear facilities and observation of operations conducted in their vicinity in the summer of 2022. Third, the report draws on a review of publicly available information and assessments of the safety and security of Ukraine's nuclear infrastructure – before and since February 2022 – produced by the International Atomic Energy Agency (IAEA), Ukrainian authorities and other experts. Fourth, the report draws on a comparative survey of military doctrine and the historical record of military operations affecting NPPs both directly and indirectly. Academic literature and expert

1. The Zaporizhzhia Nuclear Power Plant (ZNPP) and the Chornobyl Nuclear Power Plant (ChNPP). The ChNPP has not been an operational power-generating NPP since 2000.

commentary and analysis on nuclear safety and security in conflict, including in the ongoing war in Ukraine, also informed this report.

The report is structured in three parts. The first is a narrative account and analysis of the safety and security issues that have arisen during Russia's invasion of Ukraine. The second surveys the extant governance of safety at NPPs, existing international standards relating to NPPs in conflict zones and the perspective of militaries as to how NPPs are relevant to military operations. The third outlines recommendations for how NPPs can be rendered safer in conflict scenarios and how militaries can best ensure this during operations.

The terms 'nuclear safety' and 'nuclear security' are used in this report according to their IAEA definitions:

- Nuclear safety refers to: 'The achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks'.[2]
- Nuclear security refers to: 'The prevention and detection of, and response to, criminal or intentional unauthorized acts involving nuclear material, other radioactive material, associated facilities or associated activities' and 'The prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive material or their associated facilities'.[3]

In the context of attacks on NPPs or supporting infrastructure during a military conflict, the distinction between nuclear safety and security can become blurred. Where either term may be relevant, the authors have used them together. When the discussion exclusively concerns one or the other, the terms have been used according to the above definitions.

The subject of nuclear safety and security encompasses a broad range of issues, not all of which are covered in this report. The report's primary focus is the threats to the safe operation of civilian nuclear facilities and to the physical integrity of nuclear facilities in conflict – and in the Ukrainian context in particular – with a view to understanding whether and how military operations may directly result in a radiological incident. As such, nuclear and radiological security issues as they pertain to the unauthorised removal of material from facilities – as well as matters related to unauthorised access to facilities, other than as part of military occupation of a facility – have been largely excluded from this report. Considerations of the application of IAEA safeguards at Ukrainian facilities are also not treated here. That is not to say that these matters are not relevant when discussing nuclear safety and security in the context of the war in Ukraine; in fact, there are serious, justified concerns over these issues. However, these were judged to be outside of this report's scope and deserve to be treated comprehensively in a separate publication.

2. International Atomic Energy Agency (IAEA), *IAEA Safety Glossary: Terminology Used in Nuclear Safety Protection*, 2018 Edition (Vienna: IAEA, 2019), pp. 155–56.
3. *Ibid.*

I. Risks to Nuclear Safety and Security in Ukraine

PRIOR TO THE full-scale Russian invasion in February 2022, more than 50% of Ukraine's domestic energy supply came from NPPs.[4] The country hosts 15 operational nuclear reactors for energy generation, with an additional two reactors located at research facilities and four reactors in permanent shutdown at Chornobyl. As such, the significant likelihood and impact of attacks on the country's nuclear infrastructure as part of the Russian invasion should have been evident from the start. In fact, the capture of Ukraine's NPPs was a key objective in Russian military planning for the invasion.[5] The Chornobyl NPP (ChNPP) and surrounding Exclusion Zone – the site of the 1986 nuclear disaster – is located on Ukraine's border with Belarus and straddled the Russian military's axis of advance from Gomel to Kyiv. Despite this, the Ukrainian government does not appear to have significantly adjusted its forces to defend its NPPs in the lead-up to the full-scale invasion, nor could the authors ascertain the existence of any extant procedures for defending the country's operating NPPs under the conditions of a military conflict.

The physical protection of Ukraine's critical national infrastructure (CNI) – including its NPPs – is the responsibility of the National Guard of Ukraine, a unit of which is stationed at each NPP.[6] Until the full-scale invasion, these units were structured, trained and equipped primarily to protect facilities from terrorist threats, theft and sabotage.[7] This is largely in line with international standards, as the defence of NPPs against an invading military is not covered by the international nuclear safety and security regime. Ukraine had conducted a design-basis threat (DBT) for nuclear facilities, nuclear material, radioactive waste and other radiation sources in August 2015 and reportedly took into account the threats emanating from the Russian incursion into Donbas.[8] DBTs for individual NPPs were also conducted in recent years.[9] The authors also

4. State Nuclear Regulatory Inspectorate of Ukraine (SNRIU), 'Доповідь про стан ядерної та радіаційної безпеки в Україні у 2021 році' ['Report on the State of Nuclear and Radiation Safety in Ukraine in 2021'], 2021, p. 5, <https://snriu.gov.ua/storage/app/sites/1/uploaded-files/dopovid2021compressed-2.pdf>, accessed 13 April 2023.
5. Mykhaylo Zabrodskyi et al., 'Preliminary Lessons in Conventional Warfighting from Russia's Invasion of Ukraine: February–July 2022', RUSI, November 2022, p. 11.
6. Law of Ukraine on the National Guard, No. 876-VII, 13 March 2014 (amended 12 January 2023).
7. Author interview with senior member of the Ukrainian National Guard responsible for the protection of the Chornobyl Nuclear Power Plant (ChNPP) (A), Ukraine, March 2023.
8. Dmytro Chumak, 'The Implications of the Ukraine Conflict for National Nuclear Security Policy', Non-Proliferation Paper No. 53, EU Non-Proliferation Consortium, November 2016.
9. SNRIU, 'Доповідь про стан ядерної та радіаційної безпеки в Україні у 2021 році' ['Report on the State of Nuclear and Radiation Safety in Ukraine in 2021'], p. 31.

heard that an updated DBT assessment was apparently completed in 2022 but may not have been approved as of early 2023.[10] The sensitive nature of these assessments has also meant that the authors could not confirm what specific threats were identified in 2015 or more recently. DBTs normally include only those threats to a nuclear facility's physical security that the facility's operator can reasonably address and focus on unauthorised access to the facility, sabotage, terrorist attack or theft of material.[11] Defence against military attack is generally deemed to be beyond the DBT and is the primary responsibility of state authorities, and should be addressed as part of the country's wider defence and security planning.

However, it is clear that Ukrainian authorities were aware of threats to the security of nuclear facilities and material in the country following Russia's annexation of Crimea and the breakout of military activity in eastern Ukraine in 2014. In its 'National Progress Report' to the 2016 Nuclear Security Summit, Ukraine outlined efforts it had taken to strengthen the physical protection of nuclear facilities, nuclear material, radioactive waste and other sources of ionizing radiation.[12] However, based on the threats and mitigation measures addressed in that report, the primary focus appears to have been dealing with lower-level threats such as political instability and sabotage, not accounting for a Russian military assault on – or occupation of – NPPs.

In its 2021 report on the state of nuclear and radiological safety in Ukraine, the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) noted that its assessment of threats to the physical protection of nuclear facilities and material in Ukraine considered Russian military activity in eastern Ukraine and 'hybrid' socio-political threats.[13] According to the report, measures were taken to strengthen the physical protection of facilities and radioactive material in transport, facility access control was improved, and protection personnel underwent training for countering terrorism and sabotage threats. The report also highlighted the role of the National Guard in the protection of nuclear facilities and noted that inspections carried out that year concluded that the detachments responsible for NPP protection demonstrated 'sufficient levels of readiness to perform their obligations in the prevention of acts of terrorism or sabotage against NPPs'.[14] The authors could not ascertain any assessment as to the preparedness of the National Guard, or any other national preparations, to defend against full-scale military attack on facilities; although, due to its sensitive nature, such information is unlikely to be reported publicly.

The apparent failure to put in place a more substantial defence of NPPs against invading forces raises questions. Speaking to personnel responsible for the safety and security of Ukraine's

10. Author email correspondence with leading Ukrainian nuclear energy expert (F), Ukraine, April 2023.
11. Joseph S Sandoval et al., 'Threat Assessment and Design Basis Threat Briefing', Version 2 Draft, US Department of Energy, Office of Scientific and Technical Information, 5 February 2021.
12. Nuclear Security Summit, 'National Progress Report: Ukraine', 31 March 2016, <https://www.nss2016.org/document-center-docs/2016/3/31/national-progress-report-ukraine>, accessed 13 April 2023.
13. SNRIU, 'Доповідь про стан ядерної та радіаційної безпеки в Україні у 2021 році' ['Report on the State of Nuclear and Radiation Safety in Ukraine in 2021'], p. 31.
14. *Ibid.*

Power infrastructure at the Chornobyl Nuclear Power Plant, Ukraine, June 2022. *Courtesy of Jack Watling*

NPPs, it is evident that they had not enacted special measures in anticipation of conflict prior to 24 February 2022. The fact that senior Russian agents in Ukraine had obscured the threat to the Ukrainian authorities may partly explain this. Ukraine's state security service (SBU) and the US government accuse Andriy Derkach, former head of the state enterprise Energoatom,[15] of working as a long-term Russian agent along with senior SBU officers including Brigadier General Andriy Naumov who was also involved in the security of Ukraine's energy infrastructure.[16] Perhaps reflecting this internal distortion of the Ukrainian state's risk perception, Ukraine's minister of energy stated, not long before Russian forces captured the Zaporizhzhia Nuclear Power Plant (ZNPP), that the facility did not face a serious threat.[17]

15. Ukrainian Energy Ministry, 'Президентом НАЕК "Енергоатом" став Андрій Деркач' ['Andriy Derkach Has Become President of NAEK Energoatom'], 9 October 2006, <http://mpe.kmu.gov.ua/minugol/control/publish/article?art_id=103164>, accessed 4 March 2023.
16. *Hromadske*, 'SBU Exposes Russian Intelligence Network in Ukraine, which Includes MP Andriy Derkach', 24 June 2022, <https://hromadske.ua/en/posts/sbu-exposes-russian-intelligence-network-in-ukraine-which-includes-mp-andriy-derkach>, accessed 4 March 2023. For more on the role of Ukraine's nuclear infrastructure and entities connected to the Ukrainian nuclear sector in Russia's preparation for the invasion of Ukraine, see Jack Watling, Oleksandr V Danylyuk and Nick Reynolds, 'Preliminary Lessons from Russia's Unconventional Operations During the Russo-Ukrainian War, February 2022–February 2023', RUSI, 29 March 2023.
17. Віолетта Орлова [Violetta Orlova], 'Міністр енергетики Галущенко запевнив, що АЕС в Енергодарі надійно охороняється' ['Minister of Energy Galushenko Assured that the NPP in Energodar is Reliably Guarded'], *Українське Незалежне Інформаційне Агентство Новин* [*Ukrainian Independent Information Agency*], 3 March 2022, <https://www.unian.ua/war/ministr-

Crossing into Ukraine from Belarus on the morning of 24 February, Russian military forces seized the ChNPP within hours. As the Russians approached the NPP, Valentin Vitter, deputy head of security of the Chornobyl Exclusion Zone, called the National Guard detachment responsible for the protection of the NPP and ordered its surrender, citing the risk to the station as the combined arms armies of Russia's Eastern Military District rolled over the border.[18] As a senior officer in the unit noted, 'we were facing down a Blitzkrieg with pistols'.[19] Two things quickly became evident: Moscow had long planned to seize the site; and the Russian military was woefully unprepared for operating around a nuclear facility. Russia's special services seized the plant's archives and all data held at the facility.[20] The Ukrainian workforce was held hostage to maintain facility operations. Russian troops proceeded to establish a command post and supply base in close proximity to the NPP. Given the plentiful availability of structures suitable for establishing command and supply activities within the 30-km Exclusion Zone, the authors assess the decision to site these functions by the NPP to have been deliberate, and with the aim of using the facility as a shield. Alongside these clearly planned actions, Russian units dug trenches within the Exclusion Zone, digging up radioactive particles that had settled into the soil since the 1986 disaster, dragging them around the site and facility buildings and raising the radiation levels in the zone.[21]

By 3 March, Russian forces from the Southern Military District had reached the ZNPP and set about occupying the facility. Ukrainian forces marked the facility with spotlights at night, shining them directly upwards in an attempt to indicate its location for troops.[22] Despite these measures, Russian forces hit the site's training facility with tank rounds and caused a fire.[23] The risk to the civilian population in the nearby towns from conducting active military defence of the NPP led the National Guard unit tasked with defending the facility to withdraw. As at the ChNPP, the Russians rapidly set about placing military supply vehicles and command-and-control systems in the ZNPP's immediate vicinity. According to the IAEA, military equipment and stores were still present within the turbine halls of ZNPP Units 1 and 2 as of February 2023.[24] Ukrainian plant employees were forced to continue operating the facility without rotation and under duress, with some being detained by Russian forces.

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energetiki-galushchenko-zapevniv-shcho-aes-v-energodari-nadiyno-ohoronyayetsya-novini-vtorgnennya-rosiji-v-ukrajinu-11727934.html>, accessed 4 April 2023.

18. Mari Saito and Maria Tsvetkova, 'The Enemy Within', *Reuters*, 24 February 2022.
19. Author interview with A, Ukraine, March 2023.
20. Author interviews with representatives of the Chornobyl Central Enterprise for the Management of Radioactive Waste (B), Ukraine, March 2023.
21. *Reuters*, 'Unprotected Russian Soldiers Disturbed Radioactive Dust in Chernobyl's "Red Forest", Workers Say', 29 March 2022.
22. Author interview with senior member of Ukrainian Air Defence Forces (D), Ukraine, March 2023.
23. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', 23 February 2023, <https://www.iaea.org/sites/default/files/23/02/nuclear-safety-security-and-safeguards-in-ukraine-feb-2023.pdf>, accessed 16 April 2023, p. 5; author interview with a recent Zaporizhzhia Nuclear Power Plant (ZNPP) employee (E), Ukraine, March 2023.
24. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', p. 11.

While Russian forces departed from the ChNPP at the end of March 2022, the ZNPP remains under Russian control at the time of writing. The ongoing military operations around the facility, as well as the broader state of war across the country, pose significant threats to nuclear safety and security in Ukraine.

Assessing Safety and Security Risks During the Invasion

The threats that the military invasion posed to Ukraine's nuclear facilities became clear immediately, with additional risks becoming apparent over time. On the day of the invasion and Russia's seizure of the ChNPP, the IAEA lost connection with the site's radiation monitoring network.[25] Two days later, on 26 February, the ZNPP lost power supply from one of its four external power lines.[26] On 4 March, Russian forces took control of the ZNPP and – as described earlier – a projectile struck the plant's on-site training facility, resulting in a localised fire breaking out a few hundred metres from the reactor units.[27] On 6 March, the ZNPP lost power supply from another one of its external power lines.[28] Many other incidents have occurred over the past 15 months that have placed the safety and security of Ukrainian nuclear facilities at risk and raised international concerns over potential consequences. More recently, a Russian mine reportedly exploded near the engine room of a ZNPP reactor unit,[29] and IAEA personnel stationed at the ZNPP in mid-April 2023 have reported hearing daily shelling.[30] The risks of both an accidental and intentional radiological incident are considered below.

Strikes on Reactor Units

The 1986 disaster at the ChNPP still looms large in public memory; as such, it is unsurprising that the accident has repeatedly been used as a point of reference when the potential consequences of Ukraine's NPPs getting caught in the crossfire of the ongoing conflict are discussed.[31] However, the likelihood of a 1986-scale disaster is low. Unlike the graphite-moderated RBMK (*reaktor bolshoy moschnosti kanal'niy*, high-power channel-type reactor) reactors at Chornobyl – now all decommissioned – Ukraine's operating NPPs host water-cooled and moderated VVER (*vodo-vodyanoi energeticheskiy reaktor*, water-water power reactor) reactors, which are much less prone to some of the factors resulting from reactor malfunction and human error that caused

25. *Ibid.*, p. 5
26. *Ibid.*
27. *Ibid.*
28. *Ibid.*
29. *Reuters*, 'Russian Mine Exploded Near Ukraine Nuclear Plant, Operator Says', 13 April 2023.
30. IAEA, 'Update 154 – IAEA Director General Statement on Situation in Ukraine', 21 April 2023, <https://www.iaea.org/newscenter/pressreleases/update-154-iaea-director-general-statement-on-situation-in-ukraine>, accessed 27 April 2023.
31. Harrison Jones, 'Fears of Chernobyl-Style Disaster if Europe's Largest Nuclear Plant Targeted Again', *Metro*, 9 August 2022; Julian Hayda, 'Ukraine Still Fears Another Chernobyl-Size Disaster at Europe's Largest Nuclear Plant', *NPR*, 11 December 2022.

and exacerbated the Chornobyl accident.[32] The release and dispersion of highly radioactive material at a scale comparable to the Chornobyl disaster would require the penetration of a facility housing radioactive material – namely, a reactor or a spent-fuel storage facility – and the large-scale release of that material into the atmosphere and surrounding environment, likely assisted by plumes of smoke from a fire. While this is technically possible, the authors judge it to be unlikely for reasons described below.

An accidental hit on a reactor unit or a dry spent-fuel storage facility under the current state of military activity around Ukrainian NPPs is unlikely to cause a major radiological incident. The reactors currently operating at Ukrainian NPPs are located within reinforced containment structures, as per IAEA standards. These structures are designed to withstand significant internal and external hazards, including fires, explosions, earthquakes and radioactive release from other accidents. When it comes to loads from external impacts, the IAEA standards require reactor containment structures to be robust enough to withstand the force of an aircraft crashing into them.[33] Ukraine's dry spent-fuel storage facilities at the ZNPP and ChNPP are also protected in reinforced concrete structures. According to one recent ZNPP employee, a control cask at the NPP's dry fuel storage – used to monitor the state of the other casks at the facility over time – was struck by artillery shrapnel during an exchange of fire but did not sustain significant damage.[34] The authors could not verify the accuracy of this account, but it is consistent with expert analysis of the threat to dry spent-fuel storage from external impact. Furthermore, the spent fuel in dry storage facilities has been cooled for some time and is therefore significantly less radioactive than fuel inside a reactor core or the more recently withdrawn spent fuel stored in pool-type wet storage facilities.

Artillery fire, which has been the primary military threat to Ukraine's NPPs since the full-scale invasion, is unlikely to cause any serious damage to the integrity of the containment or dry spent-fuel storage structures.[35] The most widely employed fires throughout the conflict have been high-explosive artillery rounds intended to deliver fragmentation and overpressure effects against enemy personnel. Other classes of rounds employed – such as sensor-fused sub-munitions – are designed to find and strike objects with specific characteristics, such as vehicles, and would not be effective against the containment structure.

Penetrating a containment structure and, subsequently, a reactor core would require applying significant and targeted firepower. Bunker-busting rounds such as HESH (high-explosive squash

32. For example, see Mikhail V Malko, 'The Chernobyl Reactor: Design Features and Reasons for Accident', in Imanaka T (ed.), 'Recent Research Activities About the Chernobyl NPP Accident in Belarus, Ukraine and Russia', 2016, <http://www.rri.kyoto-u.ac.jp/PUB/report/04_kr/img/ekr010.pdf>, accessed 18 April 2023.
33. IAEA, *Design of the Reactor Containment and Associated Systems for Nuclear Power Plants*, Specific Safety Guide, No. SSG-53, IAEA Safety Standards Series (Vienna: IAEA, 2019), p. 7ff, Table 1.
34. Author interview with E, Ukraine, March 2023.
35. Author interview with A, Ukraine, March 2023.

head) munitions, armour-piercing rounds including APFSDS (armour-piercing fin-stabilised discarding sabot) kinetic penetrators and other direct-fire weapons including anti-tank guided weapons (ATGWs) could risk compromise to the facility, especially if repeated hits were delivered against the structure. Missiles with warheads intended to destroy hardened structures and especially hypersonic strikes from ballistic missiles could also pose a threat to the facility. Heavy air-delivered ordnance may compromise the containment structure. Nevertheless, this would likely require multiple hits, and since these are precision weapons or weapons employed against specific target classes, their use against an NPP would not be accidental. It is important to note that there is no effective means of preventing hits from ballistic missiles, since air and missile defences can only ensure partial protection.

Thus, while deliberate compromise of Ukrainian reactor units or dry spent-fuel storage facilities resulting in a significant radiological incident is possible, incidental or accidental compromise is far less likely. The authors judge such an intentional strike unlikely but not unimaginable. Circumstances in which deliberate sabotage of nuclear facilities may occur are discussed later in this report.

Two facilities at the ChNPP do not benefit from the same level of hardened protection as the reactors and dry storage sites, and may be more likely to sustain serious damage from lighter fire or accidental hits. These are the ChNPP's Interim Spent Fuel 1 facility (ISF-1) and the New Containment Structure (NCS): the enormous concrete and steel sarcophagus containing the remnants of the reactor at Unit 4, destroyed during the 1986 disaster. Unlike the dry spent-fuel storage facilities at the ChNPP and the ZNPP, ISF-1 – a wet spent-fuel storage facility – is not hardened or housed within a reinforced containment structure.[36] Constructing a containment structure to protect ISF-1 would be costly, time consuming and impractical to do while hostilities are ongoing and Russian forces and artillery remain stationed just a few kilometres away in Belarus.[37] The most practical solution would be to move the spent fuel from ISF-1 into the significantly better reinforced new dry spent-fuel storage facility – ISF-2 at the ChNPP. In fact, the transfer of spent fuel from ISF-1 to ISF-2 began in November 2020, as the former is not designed for long-term fuel storage and is running out of space to accept new spent fuel. The process was expected to take 10 years under peacetime conditions.[38] However, transfer of fuel stopped after the full-scale invasion. As the ChNPP is located within range of Russian artillery, moving fuel between the two facilities has been deemed too dangerous.[39]

Equally, although the NCS over Unit 4 is an impressive and robust structure designed to withstand earthquakes and class-3 tornados,[40] it is not designed to withstand the same kinds of loads or

36. Author observations from the site, Chornobyl, June 2022.
37. Author interview with A, Ukraine, March 2023.
38. *Ibid.*; author interview with a senior employee of the Chornobyl Zone Administration (I), Chornobyl, June 2022.
39. *Ibid.*
40. European Bank for Reconstruction and Development, 'Chernobyl's New Safe Confinement', <https://www.ebrd.com/what-we-do/sectors/nuclear-safety/chernobyl-new-safe-confinement.

impact as the containment structures of operational reactors. While Unit 4 at ChNPP has not been operational since the 1986 accident, what remains of the reactor is still highly radioactive. The installation of the NCS, which was completed in 2016, is designed to prevent the spread of radioactive particles from the damaged reactor. An attack on, and penetration of, the NCS and the old sarcophagus – which was built hastily over the Unit 4 reactor immediately following the accident and is now enclosed within the NCS – would cause the release of radioactive particles into the surrounding area and atmosphere. One member of the Ukrainian National Guard responsible for the protection of the ChNPP stated such an accident would essentially produce 'a massive dirty bomb'.[41]

Senior staff of the Chornobyl Central Enterprise for the Management of Radioactive Waste raised similar concerns regarding potential attacks on the other radioactive waste storage facilities, such as the one at Buryakivka village in the Chornobyl Exclusion Zone.[42] The authors also heard concerns over Ukraine's ability to store any radioactive waste that may result from an accident at an NPP – whether at the ChNPP or at any of the country's other facilities. According to the representatives of the Chornobyl Central Enterprise for the Management of Radioactive Waste, there is currently a shortage of storage for highly radioactive materials in Ukraine.[43] New storage facilities can be constructed but any such effort will require extensive resources, as well as a lengthy risk assessment and other government review and approval processes.[44]

Risks to NPP Power and Water Supply

The penetration of NPP structures housing radioactive materials by munitions is not the only risk to nuclear safety and security in Ukraine posed by the ongoing conflict. The interruption of systems critical to the safe operation of Ukraine's NPPs – namely, the supply of water and electricity – creates significant risks and may result in a scenario similar to the 2011 accident at Japan's Fukushima Daiichi NPP. In that instance, a 9.0 magnitude earthquake caused the automatic shutdown and loss of external power supply at the NPP's light water reactors. The earthquake was followed by a tsunami, which caused the failure of emergency power generators. With no power available to cool the reactor fuel, the units experienced nuclear fuel meltdown and hydrogen explosions (caused by zirconium reacting with the steam that resulted from rising temperatures in the reactors).[45] Only one of the containment structures housing the NPP's reactors was breached, releasing radioactive material into the atmosphere. Nevertheless, more than 100,000 people had to be relocated as a result of radioactive contamination in the areas around the reactor.

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html>, accessed 18 April 2023.

41. Author interview with A, Ukraine, March 2023.
42. Author interview with B, Ukraine, March 2023.
43. *Ibid.*
44. *Ibid.*
45. For more on what happened at Fukushima, including details on the fuel meltdown and hydrogen explosions, see David Biello, 'Partial Meltdowns Led to Hydrogen Explosions at Fukushima Nuclear Power Plant', *Scientific American*, 14 March 2011.

The ferris wheel in the abandoned city of Pripyat, Ukraine, June 2022. *Courtesy of Jack Watling*

Should reactors lose access to electricity or water supply for an extended period, Ukraine's NPPs may face similar consequences. Since the start of the full-scale invasion and as of the drafting of this report, the ZNPP has lost external power supply six times – most recently on 9 March 2023. The ChNPP lost external power supply on 9 March 2022 and again on 23 November 2022, when Russian attacks on Ukraine's national electrical grid also resulted in power outages at all of the country's other NPPs. In all instances, on-site diesel power generators were able to maintain power supply to the reactor units.

A reliable supply of power is critical for the safe operation of nuclear reactors. Reactor fuel is extremely hot and must be constantly cooled to avoid melting and causing a Fukushima-like nuclear meltdown. The cooling process involves pumping cold water into the first circuit of the reactor and removing hot water with powerful pumps. The heat is then removed using a heat exchange system; at the ZNPP, this process currently relies on water from the Dnipro River. In the case of a power loss, these pumps stop operating, thus halting the circulation of water through the reactor's first circuit, risking an overheating of the reactor core and subsequent melting of the reactor's fuel.

A constant supply of coolant is needed even when reactors are in cold shutdown – as is the case with four of Ukraine's 15 power units (one additional ZNPP reactor, previously in hot shutdown, is reportedly also being moved into cold shutdown as of the time of drafting)[46] – as the nuclear fuel remains extremely hot. The same is true of spent fuel which has been removed from a

46. IAEA, 'Update 153 – IAEA Director General Statement on Situation in Ukraine', 13 April 2023, <https://www.iaea.org/newscenter/pressreleases/update-153-iaea-director-general-statement-on-situation-in-ukraine>, accessed 16 April 2023.

reactor core; depleted fuel assemblies continue to release significant amounts of heat and must be cooled in water for some time before they can be transferred to dry fuel storage. However, as experts have rightly pointed out, the ZNPP reactors have been in shutdown for months, meaning their core temperatures are much lower than those of the reactors at the Fukushima Daiichi NPP at the time of the accident. As a result, they can be expected to remain safe for several days without power supply when in cold shutdown.[47] Ukrainian authorities offered a similar assessment to the authors. The same is true of spent-fuel facilities, as spent nuclear fuel will have had time to cool since it was extracted from the reactors. In the case of dry spent-fuel storage facilities, the spent fuel will have also spent some time in wet storage and had additional time to cool before being transferred to dry storage casks.

Another risk emanating from a loss of power stems from the need to manage the hydrogen produced by the operation of the reactors to prevent a hydrogen explosion. As a result of radiolysis of the water in the reactor, hydrogen is produced and must be removed from the reactor building. Its removal depends on the operation of powerful turbines, which require a constant supply of power. Should these turbines stop operating, gas build-up may lead to a Fukushima-like hydrogen explosion.[48]

Following the Fukushima accident, Ukrainian NPPs' safety systems and resistance to accidents were stress tested. The authors reviewed reports detailing the results and found that the tests carried out at the ChNNP and ZNPP were primarily focused on extreme natural events. They also included considerations around the loss of water or power supply in extraordinary conditions, some of which may be relevant to current conditions. A series of recommendations for improving the safety and emergency response systems at the NPPs were put forward following the stress tests,[49] and a National Action Plan for their implementation was developed in 2013. The

47. For a detailed discussion of the benefits and challenges of reactor shutdown to the safe operation of Ukraine's NPPs and the ZNPP in particular, see Mark Hibbs, 'The Narrow Field of Options for Safely Managing Ukraine's Zaporizhzhia Nuclear Power Plant', Bulletin of the Atomic Scientists, 10 March 2023.
48. Author interview with F, Ukraine, March 2023.
49. *Ibid.*; SNRIU, 'Постанова колегії про результати виконання цільової позачергової оцінки стану безпеки діючих енергоблоків АЕС та ССВЯП ЗАЕС з урахуванням подій на АЕС «Фукусіма-Даічі»' ['Resolution of the Board on the Results of the Targeted Non-Routine Assessment of the State of Safety of the Operating Power Units of the NPP and ZNPP Dry Spent Nuclear Fuel Storage, Taking into Account the Events at the Fukushima-Daiichi NPP'], 24–25 November 2011, accessed 13 March 2023; SNRIU, 'Постанова колегії щодо виконання ДСП «Чорнобильська АЕС» цільової позачергової оцінки стану безпеки енергоблоків 1+3 та СВЯП-1 з урахуванням подій на АЕС «Фукусіма-1»', ['Resolution of the Board Regarding the Execution of the Chernobyl NPP Specialised State Enterprise Targeted Emergency Assessment of the Safety Status of Power Units 1+3 and IFS-1, Taking into Account the Events at the Fukushima-1 NPP'], 3 November 2011, accessed 13 March 2023; SNRIU, 'Updated National Action Plan Upon Stress-Test Results', 2021, <https://www.ensreg.eu/sites/default/files/attachments/stress_test_nacp_ukraine_2021.pdf>, accessed 18 April 2023.

recommendations included: the placement at NPPs of additional emergency diesel generators and mobile water pumps which can maintain water circulation for heat removal in case of a loss of external power; the strengthening of containment structures; and the installation of radionuclide filters and hydrogen recombiners to reduce the likelihood of hydrogen explosions. As of 2021, 80% of the safety improvement measures outlined in the National Action Plan had been completed, with the rest expected to be finalised by 2024.[50] It is unclear how the Russian invasion has affected this timeline.

While emergency diesel generators have been able to maintain power supply to Ukraine's NPPs following every instance of external power supply loss so far, repeatedly relying on backup generators to maintain the safe operation of an NPP is a very dangerous game to play – especially in a conflict situation. The supply of diesel fuel at NPPs is not infinite and may be difficult to replenish if there are challenges in accessing the facility or there is a general diesel shortage across the country. According to one senior Ukrainian government official with responsibility for the country's chemical, biological, radiological and nuclear (CBRN) defence and security, in early March 2023, the ZNPP had sufficient fuel supply to keep the 18 emergency generators required to maintain power to its six reactor units for about 10 days.[51] This figure is likely an estimate, as Ukrainian authorities have admitted to having limited information on the situation at the Russian-occupied ZNPP and it is possible that Russian personnel have supplied the facility with additional fuel. Fuel levels also vary over time, as fuel is used up by generator operation and new supply is delivered. In November 2022, the IAEA reported that the ZNPP had fuel to operate the diesel generators for about 15 days.[52] The Ukrainian official's comments and lack of definitive information on the fuel supply highlight the precarious power supply situation at the ZNPP. Emergency systems are also designed to prioritise the safe operation of the NPP, not the supply of power to secondary facilities such as administrative buildings and staff facilities.[53] Loss of external power supply may therefore also pose challenges to staff wellbeing and their ability to conduct their work effectively. Staff morale and wellbeing issues pose a significant risk to the safe operation of NPPs and are discussed later in the report.

50. SNRIU, 'Updated National Action Plan Upon Stress-Test Results', 2021.
51. Author interview with a senior Ukrainian military official responsible for chemical, biological, radiological and nuclear (CBRN) defence (H), Ukraine, March 2023.
52. IAEA, 'Ukraine's Zaporizhzhya Nuclear Power Plant Lost Off-Site Power Again, Diesel Generators Providing Back-Up Electricity', IAEA, press release, 3 November 2022, <https://www.iaea.org/newscenter/pressreleases/ukraines-zaporizhzhya-nuclear-power-plant-lost-off-site-power-again-diesel-generators-providing-back-up-electricity>, accessed 16 April 2023.
53. Author interview with E, Ukraine, March 2023.

Besides the threat posed by loss of power to Ukraine's nuclear reactors, water supply to the ZNPP may also be at risk. In February 2023, the IAEA reported that water levels at the Kakhovka Reservoir on the Dnipro River have been dropping.[54] The reservoir supplies water to the cooling ponds that are part of the system which is used to remove heat from the ZNPP's reactors and spent-fuel storage facility.[55] Water in the reservoir is normally maintained at a higher level than in the ponds, which facilitates the ponds' replenishment and maintains reliable supply of water for cooling the reactor and spent-fuel storage, without which the reactor core and spent fuel risk overheating. In a statement in mid-February, Energoatom reported that water levels in the reservoir stood at 13.8 metres – well below their normal 16 metres. At the time, the head of Energoatom, Petro Kotin, stated that 'a level of 12.8 meters will be [an] emergency, and 12 meters will be critical'.[56] According to the authors' consultations with two Ukrainian experts in early March 2023, including a recent ZNPP employee, water in the reservoir had by then dropped to below pool levels and may have even fallen below the 12.8-metres mark.[57] The authors could not confirm this independently. As the weather begins to warm in the spring and summer, evaporation from the reservoir and pool may exacerbate the issue.[58] However, in its report from 21 April, the IAEA noted that water levels had returned to 16.2 metres.[59] In an earlier report, the Agency had attributed rising water levels to melting snow over the previous months.[60] One senior expert with intimate knowledge of ZNPP operations consulted by the authors in March 2023 did not perceive the water levels cited at the time to pose an immediate threat to the safe operation of the facility.[61]

Staff Wellbeing and Safe Operation of NPPs

Another critical threat to the safe operation of the country's NPPs – which has received significant attention from the IAEA in its public reporting on nuclear safety and security in Ukraine since the full-scale invasion – is the duress under which NPP staff are having to operate. As the IAEA has highlighted, staff across all Ukrainian NPPs are having to carry out their duties while 'dealing with the burdens imposed on their personal lives by the ongoing armed conflict, as well as with

54. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', 23 February 2023, p. 10.
55. Edwin Lyman, 'One Year Later, New Dangers Threaten Ukraine's Embattled Zaporizhzhia Nuclear Plant', Bulletin of the Atomic Scientists, 28 February 2023.
56. *Nuclear Newswire*, 'Low Water Level at Reservoir May Pose Threat to Zaporizhzhia', 15 February 2023.
57. Author interview with F, Ukraine, March 2023; author interview with E, Ukraine, March 2023.
58. Author interview with F, Ukraine, March 2023.
59. IAEA, 'Update 154 – IAEA Director General Statement on Situation in Ukraine', 21 April 2023.
60. IAEA, 'Update 153 – IAEA Director General Statement on Situation in Ukraine', 13 April 2023, <https://www.iaea.org/newscenter/pressreleases/update-153-iaea-director-general-statement-on-situation-in-ukraine>, accessed 16 April 2023.
61. Author interview with a senior expert with intimate knowledge of ZNPP operations (K), March 2023.

constant stress and anxiety'.[62] Such conditions undoubtedly negatively affect staff's ability to effectively perform what is – in normal times – high-pressure work that requires precision and the ability to confidently make high-stake decisions. Literature has pointed to the important role that the human factor plays in safe NPP operation.[63] A 2021 report on the state of radiological and nuclear safety in Ukraine notes that 18.5% of abnormal events in NPP operations that year were due to human error.[64] It was 13% the previous year.[65] In 2017, it had peaked as high as 41%.[66] Operating under the stresses of military conflict and occupation risks exacerbating the impact of human error in the operation of Ukraine's NPPs.

The situation is particularly acute at the ZNPP. The facility is located on the frontline of the conflict and has been under Russian occupation since early March 2022. As such, the NPP's Ukrainian staff are having to carry out their duties amid an active war zone and in the presence of Russian military personnel. ZNPP staff on duty when Russian forces invaded the facility were not able to maintain normal rotations. Similarly, ChNPP staff remained on duty indefinitely when the Russian military took over the facility on 24 February 2022. As of March 2023, staff at the occupied ZNPP facility were reportedly being rotated regularly, although still working longer hours and more shifts.[67] Several staff at the ZNPP – including the head of the power plant at the time, Ihor Murashov – have been detained.[68] Media reporting has also recounted instances of torture of ZNPP staff.[69]

62. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', 23 February 2023, p. 19.
63. E Swaton, V Neboyan and L Lederman, 'Human Factors in the Operation of Nuclear Power Plants: Improving the Way Man and Machines Work Together', *IAEA Bulletin* (No. 4, 1987), p. 28; B S Dhillon, *Safety, Reliability, Human Factors, and Human Error in Nuclear Power Plants* (Abingdon: Routledge, 2018).
64. SNRIU, 'Доповідь про стан ядерної та радіаційної безпеки в Україні у 2021 році' ['Report on the State of Nuclear and Radiation Safety in Ukraine in 2021'], 2021, p. 9, <https://snriu.gov.ua/storage/app/sites/1/uploaded-files/dopovid2021compressed-2.pdf>, accessed 19 April 2023.
65. SNRIU, 'Доповідь про стан ядерної та радіаційної безпеки в Україні у 2019 році' ['Report on the State of Nuclear and Radiation Safety in Ukraine in 2019'], 2020, p. 30, <https://snriu.gov.ua/storage/app/sites/1/docs/shorichna_dopovid_pro_stan_yadernou_ta_radiacijnoi_bezpeky/_2019_ukr.pdf>, accessed 19 April 2023.
66. SNRIU, 'Доповідь про стан ядерної та радіаційної безпеки в Україні у 2017 році' ['Report on the State of Nuclear and Radiation Safety in Ukraine in 2017'], p. 28, <https://snriu.gov.ua/storage/app/sites/1/docs/shorichna_dopovid_pro_stan_yadernou_ta_radiacijnoi_bezpeky/Annual%20report%202017.pdf>, accessed 19 April 2023.
67. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', 23 February 2023, p. 11.
68. Ihor Murashov was released on 2 October 2022, after several days of detention. See Karl Mathiesen, 'Head of Zaporizhzhia Nuclear Plant Released After Russian Detainment', *Politico*, 3 October 2022.
69. Richard Spencer, 'Zaporizhzhia Nuclear Plant: Workers Tell of Torture by Russian Troops', *The Times*, 20 April 2023.

One former ZNPP employee, who had been working at the NPP during the Russian occupation, recounted to the authors the psychological stress staff experienced. According to them, staff movement around the NPP – previously unrestricted – had to be coordinated with units of the Russian National Guard that had been stationed at the NPP after the invasion.[70] At times when fire was being exchanged, NPP staff had to shelter in place – often for hours at a time.[71] The occupying forces also reportedly did not allow staff to vacate technology or personal belongings from the parts of the facility which they moved into.[72] Staff from the ChNPP also told the authors that, on returning to the NPP following Russian withdrawal, they found much of their personal belongings and facility equipment looted. What technology the Russian forces did not take with them from the ChNPP, they apparently destroyed.[73]

Russian state-owned enterprise Rosatom is present at the ZNPP and has taken over management of the facility. The company was also present at the ChNPP during Russia's occupation of the facility.[74] Ukrainian authorities and experts, as well as the former ZNPP employee, confirmed to the authors that Rosatom has been forcing Ukrainian staff at the ZNPP to sign contracts with the company to retain their jobs (although it appears that Rosatom may have recently stopped requiring Ukrainian staff to be employed by the enterprise to continue working at the plant, presumably to mitigate staff shortages[75]). Many Ukrainian staff refused and left employment at the ZNPP. Others have left the ZNPP and the nearby town of Energodar due to the obvious threats to safety and security inherent to an active conflict zone. Those that have chosen to continue working at the ZNPP face pressure – and may risk penalties – from Ukrainian authorities for collaborating with Russia.[76] Despite reported attempts by Rosatom to recruit replacement staff – including nuclear experts from Russia – staff levels at the ZNPP are significantly below pre-invasion levels. Prior to the February 2022 invasion, the ZNPP hosted, by various accounts, between 10,000 and 11,000 staff; by the start of 2023, only 3,000 personnel reportedly remained.[77]

70. Author interview with E, Ukraine, March 2023.
71. *Ibid.*
72. *Ibid.*
73. Author interview with A, Ukraine, March 2023; author interviews with B, Ukraine, March 2023.
74. *Ibid.*; IAEA, 'Update 19 – IAEA Director General Statement on Situation in Ukraine', 12 March 2022, <https://www.iaea.org/newscenter/pressreleases/update-19-iaea-director-general-statement-on-situation-in-ukraine>, accessed 16 April 2023; Yogita Limaye, 'Inside Chernobyl: We Stole Russian Fuel to Prevent Catastrophe', *BBC News*, 9 April 2022.
75. IAEA, 'Update 153 – IAEA Director General Statement on Situation in Ukraine', 13 April 2023, <https://www.iaea.org/newscenter/pressreleases/update-153-iaea-director-general-statement-on-situation-in-ukraine>, accessed 16 April 2023.
76. Author interview with F, Ukraine, March 2023.
77. *Ibid.*; Nuclear Energy Agency, 'Ukraine: Current Status of Nuclear Power Installations', 14 April 2023, <https://www.oecd-nea.org/jcms/pl_66130/ukraine-current-status-of-nuclear-power-installations>, accessed 18 April 2023

Each reactor is unique and requires highly specialised staff specifically licensed to operate a given facility, making the replacement of ZNPP staff challenging. A number of Ukrainian experts also highlighted to the authors that the originally Soviet-designed ZNPP control rooms have since been modernised and differ significantly from Russian facilities, apparently making them challenging to navigate for Russian staff not trained to operate them.[78] Finally, the threat of being sanctioned for participating in Russia's invasion of Ukraine appears to be deterring potential replacement personnel from taking up employment at the ZNPP.[79]

It is worth noting that, prior to the invasion, the ZNPP was operating with some redundancy in its staffing, and that certain staff were carrying out roles that would not have been directly critical to the safe operation of the facility and even less so in its current shutdown state. As such, current staff numbers may technically be sufficient for the operation of the ZNPP in its current state. However, there is no doubt that this significant reduction in staff and expertise creates additional pressures, stress and fatigue for the Ukrainian personnel still working at the ZNPP. Furthermore, the IAEA has reported that changes in the ZNPP management have resulted in ambiguous chains of command and have left staff to contend with conflicting instructions on how to operate the plant.[80] Not only will such working conditions lead to greater levels of fatigue, anxiety and burnout among ZNPP staff than have already been observed, they pose an acute risk to the safe operation of the NPP.

Possibly in an attempt to rectify Russian staff's unfamiliarity with Ukrainian facilities, operators from Russian NPPs have been 'receiving simulator and on the job training at the ZNPP' and may be deployed to work at the facility following their training, according to the IAEA.[81] While such an approach may address the challenge of staffing shortages at the ZNPP, it also helps normalise the presence, and continued deployment, of Russian personnel at an illegally occupied facility to replace Ukrainian staff who have left – or been forced out of their positions – as a result of the invasion. Unless expressly endorsed by relevant Ukrainian authorities – which is unlikely – the further deployment of Russian personnel to Ukrainian NPPs should not be acceptable to the international community.

78. Author interview with F, Ukraine, March 2023; author interview with E, Ukraine, March 2023.
79. Author interview with F, Ukraine, March 2023.
80. *World Nuclear News*, 'IAEA Concern over Conflicting Instructions for Zaporizhzhia Staff', 15 November 2022; IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', p. 11.
81. IAEA, 'Update 153 – IAEA Director General Statement on Situation in Ukraine', 13 April 2023, <https://www.iaea.org/newscenter/pressreleases/update-153-iaea-director-general-statement-on-situation-in-ukraine>, accessed 16 April 2023.

Box 1: The IAEA in Ukraine

The IAEA's Incident and Emergency Center (IEC) has been in touch with Ukrainian authorities since the start of the full-scale invasion in February 2022, and the Agency has been providing consistent technical support to Ukraine throughout the conflict. The IAEA's Board of Governors has passed three resolutions condemning Russian activities at Ukrainian nuclear facilities, and has called for Russia to cease its actions 'against and at nuclear facilities in Ukraine' and to allow Ukrainian authorities to regain control over its facilities.[82] The IAEA has also been providing regular public updates on the situation in Ukraine, including through short news items on its webpage as well as through the publication of several detailed reports. Director General Rafael Grossi has been spearheading the Agency's efforts and has articulated 'Seven Pillars' of nuclear safety and security in Ukraine derived from existing IAEA safety and security principles.[83] The pillars include – and go beyond – many of the safety and security threats covered in this report. In September 2022, the Agency also put forward a list of seven recommendations to address the threat to nuclear safety and security in Ukraine, which included a call for the establishment of a nuclear safety and security zone around the ZNPP.[84] However, the IAEA appears to have recently moved away from the idea of securing such a zone and is focusing on the protection of the facility itself under the current circumstances.[85] The Seven Pillars and subsequent recommendations for addressing the nuclear safety and security situation in Ukraine provide helpful direction for managing the current situation. However, they are fairly high level in scope and do not consider in any significant detail the military developments on the ground or the operational objectives of the warring parties. The challenges that these realities pose to establishing and enforcing a safety and security zone around the NPP are discussed later in this report.

The Agency has also conducted several missions to Ukraine to assess the situation. The IAEA has had a permanent – albeit very limited – presence at the ZNPP since September 2022 and at all Ukrainian NPPs since January 2023. These IAEA Support and Assistance Missions consist of two–four IAEA staff and normally rotate every four–five weeks. However, it appears that the IAEA has recently encountered challenges in rotating its staff at the ZNPP.[86] The mission teams are able to review the various aspects of facility operations and equipment related to safety and security – including the operation of diesel generators and supply of generator fuel, as well as facility connection to the external energy grid. The IAEA has also continued to carry out regular safeguard inspections at Ukraine's nuclear facilities, as

82. IAEA Board of Governors, GOV/2022/17, 3 March 2022; IAEA Board of Governors, GOV/2022/58, 15 September 2022; IAEA Board of Governors, GOV/2022/71, 17 November 2022.
83. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022 – February 2023', 23 February 2023, pp. 6–8.
84. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: 2nd Summary Report by the Director General, 28 April 2022 – 5 September 2022', 5 September 2022, <https://www.iaea.org/sites/default/files/22/09/ukraine-2ndsummaryreport_sept2022.pdf>, accessed 16 April 2023.
85. IAEA, 'Update 152 – IAEA Director General Statement on Situation in Ukraine', press release, 30 March 2023, <https://www.iaea.org/newscenter/pressreleases/update-152-iaea-director-general-statement-on-situation-in-ukraine>, accessed 8 April 2023.
86. Author interview with F, Ukraine, March 2023; author interview with Ukrainian intelligence official monitoring the situation at Ukrainian NPPs (G), Ukraine, March 2023; *World Nuclear News*, 'Delayed Rotation of IAEA Experts at Zaporizhzhia Takes Place', 3 March 2023.

well as ad hoc inspections as needed – for instance, following Russian accusations of material being diverted for the production of a so-called 'dirty bomb'.

Despite these efforts to support the safety and security of Ukrainian nuclear facilities, the Agency is ultimately limited in what it can do to resolve the challenges facing Ukrainian facilities and staff. IAEA staff on the ground in Ukraine can serve in observer and technical support roles, but do not have the capacity or mandate to address some of the most pressing challenges – including the threats that ongoing military operations pose to facilities. While ensuring the wellbeing of facility staff is a critical factor in maintaining the safety and security of facilities, the IAEA's mandate and capabilities do not account for protecting NPP staff in a war scenario. Nevertheless, the Agency was reportedly in contact with relevant authorities following the detention of ZNPP head Ihor Murashov.[87] The IAEA's engagement with both Ukrainian and Russian authorities over the course of the war also means that it is in a unique position to act as an interlocutor between the two sides on issues of nuclear safety and security, at a time when no other lines of communication exist between the two countries on the subject.[88]

Future Risks for Ukraine's NPPs During the Conflict

Although what has already transpired in Ukraine is deeply concerning, there are a range of risks that could grow over time and need to be mitigated. Russia continues to try to destroy Ukraine's energy infrastructure and it is highly likely that this will persist during the winter of 2023–24, assuming the conflict protracts through this period. The Russian defence industry is currently estimated to be able to construct approximately 40 cruise and ballistic missiles per month, with its limited remaining stocks allowing for larger salvos to be periodically generated.[89] In combination with simpler systems such as Shahed-136 loitering munitions, it is reasonable to presume that Russia can continue to inflict serious damage on Ukraine's energy infrastructure at least once per month.[90] Despite some improvements in interception rates in late 2022, strikes in March 2023 – which resulted in the loss of external power to the ZNPP – showed that Russia was also able to adapt its tactics to achieve a large proportion of successful hits.[91]

The strikes on Ukraine's energy infrastructure primarily target transformer sub-stations and thermal power plants. Although these do not directly threaten NPPs, the destabilisation of the Ukrainian energy grid poses serious problems to the safe functioning of the NPPs. Operating NPPs have been forced to deal with surges in energy that they cannot distribute, forcing emergency shutdowns.

87. *Al Arabiya News*, 'IAEA Chief Grossi Seeks Release of Ukraine Nuclear Plant Head Murashov', 2 October 2022.
88. Author interview with members of the Ukrainian National Security and Defence Council, Ukraine, March 2023.
89. Author interviews with officials across the Ukrainian National Security and Defence Council, Ukraine, October 2022 and March 2023.
90. Author observations of strikes and their aftermath during the autumn and winter strike campaign.
91. Author interview with H; briefing from the Ukrainian National Security and Defence Council, delivered to the authors on the morning of the strike, Kyiv, March 2023.

Some of the acute risks were laid out earlier; however, there are also longer-term issues. Ukrainian experts – including a former ZNPP employee – as well as the IAEA – have expressed concerns over the long-term effect on the reactors of their repeated disconnection and reconnection to the main power grid.[92] Abrupt emergency shutdowns are now avoided through pre-emptive shutdowns based on warning, reducing the damage to infrastructure. Nevertheless, nuclear reactors are designed to be kept operating, with shutdowns being rare events. Routine reactor shutdowns will invariably lead to wear on systems and, over time, are likely to increase the risk of irregularities in procedures or in the functioning of the system.

Another risk that will become acute over the longer term is Ukraine's limited wet spent-nuclear-fuel storage capacity. The dangers of moving spent fuel from wet storage facilities at the various NPPs into dry storage at ISF-2 and the Centralised Spent Fuel Storage Facility at Chornobyl, as well as the on-site dry spent-fuel storage at the ZNPP, under war conditions mean that wet storage facilities are nearing capacity. Should capacity be reached, spent fuel will either have to be moved – at the risk of it coming under attack while in transit – or reactors will have to cease operation until wet storage capacity can be freed up.[93] This could provide an opportune moment for Russia to manufacture a crisis. The international community should consider ways to ensure that there is an agreed mechanism to safely transport and store this fuel before time grants Russia a mechanism to weaponise the issue.

Russia has refrained from carrying out strikes intentionally targeting NPPs directly and there is no current indication that it intends to begin doing so. Depending on the nature of the incident, radiological release could have catastrophic effects for Ukrainian territory and communities in areas surrounding the NPPs, and it is likely that radioactive fallout would extend beyond Ukraine's borders. In the case of attacks on the ChNPP or the ZNPP, the effects would almost certainly be felt in Russia. It is also unclear how Western states may react to a deliberate act of major nuclear sabotage by Russia in Ukraine. However, the possibility of a deliberate attack and widescale radiological release should not be ruled out entirely. Russian forces continue to be trained, and continue to hold significant amounts of reserve equipment, in Belarus.[94] Further rounds of mobilisation could bring additional axes into play, even if only intended as a means of stretching Ukrainian defenders over a wider frontage. Russia's SSO (special operations forces) have been observed conducting training in assaulting nuclear facilities with support from personnel recruited by the Russians who have previously worked at Ukrainian NPPs and have familiarity with the safety procedures.[95] Russian authorities have also repeatedly messaged about the risks of false-flag attacks and a dirty bomb.[96] Such messaging could indicate that Moscow is leaving the option of nuclear sabotage at the ZNPP

92. IAEA, 'Nuclear Safety, Security and Safeguards in Ukraine: February 2022–February 2023'; author interview with E, Ukraine, March 2023.
93. Author interview with G, Ukraine, March 2023.
94. Volodymyr Mykhaylov, 'Amid Worries Over Russian Forces in Belarus, Former Security Officer Says Belarusian Conscripts Won't Fight', *Radio Free Europe / Radio Liberty*, 29 January 2023.
95. Author interview with senior Ukrainian intelligence official responsible for monitoring Russian activity (J), Ukraine, March 2023.
96. *Tass*, 'Russia to Raise Issue of Ukraine's Intent to Use Dirty Bomb at UN – Lavrov', 24 October 2022.

on the table. At the time of writing, the authors assess that such Russian activity does not point to an imminent plan; rather, it indicates attempts to generate options. Nevertheless, the direct threat to Ukraine's NPPs may increase if Russia feels that it is limited in its ability to suppress Ukrainian electricity generation while these facilities continue to operate and remain connected to Ukraine's electricity grid, considering the importance of nuclear energy to the country's power supply. Russia may also resort to deliberate attacks on nuclear facilities to coerce Ukraine's partners through fear of escalation without resorting to nuclear weapons. It is worth stressing that the radiological release from an attack on an NPP would not be comparable to the consequences of a nuclear weapon detonation and the two should not be conflated.

A key outstanding question is how Russian forces may react if the Ukrainian armed forces successfully break through Russian defensive positions in Zaporizhzhia. The risk in this scenario could emanate from a direct assault on the facility by the Ukrainian armed forces as was attempted in October,[97] or more likely from its encirclement as the Russian occupation of the site can be rendered unsustainable without fighting for control of the NPP directly. Retreating Russian forces may seek to engineer an incident at the facility – or threaten to do so – and blame the Ukrainian armed forces. There are two reasons why such an act may be considered. First, it could have the tactical effect of slowing down or stalling any Ukrainian exploitation of a breakthrough, requiring the Ukrainian armed forces to manage the consequences of the radiological incident instead. Second, Moscow may judge that the fear of a radiological incident among the international community could lead to a push by Western allies for Ukraine to accept a ceasefire, or desist from advancing on the Zaporizhzhia axis, at the risk of losing international support. The Ukrainian experts and officials the authors consulted in March 2023 consistently assessed that Russia is using its occupation of the ZNPP as blackmail (*shantazh*) to advance its military objectives in Ukraine. In reality, the West is unlikely to undertake such bargaining; however, there is a tendency towards optimism bias within Russian decision-making. The question is whether Russia convinces itself that it stands to benefit from causing a radiological incident at a Ukrainian NPP. The risk to the lives of its own personnel or Ukrainian civilians is unlikely to deter it from such a course of action. Although there is no evidence that a decision has been made in Moscow to carry out direct nuclear sabotage, variations of this kind of behaviour are widely discussed among Russian officials, including those in senior positions relating to the conduct of Russia's occupation.

It may be tempting to look at the various threats to nuclear safety and security that Russia has created in Ukraine as a technical issue which can be mitigated by the deployment of additional safety equipment or over which Russia may be willing to negotiate for short-term improvements of the situation. In reality, Ukraine's nuclear infrastructure continues to be held at risk by an actor that has already shown a limited regard for nuclear safety and security, with its behaviour only seriously constrained by the perceived practical risks as compared with the anticipated reward. In this context, mechanisms for improving behaviour move into the realm of deterrence or the infliction of consequences for violations of international standards and law which are able to shape behaviour. This requires a more proactive approach beyond the capabilities and capacity of international organisations such as the IAEA.

97. Maxim Tucker, 'Ukraine's Secret Attempt to Retake the Zaporizhzhia Nuclear Plant', *The Times*, 7 April 2023.

II. Perspectives on NPP Safety in Conflict

HAVING CONSIDERED THE risks to NPPs in Ukraine, it is important to examine the state of nuclear safety in conflict more broadly. This chapter, therefore, covers two issues. First, it examines the history of NPPs in conflict and the established requirements for ensuring their safety in this context. Second, it examines NPPs from a military viewpoint and outlines the effects a military may plan to deliver against NPPs. This chapter examines effects that are consistent with international law as well as those that are not.

Broader Context for the Safety of NPPs in Conflict

The current situation in Ukraine is the first time that operational NPPs have come under direct fire or been occupied by an invading military force. However, it is not the first time that civilian nuclear infrastructure has been caught in the crosshairs of a military conflict. During the Iran–Iraq War in the 1980s, the Bushehr NPP in Iran was shelled by Iraqi forces, although the facility had not yet been loaded with nuclear fuel.[98] Reactors in Iraq and Syria have also been destroyed in military strikes; both were struck before they could become operational.[99] More relevant to the current situation in Ukraine is the 1991 experience of the Krško NPP in Slovenia, which found itself in the proximity of military clashes following Slovenia's declaration of independence from Yugoslavia – although, unlike in the case of the Ukrainian NPPs, the facility was never directly attacked or occupied.[100]

A number of today's operating NPPs are in areas that are prone to conventional military conflict, raising questions over the risks that these facilities may face in the future. This may include the Bushehr NPP in Iran and the UAE's Barakah NPP in the case of a military conflict in the Gulf. An escalation of tensions between India and Pakistan, or between Armenia and Azerbaijan in Nagorno-Karabakh, may put South Asian and Armenian NPPs at risk, respectively.[101] The resumption of North Korean missile tests in 2022 and 2023 is also a timely reminder of the

98. IAEA, 'Request by the Resident Representative of Iraq to the International Atomic Energy Agency', Information Circular, INFCIRC/319, September 1984.
99. Or Rabinowitz and Giordana Pulcini, 'The Israeli Raid Against the Iraqi Reactor - 40 Years Later: New Insights from the Archives', *Sources and Methods*, a blog of the Wilson Center, 3 June 2021; Oliver Holmes, 'Israel Confirms it Carried Out 2007 Airstrike on Syrian Nuclear Reactor', *The Guardian*, 21 March 2018.
100. A Stritar and B Mavko, 'Vulnerability of the Nuclear Power Plant in War Conditions', First Meeting of the Nuclear Society of Slovenia, Bovec, 12 June 1992, <https://www.osti.gov/etdeweb/servlets/purl/20892171>, accessed 8 April 2023.
101. Alexey Kovynev, 'Nuclear Plants in War Zones', *Nuclear Engineering International*, 19 March 2015.

potential for strikes on NPPs and supporting critical infrastructure in East Asia, including operational reactors in Japan and South Korea.

As the international community becomes increasingly conscious of the need to move to sustainable energy sources and aims to reach net zero carbon emissions by 2050, nuclear power's global role – and, consequently, the number of NPPs and small modular reactors (SMRs) – is likely to grow. In its 2022 projections for nuclear electricity generation, the IAEA estimated that nuclear generating capacity may reach 873 GW(e) by 2050 – more than double current levels – in a high-case scenario. In a low-case scenario, nuclear power generation capacity remains at about current levels.[102] The International Energy Agency (IEA) has also noted the important role that nuclear power is likely to have in a global transition to zero-carbon emissions by 2050; the IEA's Net Zero Emissions Scenario suggests a doubling of global nuclear power generation capacity from 2022 to 2050.[103] According to the World Nuclear Association, 60 additional nuclear reactors were under construction worldwide as of March 2023.[104] The US, Russian and Chinese militaries have also expressed an interest[105] in the use of SMRs for military purposes, which could see the deployment of these smaller, easier-to-build reactors to forward operating bases in support of military operations. Understanding the risks to nuclear energy infrastructure from military conflict – including why and how military forces may target or occupy nuclear power units – and identifying how these risks can be prevented and mitigated must be a key component of global efforts to strengthen nuclear safety and security.

Despite these trends, there are no extant international regulations for operating NPPs in a conflict context. As per IAEA standards on the physical protection of nuclear materials and facilities (INFCIRC/225/Revision 5), procedures for the physical protection of Ukraine's NPPs would have been developed based on a threat assessment and the articulation of a DBT. A DBT is meant to inform nuclear security efforts by considering the threats of 'unauthorized removal of nuclear and other radioactive material or sabotage' by insider and external actors.[106] Physical protection measures should then be developed based on that assessment.

102. IAEA, 'IAEA Projections for Nuclear Power Growth Increase for Second Year Amid Climate, Energy Security Concerns', press release, 26 September 2022, <https://www.iaea.org/newscenter/pressreleases/iaea-projections-for-nuclear-power-growth-increase-for-second-year-amid-climate-energy-security-concerns>, accessed 8 April 2023.
103. International Energy Agency, 'Nuclear Power and Secure Energy Transitions: From Today's Challenges to Tomorrow's Clean Energy Systems', June 2022.
104. World Nuclear Association, 'Plans for New Reactors Worldwide', updated April 2023, <https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx>, accessed 8 April 2023.
105. Lukas Trakimavičius, 'Nuclear: Does the West's Military Need Small Modular Reactors?', Energypost.eu, <https://energypost.eu/nuclear-does-the-wests-military-need-small-modular-reactors/>, accessed 8 April 2023.
106. IAEA, 'Design Basis Threat (DBT)', <https://www.iaea.org/topics/security-of-nuclear-and-other-radioactive-material/design-basis-threat>, accessed 8 April 2023.

INFCIRC/255/Revision 5, which sets out recommendations for DBTs and other measures for the physical protection of nuclear facilities and material, is limited in the scope of risks it addresses and does not account for threats posed to nuclear safety and security in the context of a military conflict. The documents limit their recommendations to the assessment of the risks of unauthorised removal of nuclear or radiological material with the intent to construct a nuclear explosive device or which could lead to subsequent dispersal of the material, as well as risk of sabotage. Some of these risks are likely to be relevant in a military-conflict scenario; for instance, Section 5 of INFCIRC/255/Revision 5 refers to 'stand-off attacks' as a type of sabotage: defined as 'An attack, executed at a distance from the target nuclear facility or transport, which does not require adversary hands-on access to the target, or require the adversary to overcome the physical protection system'.[107] However, the document does not account for the kind of sustained military activity and occupation of facilities by invading military forces that Ukrainian NPPs currently face. Nuclear facility operators cannot reasonably be expected to respond to threats to nuclear facilities outside of what is articulated in the DBT; anything outside of it – including military attack – is the responsibility of state authorities as part of broader national security and defence planning.

The Convention on the Physical Protection of Nuclear Material (and its Amendment) (CPPNM) and the International Convention on the Suppression of Acts of Nuclear Terrorism (ICSANT) – Ukraine is a signatory to both – also include provisions addressing sabotage of nuclear facilities, similar to the threats Ukrainian NPPs currently face. Notably, Russia proposed the draft ICSANT to the UN General Assembly in 1996, arguing that the earlier CPPNM did not go far enough in countering the danger of nuclear terrorism.[108] However, both the CPPNM and the ICSANT explicitly state that the conventions do not cover the activities of armed forces during an armed conflict or military exercise.[109] Contained in an extensive series of publications, IAEA standards on nuclear safety[110] and security[111] set out other guidance and expectations for governments on the protection – as well as the safe design, operation and handling – of nuclear and radioactive materials and relevant facilities. Some of these are likely to be helpful in preventing and addressing certain threats to nuclear safety and security that countries may encounter in a military conflict. Yet, none have been designed for express application in a military conflict scenario or to respond to the full range of threats and challenges that emerge in such a scenario.

107. IAEA, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5)*, IAEA Nuclear Security Series No. 13 (IAEA: Vienna, 2011), Section 5.
108. 'International Convention on the Suppression of Acts of Nuclear Terrorism', 2005.
109. Chumak, 'The Implications of the Ukraine Conflict for National Nuclear Security Policy', p. 7.
110. IAEA, 'IAEA Safety Standards Protecting People and the Environment', poster, September 2016, <https://www-ns.iaea.org/downloads/standards/safety-standards-wheel-poster.pdf>, accessed 16 April 2023.
111. IAEA, 'Nuclear Security Series', <https://www.iaea.org/resources/nuclear-security-series>, accessed 8 April 2023.

NPPs in Military Planning

Any attempt to shape the approach militaries take towards NPPs must consider how NPPs are likely to be approached in military planning. First, there is the existing legal framework governing how militaries should operate in relation to NPPs. Second, there is the matter of how militaries are likely to operate within this framework to pursue advantage. Third, there is the question of militaries that disregard existing IHL provisions to pursue military advantage.

A range of provisions within the laws of armed conflict (LOAC) and IHL protects NPPs from being military targets. Article 56 of the Additional Protocols to the Geneva Conventions Protocol I prohibits attacks against 'works and installations containing dangerous forces', including NPPs.[112] However, an exception to the provision lifts this protection if the NPP 'provides electric power in regular, significant and direct support of military operations and if such attack is the only feasible way to terminate such support',[113] as well as for military objectives in its vicinity 'if they are used in regular, significant and direct support of military operations and if such attack is the only feasible way to terminate such support'.[114] At the same time, Article 56 maintains that 'the civilian population and individual civilians shall remain entitled to all the protection accorded them by international law',[115] which may be inconsistent with the earlier exceptions.

Article 15 of Protocol II also prohibits attacks on NPPs 'even where these objects are military objectives, if such attack may cause the release of dangerous forces and consequent severe losses among the civilian population',[116] with no exceptions. However, the 1987 explanatory note to the article highlights the provision's focus on expected civilian losses, noting that 'objects are not protected in themselves, but only to the extent that their destruction would release forces dangerous for the civilian population' and that 'assuming such a work or installation were a military objective, it could be attacked as long as the civilian population were not seriously endangered thereby'. The note goes on to explain that 'severe losses' is a term taken from military terminology and assessments should be made in good faith.[117] Furthermore, the provisions in the Additional Protocols refer only to nuclear power generating stations and do not explicitly extend protections to other nuclear infrastructure, such as nuclear research reactors or spent-fuel storage facilities.[118]

112. 'Protocol Additional to the Geneva Conventions of 12 August 1949, and Relating to the Protection of Victims of International Armed Conflicts (Protocol I)', 1977, Article 56.
113. *Ibid.*, Para. 2(b).
114. *Ibid.*, Para. 2(c).
115. *Ibid.*, Para. 3.
116. 'Protocol Additional to the Geneva Conventions of 12 August 1949, and Relating to the Protection of Victims of Non-International Armed Conflicts (Protocol II)', 1977, Article 15.
117. Commentary of 1987 to *Ibid.*, Paras 4819–21.
118. For a more detailed discussion of the legal provisions covering military attacks on nuclear installations, see John Carlson, 'Prohibition of Military Attacks on Nuclear Facilities', Vienna Center for Disarmament and Non-Proliferation, 12 September 2022 and Michal Onderco and Clara Egger,

In addition to the Geneva Protocols, the IAEA and UN Security Council have also condemned attacks on nuclear facilities.[119] For instance, the 1985 IAEA General Conference passed a resolution on the 'Protection of Nuclear Installations Devoted to Peaceful Purposes Against Armed Attack', which noted that the General Conference 'considers that any armed attack on and threat against nuclear facilities devoted to peaceful purposes constitutes a violation of the principles of the United Nations Charter, international law and the Statute of the Agency'.[120] The issue of attacks on nuclear infrastructure was also addressed at the 1985 Review Conference of the Nuclear Non-Proliferation Treaty (NPT), with specific reference to the threats to security and the international safeguards regime posed by the 1981 Israeli attack on the Osirak reactor in Iraq.[121] In 2009, the IAEA General Conference pointed to its earlier resolutions addressing attacks on nuclear facilities and reiterated the importance of protecting nuclear installations.[122]

LOAC concerning attack proportionality and the protection of civilians are also relevant in this instance. Protections against attacks on NPPs have been included in Rule 42 of customary IHL, which concerns itself with attacks on works and installations containing dangerous forces.[123] As others have pointed out elsewhere,[124] Russia has included similar prohibitions against attacks on objects containing dangerous forces in its military manuals and in its application of IHL; the latter makes specific reference to nuclear power stations but includes a caveat to their protection similar to that of the Geneva Conventions. A 1996 Russian Constitutional Court opinion also confirmed Russia's obligation to the protection of facilities housing dangerous forces as per Protocol II of the Geneva Conventions.[125]

Despite these provisions, there is a range of military acts that is both consistent with a state's legal obligations and yet poses risks to NPP safety. Conventional military operations are fundamentally the use of physical force to compel an adversary to comply with the will of the party applying the military instrument. To achieve this, a military must incapacitate the target's

'Why a New Convention to Protect Nuclear Installations in War is a Bad Idea', Bulletin of the Atomic Scientists, 6 December 2022.

119. See, for example, IAEA, 'Measures to Strengthen International Co-Operation in Matters Relating to Nuclear Safety and Radiological Protection', GC(XXXIV)/RES/533, October 1990; UN Security Council, 'UN Security Council Resolution 487', S/RES/487, 19 June 1981.
120. IAEA, 'Protection of Nuclear Installations Devoted to Peaceful Purposes Against Armed Attacks', GC(XXIX)/RES/444, September 1985, operative paragraph 2.
121. Center for Nonproliferation Studies, 'Final Declaration of the Third Review of Conference of the NPT 1985', Inventory of International Nonproliferation Organizations and Regimes, <https://www.nti.org/wp-content/uploads/2021/09/NPTRevCon85.pdf>, accessed 18 April 2023.
122. IAEA, 'Prohibition of Armed Attack or Threat of Attack Against Nuclear Installations, During Operation or Under Construction', GC(53)/DEC/13, September 2009.
123. International Committee of the Red Cross, 'Customary IHL', List of Rules, Rule 42, <https://ihl-databases.icrc.org/en/customary-ihl/v1/rule42>, accessed 8 April 2023.
124. George M Moore, 'How International Law Applies to Attacks on Nuclear and Associated Facilities in Ukraine', Bulletin of the Atomic Scientists, 6 March 2022.
125. *Ibid.*

ability and will to resist. Almost all modern military concepts emphasise trying to simultaneously apply as much pressure on the target military and state as possible. The Chinese concept of Systems Confrontation is premised on simultaneously targeting an adversary's combat forces, logistics, command and control, infrastructure, and other critical bottlenecks in its operations.[126] Network Centric Warfare, which – despite being superseded as doctrine – remains embedded in the logic of NATO operations, endeavours to disrupt the enemy deep, denying command and control, then logistics, to enable the defeat of military units in detail.[127] The application of these concepts has always produced attacks on CNI. In the context of initial break-in operations to suppress and destroy enemy air defences, for example, military necessity requires the disruption of enemy command and control, part of which is enabled by the supply of power. NATO struck power infrastructure in Serbia,[128] for example, as part of its air campaign against the country. It is therefore almost inevitable that states will, in the opening phase of operations, attack another's electricity grid; if that state depends heavily on NPPs, this will force it into operating from reversionary generators. It is important to distinguish this kind of attack on an energy grid – carried out in support of a specific military line of effort that is temporally confined – from the deliberate destruction of civilian energy infrastructure because of its importance for the civilian population, as Russia is carrying out in Ukraine. However, the distinction may not always be clear and the two objectives need not be mutually exclusive. Russia's concept of Strategic Operations for the Destruction of Critically Important Targets is a more systematic approach to CNI destruction than severing access to it to enable military manoeuvre.[129]

Because a state's sovereignty requires defence of its CNI, states will seek to defend NPPs. Insofar as these forces are co-located with the facility, their being targeted will risk incidental damage to the facility and – depending on the context – militaries may judge that such attacks are both militarily necessary and proportionate in terms of the risk of a radiological incident. It is also important to note that emergent military concepts – such as the UK's Multi-Domain Integration – explicitly emphasise the role of non-military tools as components of a national struggle and in doing so could cause the enablers for these tools to become valid targets.[130] This harnessing of traditionally non-military tools to further military ends may reasonably justify some targets being classified as military objectives consistent with the principle of distinction that would historically have been classified as civilian objects.

It is reasonable to assume that conflict will affect NPPs in the future and that an outright prohibition on militaries affecting NPPs would be unworkable. Nevertheless, militaries plan

126. Jeffrey Engstrom, *Systems Confrontation and System Destruction Warfare: How the Chinese People's Liberation Army Seeks to Wage Modern Warfare*, RR1708 (Santa Monica, CA: RAND, 2018).
127. Edward A Smith Jr, 'Network-Centric Warfare', *Naval War College Review* (Vol. 54, No. 1, Winter 2001), pp. 1–17.
128. *CNN*, 'NATO Strikes at Yugoslav Power Plants', 23 May 1999.
129. Michael Kofman et al., 'Russian Military Strategy: Core Tenets and Operational Concepts', *CNA*, August 2021.
130. Ministry of Defence, 'Multi-Domain Integration', Joint Concept Note 1/20, November 2020.

Hotel Polissia in the abandoned city of Pripyat, Ukraine, June 2022. *Courtesy of Jack Watling*

based on the effects they wish to deliver, and an examination of those that may lead military operations to affect NPPs is useful to determine what regulations might allow militaries to operate while maximising NPP safety. These effects include:

- Deny energy to an opposing military.
- Deny energy to an adversary state.
- Secure energy production.
- Secure nuclear facilities from access by hostile actors.
- Fix enemy forces around a piece of CNI.
- Suppress or destroy military systems operating from the territory surrounding an NPP.

In terms of regulating how these effects are delivered, it is important to note that the first two are best achieved by attacking the connections between an NPP and the wider grid, rather than the NPP itself. Others are in tension. For example, regulations must allow a military to maintain close enough proximity to a facility to offer it protection, while also reducing the likelihood that its presence would legitimise the site as a military target and thereby risk accidental damage to critical structures. Where a site is clearly being used for military purposes, providing energy to military systems, it forgoes protection. It is therefore important that states do not game the threat to civilians from the proximity of an NPP to protect a site that is being exploited for military purposes. Within this context, it is clear that any proposals for the establishment of a large nuclear safety and security zone around Ukraine's NPPs, where military forces would be prohibited from operating, would be largely unworkable in the current conflict,[131] as such a

131. Fredrik Dahl, 'IAEA Proposal for Ukraine Nuclear Safety and Security Protection Zone Wins Support as Talks Begin on Its Establishment', IAEA, 22 September 2022, <https://www.iaea.org/

zone would prevent the effective control of the site or its being protected by defensive systems. The Energy Research Institute of the Russian Academy of Sciences recently called for the establishment of a demilitarised zone around the ZNPP with a radius of 40 km, where only the presence of Russian military forces would be permitted; it should go without saying that such a suggestion cannot be treated seriously.[132]

It must also be acknowledged that some actors have little interest in complying with regulations, even if they are signatory to them. For instance, by targeting NPP-supporting infrastructure, occupying NPPs with military forces and reportedly placing military systems within reactor buildings, a case can reasonably be made that Russia is in violation of IHL provisions prohibiting the targeting of nuclear facilities. Iran, for its part, has prepared long-range strike systems as its primary means of deterrence by holding CNI across the Gulf at risk. In the context of such actors – which are willing to disregard IHL and other international standards – the question should not be how to strengthen or expand regulations and standards, but instead how to deter their targeting NPPs.

There are several reasons why such a state may target an NPP. First, a state may threaten this as part of its deterrence posture. Second, it may aim to damage an NPP to tie down adversary resources. Third, a state may threaten an NPP because a radiological incident could deny the adversary an axis of advance. Fourth, a state might target an NPP as a means of compellence because of the fear it instils in a target.

Militaries also have interests that constrain what they may be prepared to do near NPPs. First, a major incident at an NPP may create a humanitarian and ecological disaster that will require the diversion of considerable resources from a military's main effort, and possibly more than the effect on the enemy's forces. Second, an accident at an NPP risks creating a radiological hazard to friendly troops and slowing down operations, absorbing significant and scarce CBRN capabilities, or denying axes. Third, a destroyed or damaged NPP may prevent the facility from being used to provide power for the territory brought under control by a military after the completion of combat operations. Finally, the international backlash against a state that causes an incident at an NPP may bring about its isolation and have secondary consequences that are disproportionate to the military interests in striking or seizing the facility. Ultimately, however, constraining an unscrupulous military from targeting an NPP must be achieved through

newscenter/news/iaea-proposal-for-ukraine-nuclear-safety-and-security-protection-zone-wins-support-as-talks-begin-on-its-establishment>, accessed 17 April 2023.

132. Energy Research Institute of the Russian Academy of Sciences, 'Открытое письмо сотрудников Института энергетических исследований Российской академии наук коллегам из МАГАТЭ с целью обеспечения безопасности на территории Запорожской атомной электростанции' ['Open Letter from the Employees of the Energy Research Institute of the Russian Academy of Sciences to Colleagues from the IAEA with the Aim of Ensuring Safety of the Territory of the Zaporizhzhia Nuclear Power Plant'], available at <http://web.archive.org/web/20230330125713/https://www.eriras.ru/data/1354/rus>, accessed 26 April 2023.

Zaporizhzhia Nuclear Power Plant in the course of the war in Ukraine, Ukraine, 22 August 2022. *Courtesy of Reuters / Alexander Ermochenko*

deterrence rather than regulation, although regulation can increase the difficulty and reduce the effect of any activity deliberately targeting an NPP.

In summary, therefore, there are a range of effects militaries may plan to deliver in relation to NPPs that pose challenges to their safety. Some of these effects are legitimate within the LOAC and IHL. Other actors may have incentives to disregard their legal obligations. It is therefore necessary to establish regulations for military operations affecting NPPs that allow the military to achieve its legitimate objectives while minimising the safety issues raised through its conduct. At the same time, to account for actors that may disregard regulations, deterrence strategies will need to be developed that consider the particular military objectives the attack on NPPs and supporting infrastructure is meant to achieve and which deny that objective or make it too costly to pursue.

III. Recommendations for Improving the Safety and Security of NPPs in Conflict

THE RECOMMENDATIONS OUTLINED in this chapter to improve the safety and security of NPPs in conflict can be divided into three groups. First, the authors put forward immediate recommendations for improving the safety and security of nuclear facilities in Ukraine. Second, the authors outline recommendations for the alteration of NPP design, and security and safety considerations to better ensure their safety in conflict scenarios. Third, recommendations are identified for the conduct of militaries around civilian NPPs.

Ensuring Nuclear Safety and Security in Ukraine

There are several measures of immediate importance that should be a priority for the international community in its response to the threats to nuclear safety and security in Ukraine. The authors' recommendations, based on the analysis presented in this report, are outlined below.

Recommendation 1: Ensure the personal safety and welfare of staff at NPPs, including sufficient staffing levels. International pressure on Russia – and Rosatom in particular – should be maintained and increased to allow workers at the ZNPP (and any facilities that may be occupied in the future) to rest and rotate frequently, and to be able to carry out their work without undue pressure. Ukrainian staff who wish to continue working at the ZNPP should not be forced to sign contracts with Rosatom; this may help reduce some of the stress that Ukrainian staff who do not wish to work for Rosatom face, and may allow the ZNPP to retain a greater number of staff to ensure its safe operation. Ukrainian authorities should take a carefully considered case-by-case approach to responding to Ukrainian ZNPP staff decisions to cooperate with occupying forces or Rosatom in the operation of the ZNPP, weighing staff obligations to ensuring the safe operation of the NPP against the normal expectations that staff should not assist Russian occupation and would be punished for doing so. The IAEA should work with Ukrainian and Russian authorities, as well as the wider international community, to assess and identify solutions to any shortage of licensed staff available to safely operate the ZNPP in its current condition. Any solutions to the staffing challenge should not involve the presence of technical staff at Ukrainian NPPs that have not been approved by Ukrainian authorities.

Recommendation 2: Ensure sufficient licensed Ukrainian staff are ready to resume operations at the ZNPP following Russian withdrawal from the facility. In the event of a withdrawal of Russian military forces and other personnel from the ZNPP, Ukrainian authorities must be ready to provide the necessary staff and support to ensure the facility continues safe operation. As had been the case following Russian withdrawal from the ChNPP, looted and damaged equipment and

systems will have to be reconstituted, which may require support from international partners. Ukrainian authorities should ensure that the necessary measures are in place domestically and should work with international partners to prepare for a rapid return of the ZNPP to safe operation by Ukrainian staff.

Recommendation 3: Facilitate the safe transport of spent nuclear fuel to dry storage facilities, where appropriate. Spent nuclear fuel that is ready to be moved to dry storage facilities at the ChNPP and the ZNPP should be transferred to the appropriate facility and thus make room for the storage of additional spent fuel as necessary. Spent fuel currently being stored at the wet storage facility in ChNPP should be moved to the ISF-2 dry storage facility, where it will benefit from greater physical protection, as soon as possible. Measures need to be put in place to allow these transfers to take place safely. Ukraine's National Guard is normally responsible for the safety and security of nuclear fuel transport; under the current circumstances, escorts by international representatives – from the IAEA or other UN bodies – could be considered.

Recommendation 4: Assess availability of highly radioactive waste storage facilities and certify additional storage if needed. If necessary, risk assessments and other approval processes for the construction of additional highly radioactive waste storage facilities should be expedited by Ukrainian authorities. Necessary resources for the rapid construction of additional facilities should be made available – potentially with support from international partners. This will help ensure that highly radioactive waste resulting from any radiological incident that may occur at a Ukrainian NPP can be managed quickly. Should this additional storage prove unnecessary upon the conclusion of military hostilities in Ukraine, the facilities may be used to store radioactive waste from the ChNPP or for the normal operation of Ukrainian facilities in the future.

Recommendation 5: Provide CBRN, emergency response and other necessary equipment, training and support to the Ukrainian military, emergency services and NPP operators. This includes providing support for the restoration of radiation monitoring and emergency response equipment that Russian forces looted or damaged at the ChNPP. Such support should be a priority to mitigate or minimise the impact of radiological incidents in Ukraine, should they occur. This approach may also reduce the potential tactical impact of a deliberate incident instigated by Russia and thereby make it less attractive. Such support could be provided by the IAEA (including continued support from the IEC), individual governments or multilateral organisations.

Recommendation 6: Provide regular updates on the supply of fuel for emergency generators at Ukrainian nuclear facilities, as well as the water levels in the Kakhovka Reservoir. The IAEA has provided intermittent updates on the water levels in the Kakhovka Reservoir, which supplies water used to cool the ZNPP reactors. The IAEA should provide regular public updates on the reservoir's water levels and other factors that may affect the supply of water to the ZNPP. Updates on Kakhovka Reservoir water levels in the Agency's last two updates on nuclear safety and security in Ukraine (dated 13 April and 21 April) are welcome.[133] Similarly, the

133. IAEA, 'Update 153 – IAEA Director General Statement on Situation in Ukraine', 13 April 2023; and IAEA, 'Update 154 – IAEA Director General Statement on Situation in Ukraine', 21 April 2023.

supply of diesel fuel for the emergency generators at each NPP should be made public and regularly updated. IAEA staff stationed at various Ukrainian NPPs – especially the ZNPP, where Ukrainian authorities have limited situational awareness – should be permitted to ascertain and report this information. Should a change be observed in water supply or the availability of diesel fuel, the IAEA should seek to establish and report on the cause. The Agency should also publicise the consequences of key thresholds being crossed to increase the reputational harm for whoever causes such an event to occur and to prepare the ground for the international community to demand robust action be taken if critical support systems – such as water supply – are compromised.

Recommendation 7: Ensure the safe supply of diesel fuel, maintenance parts and services, and other materials necessary for the safe operation of Ukraine's NPPs. These supplies should be allowed to move freely and regularly into all Ukrainian facilities, to ensure that all safety systems, including emergency generators and water pumps, can continue to operate for extended periods of time as needed. The stress put on the reactors due to frequent disconnections from the power grid is likely to lead to an increased need for maintenance, which must be met. Fuel and component delivery to the ZNPP may require the establishment of a dedicated 'green corridor' or international escort – for instance, by the IAEA or another UN agency. As per the previous recommendation, the cause of the falling levels in the Kakhovka Reservoir must be ascertained and addressed. All options for ensuring constant water supply to the ZNPP must be considered.

Recommendation 8: Penalise Rosatom staff operating at the ZNPP – and which had been present at the ChNPP – for participating in Russia's occupation of Ukraine. Rosatom management and staff presiding over and involved in the operation of the ZNPP – and which had been present at the ChNPP – are not licensed by Ukrainian authorities to operate these facilities and have taken over the management of an illegally occupied facility. National governments, multilateral organisations (namely, the EU) and the international community (through the IAEA and its Board of Governors) must condemn this activity in the strongest terms. Rosatom executives and any of their staff involved in the operation of Ukrainian facilities should be sanctioned by Ukraine's partners. They should be excluded from participation in any international activities or forums that do not exclusively concern the safe and secure operation of the ZNPP with the ultimate objective of returning it to Ukrainian management and operation. Such measures will be not only punitive in nature but will also help to deter further Russian staff from accepting work at occupied Ukrainian facilities. Penalising and discouraging Russian personnel from operating occupied Ukrainian NPPs risks contradicting Recommendation 1, but the solution to insufficient staffing levels should not further reinforce Russian control of facilities. As per Recommendation 1, the IAEA should work with Ukrainian and Russian authorities, as well as the wider international community, to appropriately staff the facility with qualified Ukrainian or international staff that are not collaborating with the Russian occupation of the facility and which have been approved by Ukrainian authorities. At the same time, customers of Russian nuclear fuel, enriched uranium and other nuclear-energy-related goods and services around the world – including in the US and Western Europe – should look to diversify away from Russian

supplies as soon as is practicable.[134] This will avoid further enabling entities (namely, Rosatom) directly engaged in supporting the Russian occupation of Ukraine.

Recommendation 9: Establish deterrence against a deliberately manufactured radiological incident by making clear to Russia that any such incident would be followed by a massive response to mitigate damage and expanded support for Ukraine's war effort. As discussed earlier, Russia may judge a radiological incident in the event of its withdrawal from the ZNPP to be an attractive option – a serious yet controllable escalation. Deterrence must therefore be established by making clear that any such incident will have consequences that are contrary to Russia's interests. The best means of doing this would be for Ukraine's international partners to emphasise that a major radiological incident at the ZNPP will lead to the deployment of international CBRN troops to assist Ukraine in dealing with the response – and that an attack on these troops will be considered an attack on the states that deployed them. Thus, Russia must believe that any such incident will not reduce the international community's support for Ukraine. Instead, such an incident would be the basis for expanded support for Kyiv and the direct offer of assistance by deployed personnel from Ukraine's partners. Given that the Russian leadership knows that it is not able to confront NATO forces, such a position should deter it from believing that Russia could control the consequences of any such action and therefore undermine any calculus that favours rewards over risks.

Preparatory Measures for Ensuring Security of NPPs in Future Conflict

Outside of the immediate threats to nuclear safety and security in Ukraine, national governments and the IAEA should make preparations to respond to similar threats to nuclear infrastructure arising in future conflicts elsewhere in the world. To this end, the authors recommend the following lines of effort.

Recommendation 10: Consider, and adopt the necessary prevention and mitigation measures for, state-level military conflict and occupation of nuclear facilities by an invading force as part of national threat assessments, DBTs, and wider national defence and security planning. The highly sensitive nature of nuclear safety and security threat assessments, DBTs, and broader state-wide national security and defence planning means that it is difficult to ascertain in the public domain the degree to which military conflict and occupation of nuclear facilities is already considered as part of these processes. This should be rectified in countries where such situations have not been considered; national and facility-specific threat assessments should be conducted to account for the threat of military attack and occupation to nuclear safety and security. Nuclear operators and regulators, intelligence agencies and defence departments must work closely in this process; responsibilities and lines of communication should be clearly

134. For more on international and Western dependencies on Russian nuclear supplies, see Darya Dolzikova, 'Atoms for Sale: Developments in Russian Nuclear Energy Exports', RUSI, February 2023; and Darya Dolzikova, 'Catch-235: Western Dependence on Russian Nuclear Supplies is Hard to Shake', *RUSI Commentary*, 12 April 2023.

defined. National response to military attack and occupation of nuclear facilities will almost certainly fall outside of the DBT and the mandate of nuclear operators or the bodies tasked with nuclear facilities' safety and security in peacetime. However, DBTs should nevertheless include considerations around the threat of military attack and occupation. The resilience of nuclear energy infrastructure – including supply chains and fuel storage and transfer – should be strengthened accordingly. Nuclear regulators, facility operators and protection forces should be prepared to operate facilities safely and securely in conflict situations, with appropriate support from the armed forces. Best practices should be shared among states, while remaining conscious of the limitations that the sensitive nature of these threat assessments and planning pose.

Recommendation 11: Include considerations on military attack and occupation of nuclear facilities in the IAEA's nuclear safety and security standards. The IAEA should prioritise the articulation of recommendations on assessing, preventing and mitigating the threats to nuclear safety and security posed by military attack and occupation of nuclear facilities and supporting infrastructure. These recommendations should supplement IAEA guidance on the physical protection of nuclear facilities and material from theft and sabotage, as well as other IAEA guidance on nuclear safety and security. Recommendations should be as specific as possible and may include additional guidance on: improving the physical resilience of nuclear facilities and supporting infrastructure; managing frequent loss of power and emergency shutdown of facilities; the establishment of supply corridors and lines of deconfliction between the warring parties; the IAEA's role in supporting the safety and security of facilities in wartime; and staff wellbeing and procedures for the operation of facilities with limited staff. It may also be necessary to modify existing practices. For example, the regulations for ensuring the safety of a site during an earthquake may involve the use of sensors and autonomous systems that military activity could trigger inappropriately – and these systems may require reversionary modes or overrides. Another critical area for regulation should be the management of systems data at a site when this may be of intelligence value to the warring parties but also important for the site's safe operation. The IAEA's experience in supporting nuclear safety and security in Ukraine since the full-scale invasion – including the deployment of its Support and Assistance Missions, as well as the articulation of the Seven Pillars of nuclear safety and security and related recommendations – can inform future guidance and standards. The experience of Ukrainian authorities, experts, military personnel and NPP operators should also be leveraged to inform these efforts.

Recommendation 12: Harden physical protections in the design of new NPPs. It is important to note that no amount of air and missile defence can assure an NPP from deliberate direct strike. Site hardening, however, can significantly reduce the threat from such strikes. At present, the containment facilities for reactors and dry spent-fuel storage are likely sufficient to protect sites from most conventional munitions classes, except for those deliberately designed to penetrate concrete structures. States investing in hypersonic glide vehicles may expand the range of munitions and the number of vectors from which direct strikes threaten the integrity of containment. Nevertheless, prioritising innovation in the design and construction of smaller reactors that may be easier to protect, the development and deployment of more accident-

tolerant reactor fuel,[135] and subterranean structures could improve the resilience of these sites. The building up of earth around the perimeter of reactor units and other sensitive facilities may be a more realistic and economically viable solution in the short-to-medium term.

Equally important is the resilience of safety and emergency response systems, such as back-up generators (and their fuel supply) and mobile pumps, the lines connecting the generators to the reactor units, the piping to the water source for the site, as well as radiation monitoring and emergency response systems. These could all be struck or otherwise disconnected in a conflict scenario; burial of this equipment where possible may be an effective means of significantly increasing its survivability. Because ventilation points become key points of vulnerability to military strikes for any significantly hardened or subterranean structure, ensuring that they do not pose a threat would be a key challenge to address ahead of future NPP design.

Recommendation 13: Harden existing NPPs. Hardening existing structures against deliberate strike can be extremely difficult and resource intensive; but some modifications can likely be made to better protect sites from incidental strike. This would include hardening plant support systems such as generators and back-up fuel storage. Other measures that would significantly improve the resilience of these sites is the clearing of a surrounding area from fire risk and the construction of a glacis around the perimeter to shield the site from direct fire. Such a glacis would significantly reduce the risk of rounds from units in contact – especially kinetic penetrators and ATGMS that could pose a penetration risk to critical NPP facilities – from overflying targets in combat and striking the facility. This would not remove the threat from indirect fire, but the hardening of key support machinery and removal of flammable materials should reduce the risk from anything but deliberate strikes. Hardening water pipes from the facility so that they are dug into the earth and are not at risk of being ruptured by the passage of heavy armoured vehicles over them is also advisable.

Measures for Minimising Risk to NPPs During Military Operations

Although states can modify or design NPPs to reduce the risks to the facility in conflict, it is also necessary for militaries to agree on rules for operating around and fighting over NPPs that account for the safety of these sites. The following recommendations are intended to significantly improve the safety of NPPs without undermining the logic of military operations or allowing the rules to be gamed in such a way as to encourage agreement violations.

Recommendation 14: Establish a 1-km demilitarised zone around NPPs. The notion of a demilitarised zone around NPPs has merit as a means of distinguishing military targets from civilian objects. As such, it would be sensible for the IAEA to reprise efforts to establish a nuclear safety and security zone around the ZNPP. Serious consideration must be given to what such a zone may look like in practice in this particular instance – and what principles can be applied

135. Nuclear Regulatory Commission, 'Accident Tolerant Fuel Regulatory Activities', <https://www.nrc.gov/reactors/power/atf.html>, accessed 8 April 2023.

for establishing such zones around NPPs in future conflicts. A large demilitarised zone is likely impractical. To use a nominal example of 10 km, this would mean that a hypothetical NPP near Narva would prevent military manoeuvre across one third of Estonia's border with Russia. It is unlikely that either Russia or NATO would accept such a canalisation of its battlespace in conflict. A smaller demilitarised zone, however, would be sufficient to reduce the likelihood of accidental strikes on the station and is more promising. Given that the least accurate artillery classes tend to have a circular error probable at maximum range of less than 300 metres, even accounting for a major error of judgement by fire controllers, a 1-km demilitarised zone seems both sufficient and viable. This would also create a standard for the distance from the site of the glacis proposed earlier. The establishment of such a demilitarised zone also requires that no military equipment – including defensive systems – be stationed at the NPP or in the demilitarised area around it. By agreeing that military units defending a site should not come within this zone, it would be possible for a military to screen and defend the site, cover it with air defence, and perform other functions, without locating military units sufficiently close to draw fire that could put the NPP at risk. This would also enable an attack to engage defenders and to contest control of the points of ingress and egress – thereby contesting control of the site – without needing to put manoeuvre forces on to the facility. Responsibility for site safety internally would thus need to be agreed to be civilian or paramilitary, with an agreement that agencies should not carry weapon classes other than small arms.

Such a demilitarised zone would also remove ambiguity around the conditions granted to NPPs under the Geneva Conventions and other international law – namely, that such facilities are not to be attacked unless they are providing significant military support which cannot feasibly be terminated other than by military attack. If a party were to breach the demilitarised zone, then it ought to be understood that the protections of the site revert to judgements of proportionality and military necessity and that the side violating the demilitarised zone ought to bear a defined – albeit proportionate – culpability for the consequences of the site's militarisation. These rules should only apply to civilian NPPs and are clearly not relevant to military capabilities that depend on nuclear power or reactors being used to provide energy for military systems.

Recommendation 15: Grant special protected status to critical NPP safety, security and emergency response systems. If a force can isolate and therefore exert control over a civilian NPP, some reasonable expectations should be agreed on. First, no action by the controlling administration should damage or risk the functioning of systems that are critical to the safe and secure operation of NPPs, as well as to emergency response – including radiation monitoring. There should also be an agreed mechanism for the protection of declared convoys moving civilian staff certified to operate NPPs, fuel for reversionary generators and other critical spare parts to the facility. All parties should also add the demarcation of vents and water intakes and outlets for the site to no-strike lists.

Recommendation 16: Define an obligation for the establishment of deconfliction lines by militaries operating around NPPs, as well as the nuclear regulators or other responsible authorities in the concerned states. Ensuring that these measures are observed requires an ability to deconflict between the warring parties. To this end, parties should be required to

establish a deconfliction line between the respective commands responsible for the area of operations containing an NPP, as well as the nuclear regulators, operators or other relevant authorities in the relevant states. In the event of a radiological accident or other safety and security incident at the site, failure to crew the deconfliction line should confer liability on a command. Obligations should also be established for a force to cooperate in protecting civilian traffic intended to assist in dealing with an identified safety incident. This deconfliction mechanism should also allow access and regular rotation of IAEA staff to the site.

Recommendation 17: Establish regulations relating to effects of cyber and electromagnetic activities applied in the vicinity of NPPs. As regards military effects targeting NPPs, capabilities such as electronic warfare effects, and especially cyber attacks, could impact the functioning of an NPP. In the case of electronic warfare, the disruption of critical sensors, precision timing and other functions could lead to protocols being initiated in autonomous control systems that are highly suboptimal. In the case of cyber attacks, these could damage control systems for the NPP. The air-gapping of NPP systems is an impediment, but not an impenetrable barrier, to military cyber capabilities. It would therefore be sensible to standardise the frequencies and functioning of sensors used at NPPs. Technical specifications should be made available to governments – though not necessarily the public – and regulations constraining the use of electronic warfare effects against NPPs should be articulated. Cyber effects are different from electronic warfare effects because they are bespoke, especially against an air-gapped system. Here, it should be agreed that cyber attacks that are liable to cause the malfunction of safety systems, or enact protocols that threaten plant safety, should be considered a breach of international law when used against a civilian NPP.

Conclusion

THE THREATS TO nuclear safety and security in Ukraine resulting from Russia's invasion pose a range of acute and chronic risks. The likelihood of a Chornobyl-like catastrophe is limited unless Ukraine's NPPs are targeted deliberately. However, the potential for a Fukushima-like radiological incident, or the spread of radioactive particles resulting from a strike on a radioactive waste storage facility, while still not highly likely, cannot be discounted. It is important that the international community works to support Ukraine in mitigating the impact of such a scenario, endeavours to deter Russia from further endangering NPPs, and is proactive in addressing the chronic challenges before they become acute. Russia's disregard for its own commitments to the protection of nuclear facilities should also be punished.

Although Russia's actions in its disregard for nuclear safety and security and the IHL protections granted to nuclear facilities are egregious, it should also be recognised that threats to nuclear safety and security in conflict zones will arise even if combatants adhere to the LOAC and IHL. Attacks on CNI – including energy generation – are part of most states' military doctrines and there are legitimate military objectives to be achieved in seizing control of civilian NPPs. For example, severing power supplies as part of an initial suppression and destruction of enemy air defences would be consistent with international law but could pose secondary challenges to NPPs which would be thrown into emergency shutdown. As more states turn to nuclear power to deal with the threat from climate change, it is likely that NPPs will become more prevalent in conflict zones, and that controlling them will become a key military objective. Even though gaining control of an NPP does not necessarily require assaulting the structure, fighting in the vicinity of NPPs carries considerable risks.

The war in Ukraine has demonstrated some significant deficiencies in the international regulation of NPPs and gaps in safety and security standards. As the challenges presented in Ukraine are likely to be repeated in the future, the international community must use the lessons from the conflict to update the design, operation and oversight of NPPs to improve their safety and security. It is also worthwhile for militaries to consider what measures they can implement to reduce the risk of accidental damage to NPPs while enabling them to conduct legitimate military tasks.

This report has made a range of recommendations. Any proposals that rely on the outright prohibition of military action targeting NPPs are unlikely to be effective or to withstand the test of time. Instead, understanding why and how NPPs are likely to factor into military planning, including the types of attacks that may be directed at them, will help determine how best to prepare for their defence and potential occupation. Preparations can be made at the point of NPP design and construction in the first instance, to ensure physical resilience of key structures and support systems. Measures taken during a conflict – such as the establishment of deconfliction lines or a 1-km demilitarised zone around NPPs – can help to further reduce the likelihood of

radiological accidents. Cooperation between industry, national nuclear regulators and ministries of defence, as well as leadership by the IAEA and individual countries or groups of states, will be key in further articulating the necessary measures and standards to support nuclear safety and security in future military conflicts and ensuring their effective implementation.

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