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Historical perspective of a nuclear power plant at risk in a war zone

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The past seven decades the design and structural material of nuclear installations has improved and their safety precludes the possibility of severe accidents in GEN-III and III$^+$ nuclear power plants (NPP). Zaporizhzhya GEN-III$^+$-NPP (Ukraine), is used as subject of discussion. This NPP suffered a military attack in 2022, and shelling damaged a building in the vicinity of the spent nuclear fuel storage facility, as well as the site's radiation monitoring sensor. We discuss the possibility of a severe nuclear accident and the release of radioactive material, as a consequence of an adverse structural damage. Clearly, damage to a GEN-II or -III$^+$ reactor-dome by military ordnance can only be estimated from data gained during past nuclear accidents in a war zone, or in the neighborhood of military targets. We report historical experiences of reactors in a war zone or under direct military attack. Based on the available data we will discuss possible scenarios applicable to a nuclear installation in Ukraine. The concrete containment of buildings protecting the nuclear vessel and its LEU-fuel loaded core, are typically not designed to withstand military attacks. We will discuss possible consequences of a severe structural damage due to weaponry. Estimations will be made considering the VVER-1000 Zaporizhzhya ZNPP, class GEN-III$^+$ built near the city of Enerhodar, Ukraine. This reactor has a 2-m-plus-steel-reinforced containment. It is also discussed that spent-fuel temporal reservoirs in war zones, are higher-risk structures with higher likelihood of severe radioactive material release than NPP reactors.

Keywords: Nuclear reactor; war zone; reactor damage; radioactive matter release.

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1. Introduction

Historical experiences [1], related to the possible damage of nuclear reactors either of natural origin or man-made activities, have been accumulated since 1953; the year when the first commercial reactor came into operation at Obninsk (Russia). Since then, improvements have been introduced which have advanced design and structural materials.

Military escalation may arise in multiple ways: a territorial or natural resource feud, an internal political event that spills over the border, a malfunction of military equipment, a misinterpretation of intent, a terrorist attack. There is no single cause for military conflict [2] which makes it all the more complex to predict.

At this time is hard to gauge the real cause(s) of the armed conflict in Ukraine, though there are multiple perspectives [3–6] trying to explain the event. The future may shed more light and the foreign affairs and history experts will eventually tell us more.

Common sense of NPP designers suggested that a terrorist attack or a military strike should be excluded from new safety approaches. The main reason is based on the philosophy that release of radiotoxic material would be the most important deterrent. That judgment proved to be incorrect as the it has attested the list of military interventions on and around NPPs, in Iran (1978, 1980, 1981) [7, 8] Iraq (1984-1987, 1991), South Africa (1982), Israel (1991), Syria (2007), Pakistan (2009), and more recently Ukraine (2022). In the latter one a NPP and spent fuel storage were involved—see Table I for additional details.

The dangers of warfare in the immediate neighborhood of nuclear sites cannot be overlooked, however human errors and natural accidents have been historically, the main cause of fatal accidents at NPPs. Some instances of the latter are the Three Mile Island incident [9], the accident at Chernobyl [10] and the catastrophe at Fukushima [11]. In view of those types of incidents the containment buildings are required by-design, to withstand extreme events.

There are several protective barriers which are a standard design that protects nuclear fuel pellets. These uranium dioxide ceramic units are typically encapsulated by sealed tubes made of zircaloy, which has high tenacity and are corrosion resistant. Encapsulation makes fuel cells, resistant to wear and high temperatures, thus considered durable engineered materials. Additional safety measures consist of protecting layers, that serve to contain nuclear fuel and fission fragments to diminish or completely suppress leakage. Other safety measures consist of nesting barriers. These are found in three main versions: (a) a large SS-316 vessel with a wall thickness that in some cases reaches 40 cm PWR type reactor, (b) a shell of steel few-cm thick covered with reinforced concrete with up to 183 cm, and (c) an intermediate wall often placed between the vessel and the external wall, that also insulates heat and is a barrier with thickness that depends on the NPP type.

It is then expected that, depending on the severity of a military attack, a civilian nuclear facility would experience a large structural compromise outside the reactor vessel before the inner structure. Nevertheless, the risk of a major radioactive leak is ever present, given that explosions at the reactor core or spent fuel storage, can not be excluded nor the subsequent contamination to buildings, land and vegetation.

In broad terms, borrowing from the descriptions of Goldberg and Rosner [12], it can be said that Gen I reactors were basically prototypes that produced power and were launched to satisfy civilian energy needs. Developed between the 1950s and mid 1960s. They basically derived from military nuclear power reactors. Gen II reactors are commercial reactors that were conceived to be economical and reliable. Gen III are improved Gen II reactors, visualized to have a long lifetime, > 60 years. Improvements are mostly in the areas of fuel technology, thermal efficiency, modularization, safety, and standardization. Gen III$^+$ are reactors that supersede Gen III, especially in terms of safety of passive type. They are designed to have higher burnup, *i.e.* less fuel consumption and waste production. Finally we have Gen IV [13], which are expected to be fundamentally different while including all advantages of prior generations. Designs include a closed fuel cycle, which implies minimum waste and proliferation resistant. It is expected that they could support hydrogen production and water desalination. Gen IV reactors are presently under development.

2. Containment structure of nuclear facility centers and NPPs

Soon after the Fermi-Szilard reactor entered operation during the WWII, it was evident that nuclear power generation had to be considered under special types of structures, without compromising or reducing functionality and safety.

Radioactive sources at research centers and NPPs are kept in containment by a structure designed and constructed with double purpose: first, as a biological shield against radiation exposure or radioactive matter leakage, and second, as a walled structure that fends off external mechanical stress. The latter has typically the purpose of reducing the risk against a nuclear catastrophe resulting from natural causes and human activity, *e.g.* an earthquake or an airplane crash [14–16]. These technical considerations have demonstrated their importance and resilience in past accidents and military attacks.

The existing technology developed during constructing war shelters and evaluating damage inflicted upon physical structures, has been applied also to the first commercial NPP at Obninsk—connected to the power network on June 1954 at Kaluga Oblast, Russia. We have another example at Calder Hall at Windscale U.K., August 1956.

A large set of experience has been accumulated from human errors and other accidents, related to containment and nuclear technology, and related materials. As it has been mentioned, major safety innovations to NPP buildings relied on war time bunker structures erected by extreme-event bunker engineering. Some of them have been remarkably well built. For instance, the construction of structures of reinforced concrete having a density of 600 kg/m^3 and a height exceeding 10 m. Such a structure was built to withstand a 10-tonne-bomb direct impact, Szydlowski *et al.* [17].

Bunker construction technology was promptly applied to protect sites considered as potential sources of radioactive contamination such as NNPs, research reactors, fuel processing, and isotopic enrichment, or fabrication of radiation-containing items. This included uncontrollable situations such as uranium mines and related activities.

Notwithstanding the availability of safety technologies, a criticality incident at a nuclear-fuel processing facility occurred in 1999 at Tokaimura [18]. Similar incidents have happened elsewhere, *e.g.* the SL-1 nuclear-core meltdown (USA) and radioisotope processing contamination (Ozersk, Russia, 1957) at the Mayak facility. Other occurrences due to human errors worth mentioning are: Windscale, UK. (1957); Three Mile Island, USA, (1979); Saint-Laurent, France, (1969 and 1980); Chornobyl, Ukraine, (1986); Vandellos, Spain, (1989); Davis-Besse, USA, (2002); Paks, Hungary (2003).

One recent well-advertised case has been the incident at Fukushima NPP (F-NPP), Japan (2011). Due to a technical convenience the plant was placed right on the sea shore. It was damaged by an unexpectedly devastating tsunami. Against the seldom-occurring-above-7-m-height sea-wave, the plant was protected by a 10-m high seawall, a barrier height considered as sufficient protection [19]. Unfortunately, the seawall proved to be low enough and flooding ensued which overflowed the auxiliary power generators, thus disrupting the emergency cooling pumps.

In spite of the large mass displacement, the seawall survived the overflow. That was an important issue since it prevented considerably higher damage to the existing ancillary equipment and spent fuel storage.

Most NPPs of 3rd and 3^{rd+} generation, a.k.a. GEN-III and III$^+$, are containment structures made of reinforced concrete. They constitute the enclosure that surrounds the reactor core, cooling pump and in some cases the heat exchanger.

A typical housing structure [20] is shown in Fig. 1.

A mixture of cement, aggregate and water—among other materials—dresses a mesh that can withstand high stress conditions, with values in the realm of 70 MPa, Fig. 1. Concrete densities in use range between 2240 - 2400 kg/m^3. Conventional reinforced concrete can further improve the structural and functional performance by employing fiberglass [23].

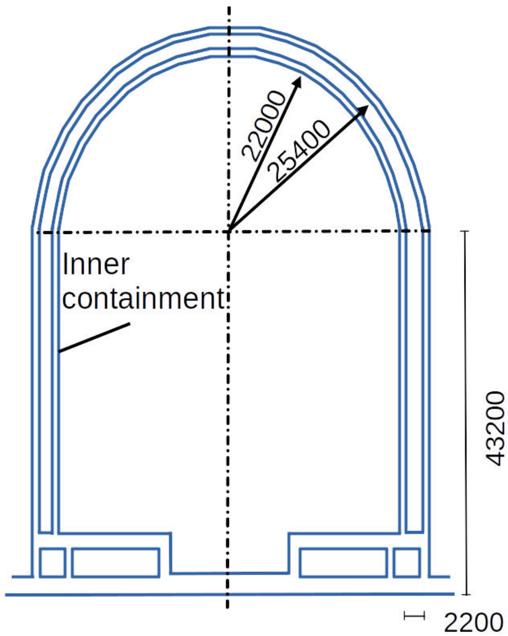

FIGURE 1. Reinforced cement structure housing ZNPP [20]. Units are [cm].

The lack of sufficiently-reinforced containment of the Chernobyl-RBMK—a graphite-moderated light-water reactor type—led to the consequences witnessed back in 1986.

As mentioned above, the lessons learned from past adverse events, have improved building methodologies and safety standards over time. Progressive improvement is expected to continue in the future. Certainly, this way to proceed will substantially reduce the vulnerability of NNPs involved in military conflicts or located in war zones.

The next section concerns nuclear reactors that have been involved in war zones or part of a planned military attack.

3. Historical experiences of GEN-II reactors in a war zone

Typically, most of the NPP buildings are essentially based on reinforced concrete with structural steel designed to contain fuel, moderator, refrigeration and supply equipment. Standard concrete is employed for the main structure, often surmounted by a thick dome or a cement flat plate. The reactor containment is a strong structure designed to resist high magnitude earthquakes, terrorist attacks, or even the accidental or intended crash of a large commercial plane. However, they are not built to withstand missile driven explosives. The differences are of course subtle, but significant.

At this time, the consequences of a direct military attack could only be pondered from information related to reactor accidents and damages resulting in immediate surrounding areas. For the most part, based on historical experiences.

Structurally speaking, a bunker is the structure that resembles the most, the type of protecting structure required by an NPP. At this same time it can be said that these types of structures can be damaged by a so-called bunker buster, which can have truly devastating consequences. Some bunker-busters are specifically designed to penetrate through reinforced concrete, and are able to traverse dozens of meters of 35 MPa concrete, or equivalently 8 m of 69 MPa concrete, using an explosive carrier equipped with a frontal high temperature jet gas. These are massive ordnance penetrators, designed to hit an objective protected by more than 10 m of reinforced concrete [22].

Robert Nelson [23] states that a missile follows a roughly linear correlation penetration-depth-vs-speed up to speeds approaching 1 km/s. Higher speeds break the correlation due to plastic deformation of the materials, *i.e.* when the impact pressure of the target approaches the yield strength of the penetrator, $Y_p = \rho_t v^2/2$, where Y_p = yield strength of the penetrator missile, ρ_t = density of the target, v = velocity of the penetrator missile. This translates into about 10 to 20 m maximum penetration in dry rock. Another source [24] briefly describes hypothetical penetrators that could possibly reach 60-m depths in limestone ground, using so-called improved strategies and materials.

Table I includes a list of some cases of reactors in a war zone or under direct military attack. These types of events can give us an idea of possible vulnerabilities of NPPs in war zones.

The first commercial nuclear power plant threatened by air-raid, was the Krško-NPP (Slovenia) during the 10-day war back in 1991. At that time, it was suggested the possibility that a military conflagration may release a large radiological damage to the surrounding region. The report published, highlighted important aspects to consider and encouraged the introduction of new nuclear safety measures. It was recommended that the cold shutdown mode be carried out at all NPPs, in due course [29].

The safety report urged to address those elements that would enable NPPs in wartime conditions, to guarantee the integrity of essential systems and thus reduce risks and, above all, vulnerability in the event of armed conflicts. The main objective was to avoid large radiotoxic matter being released, in the extreme case of a reactor core impairment.

The first two Iraqi plants, Tammuz-1 and Tammuz-2, were destroyed by intense military bombing [30]. The former in April 1978. The latter in 1980, while under construction by a French contractor. Tammuz-2, was assaulted by 16 fighter jets. Each of these jets was fitted with unguided, low-drag general-purpose bombs with a time-delay fuse. These bombs were released from a height of 1,067 m at 5-s intervals. Two bombs, each with 1,000 kg, bounced off the reactor dome. Others exploded and induced structural damage to the water cooling circuit and liquid radioactive waste treatment warehouse, among other structures, which forced the reactor to be decommissioned. The cleaning process took years and it required the disposal of 50 tons of solid and 30 m^3 of liquid waste [31]. Radioactive matter, ^{60}Co, was reported at the site with activity about 20 GBq. In the reactor tank slag were detected containing ^{137}Cs and ^{60}Co, with activity about 15 kBq/L and 8 kBq/kg, respectively.

TABLE I. List of reactors or nuclear centers involved in past military activities. Glossary: Low Enrichment Uranium reactor fuel (LEU); Highly Enriched Uranium (HEU); Weapon grade uranium (WGU); Spent Fuel (SF); radioactive materials (RM).

NPP/Center	**Country**	**Type of source**	**Reactor type, power**	**Year**	**Damage**	**Ref.**
Krško	Slovenia	LEU/Spent Fuel	PWR (700 MWe)	1991	None	
Osirak (Tamuz-1)	Iraq	WGU, designed to be loaded with 27.5 pounds of 93% of ^{235}U	40 MW	1978	Destroyed by Iranian and Israeli air strikes	Capezzuto, 1993 [25]
Tamuz-2 IRT - 5000, Soviet origin	Iraq	Operated in 1981 for training	HRU-pool type research reactor of 500 kWh	1991	Israeli air strikes	Capezzuto, 1993 [25]
Busher	Iran	Krafwerk Union, Germany	BNPP	1980 - 1988	Reactor dome	Wisconsin Risk Rep., 2003 [26]
Dir a-Zour	Syria	Uranium and plutonium	Gas graphite reactor, North Korea	2007	Destroyed by Israeli air raid, 500-kg-warhead missile	
Five NPPs	Indian (5 NPP) - Pakistani (2 NPP) conflict	Nuclear fuel, reprocessing facility, HEU	CANDU, PWR	1965 and briefly 1999	None	
Armenian (2 NPPs)	Armenian-Azerbaijani conflict	Nuclear fuel and spent-fuel temporal store	VVER-440	1991 - 1993	Far from the theater of operations	Kovynev (2015) [27], Altikat *et al.* (2015) [28]
Ukraine	Chernobyl Rivne Zaporizhzhya, Ukraine	LEU-fule, spent fuel storage	15 NPPs 440 and 1000 MWe	2014	War zone	

To disrupt the Syrian nuclear program, a military operation was planned and executed under the covert name Operation Outside the Box, back in 2007. The strike was not legally justified by Israel and Syria did not protest [32, 33]. It was later found out, that large quantities of graphite and barium sulfate had been purchased by the Syrian government. This reactor resembled a North Korean version, presumed capable of Pu production [34]. At the time, the IAEA released a statement indicating that it had no knowledge of any undeclared nuclear activities in Syria [33].

According to international nuclear law, the transparency principle [35] signals that international organizations must be informed by any government, about any nuclear activity that could potentially result in incidents or abnormal occurrences with potential impact in public health, safety and the environment.

The Indo-Pakistani conflict has occurred at several points in time, first in 1945. Both countries, India and Pakistan, have nuclear weapons pointing at each other, establishing a *de facto* military situation, in which consequences of mutual annihilation exist. As of 2019 [36] the threat of a nuclear conflict between these two countries appears to be ever present, due to their rapid expansion of nuclear arsenals, and unresolved socioeconomic and political issues.

Construction of the Bushehr NPP in Iran began in 1975, by Kraftwerk Union of Germany. However, the Iranian revolution of 1979 prevented its completion. During the eight-year war with Iraq, the reactor structure was hit by military ordnance [37]. A new NPP was built by ROSATOM in 1995. The Iranian nuclear research program continued with the installation of a uranium enrichment facility to produce highly enriched uranium. Iran signed a Nonproliferation

Treaty (NPT) in 1970, and today it is expected that enrichment level of 3.5% will be maintained—typical enrichment for pacific nuclear applications.

The two Armenian NPP (ANPP) at Metsamor in 2019 provided about 30% [38] of the electricity supply of Armenia. The ANPP is a first-generation Soviet-made twin-reactor NPP—today with multiple safety upgrades—that can produce about 880 MWe, commissioned in 1976 and 1980. Closure of ANPP for about six years ensued the earthquake of 1988. The decision came along based on the lack of concrete containment domes in the design—an aspect that has not been upgraded—which meant that a structural breach would possibly vent the system directly to the atmosphere [39, 40]. This region is earthquake-prone and in addition there is the ongoing conflict of Nagorno-Karabakh between Azerbaijan and Armenia since the late 1980's [39]. Clearly, this NPP poses a condition of concern.

In the conflict in Ukraine any of the 15 UNPP could suffer from an ordnance hit. The concrete containment of buildings protecting the nuclear vessels, its LEU-fuel loaded core and its temporarily nuclear material store, facility and infrastructure, are exposed at risks that exceed those usually connected with similar installations. This observation generally extends also to research centers, *e.g.* Kharkiv, that store nuclear material in an area where heavy military activity has been ongoing.

4. GEN-III and -III$^+$ reactor building structure

National and international nuclear regulatory authorities [41, 42] require that the reactor housing be a double containment structure specifically an inner containment in prestressed concrete having a larger thickness in comparison to the external reinforced wall. The inner containment is to be made of a high-yielding concrete with the aim of providing extra structural safety in the case of accidents involving, *e.g.* operational high pressures and temperatures, or external mechanical stresses. These are translated into events like earthquakes or severe weather-floods, tornadoes—and the impingement of aircraft and turbine blades [43]. Present construction techniques, may not contemplate to withstand high-power ordnance impact. However, that perspective will have to change in light of experiences in military conflict zones.

Concrete containment buildings (CCB) function as a physical barrier to radioactive material, before release to the environment. Some early thermal reactors were built without containment, as is the case of the Armenian twin reactor at Metsamor, discussed earlier. Of course, details of the function of the CCB are adequate to each type of reactor [43].

Clearly, one limitation in the reactor operational life is imposed by aging of concrete structures [43]. Some of the reactors in a war zone are close to be decommissioned—consider that their designed life may have been originally about 30 to 40 years. Even if the condition of the concrete

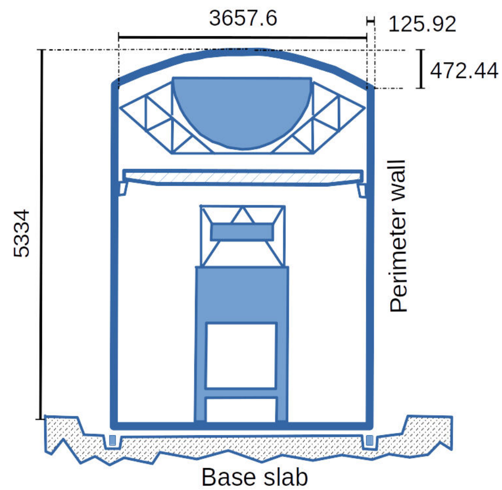

FIGURE 2. A typical building structure of a GEN II, NPP. The reactor core is housed at the inner sector (central square), usually settled on a rocky base. An extra perimeter wall is typically constructed for added protection [40]. Units are [cm].

structures is satisfactory in case of attack, their vulnerability is still of high level.

The exception is the Zaporizhzhya nuclear power plant (ZNPP) complex of six reactors VVER-1000 type, the Russian acronym for water-water energetic reactor (Vodo-Vodyanoy Energeticheskiy Reaktor); it was built with better technology and economy in comparison to previously built NPPs [20]. Regarded as an advanced reactor because it is based on the concept of beyond-design-accident-basis (BDBA), *i.e.* based on the combination of passive and active safety systems, and as such, includes several advanced features regarding its safety. Due to these characteristics they have been classified as GEN-III$^+$. Unlike the Chernobyl reactor, each reactor in the ZNPP complex, is enclosed in a pressurized steel vessel, which in turn is housed inside a massive reinforced-concrete containment structure. The plants also have multiple safety back-up systems to prevent radioactive matter from being released in the environment, even in the event of being a target by an off-route missile.

The reactor core and heat exchanger inside the containment structure are sufficiently shielded against weapons so far employed in the conflict. That is not the case for spent fuel storage outside the plant.

Most NPP—including those at ZNPP site—have pools of water to store temporarily spent fuel in order to be transported safely to a final destination (reprocessing facility or disposed adequately, e.g in old mines). During the cool-down time process, water pools provide removal of radioactive (residual) heat requiring radiation shielding of a thickness that is inadequate protection against an accidental or intentional damage. In the case of extreme circumstances loss of cooling-water, *i.e.* heat removal from the reactor core or the pool is of high risk, as the Fukushima case did show. Even a relatively small interruption could cause over-heating or blast few cluster-rods, which would start a chain of damaging events, endangering both, public health and the environment with radioactive material.

It was reported that "one mitigating factor is, that any fuel rods that have been in the pool for several weeks or months are less dangerous than they were at the beginning, because the main cancer-causing isotope, ^{131}I, decays quickly" [45]. Evidently this journalistic information is incomplete. Spent nuclear fuel contains almost the same amount of uranium than at the time when the reactor was loaded and radiotoxic fission material, *e.g.* $^{239+240}$Pu. It is called spent nuclear fuel only because it can no longer sustain a chain reaction. Nuclear fission of ^{235}U nuclei, originates at most 240 lighter radioactive isotopes with well-known atomic weight distribution. Most of these isotopes are of short half-life that on average is around 80 s. Unfortunately, other long half-life isotopes, referred to as minor actinides (MA), are still present, and if released to the environment may stir up long term trouble. In fact, this is the principal argument against nuclear energy.

5. Zaporizhzhya nuclear power plant (ZNPP)

On the 4th of March, a high-risk situation arose at the Zaporizhzhya nuclear power plant, when a missile loaded with high power explosive lost its predetermined target and hit a training building few hundred metres from the ZNPP unit No. 1. It was reassuring that shortly after the attack, the IAEA officials stated that the explosion had not affected "*essential equipment*" meaning that the reactor(s) was(were) not damaged and that its(their) main safety system came out unscathed. Two days later, *Energoatom* officials informed that unit No. 6 was under "*emergency repair*". The possibility that the latter was the consequence of military attack to the plant could not be excluded. Later damage to the transformer block apparently inactivated two of the four high voltage lines.

At the power station only the unit No. 4 was in full operation at the time of the military intervention, meanwhile the status of the others were: unit No. 1 underwent maintenance outage; units No. 5 and 6 were operating in low-power mode; the last two units No. 2 and 3, probably for safety reasons, were in the process of shutdown mode.

The multiple active and passive security systems gained over decades of research and technological improvements were gradually introduced in the new NPPs. However, the present situation could not provide sufficient guarantee to eliminate the risk of a reactor core meltdown, arising from the present conflict. Considering the situation of the ZNPP complex with six plants, thus six nuclear cores, they are all highly vulnerable to loss of electrical power despite powerful backup generators. These too could be disrupted with dangerous consequences, as the Fukushima case showed.

Another source of nuclear risk could materialize if the external protection of the pools of spent nuclear fuel failed, where highly radioactive clusters are accumulated. These, although designed following strict fundamental security objectives and principles, have reduced concrete protection.

An explosive-induced damage, either at the nuclear core, the internal- or external-pools, will, beyond doubt, lead to a déjà-vu nuclear disaster. Similarly, a destructive blast on the emergency electric generator would bring us to a situation which we have witnessed in the past.

Despite our engineering inability to design complex systems resilient to all eventualities, several modifications have been applied to prevent the most frequent events likely to occur. These, described in detail elsewhere, result from six decades of experiences and evidence that nuclear power is a safe source of energy to generate electricity. The nuclear energy industry so far, is one of the safest human activities that now and in the future will benefit our society. The mass media has often overlooked most positive aspects of this kind of energy source.

6. External ordnance impacts on GEN-III$^+$ NPPs

Experiences of WWII-bunkers resilience-to-shelling promoted new methodologies to improve on building structure and shelter protection. Most of them are included with the improvement on the nuclear reactor protective structures.

Together with structural safety improvements, explosives have also grown in sophistication in order to penetrate everthicker shelter's wall; one weapon along this line of thought, is the so called bunker-buster. The casing is made of hardened Fe-Co alloy to allow an impressive penetration up to 8 m of reinforced concrete. Evidently, against these or even more powerful bunker-busters [46], nuclear reactor shielding cannot be structured due to the costs involved.

Past experiences did show that high-performance concrete offers excellent protection from a powerful explosion, resisting high temperatures for long periods of time. In addition the containment's robust steel mesh provides extra strength against larger blast loads.

A typical NPP classified as GEN-III$^+$ has a reactor core housed by reinforced concrete. It can be a 120-cm thick circular perimeter wall. This structure, supports the dome, that is a covering top that may be half-meter thick. Other contention barriers are: a nuclear core mantle of 3-cm SS-316, an enclosure of 9.15-cm thick heat shield; in the case of PWR a pressure vessel of 22.8-cm SS-316; a 175-cm thick concrete reinforced by a steel mesh. Assuming a factor of one or two between steel and concrete's resistance to blast load [43], we ponder that the reactor's most sensitive assembly, the core, is protected—at least in theory—by a concrete-equivalent thickness up to 355 cm.

Following the German classification of resistance-fortification to artillery fire (1938), the reactor core is class A shielding—the highest. A structure capable of resisting direct artillery fire of a 520-caliber shell with a load of 1000-kg-explosive, Szydlowski *et al.* (2018) [17].

The relationship between a reinforced concrete wall thickness S [mm], withstanding artillery fire of shells having diameter Φ, is described by the approximate expression (1) [17]:

$$S[\text{mm}] = 5\Phi \quad [\text{mm}], \tag{1}$$

where Φ represents the artillery's shell diameter. Note that the explosive's weight is not included in the equation.

In the conflict, most civilian casualties have been, presumably, the consequence of heavy-artillery blasts, rocket-driven explosives and airstrikes. It is possible that few, if any, bunker-buster weaponry have been employed near ZNPP, but we cannot really know.

Characteristics of explosive ordnance [48] employed in the Russia-Ukraine conflict have been reported. For instance, the Mk 84 of 1000 kg, used at the Osirak reactor, as well as others of the same caliber, have a penetration length in the range of one or two meters, *i.e.* below the concrete-equivalent thickness of a ZNPP building. The Russian-made Concrete-Piercing Bomb of the BETAB-500 [49] group, apparently has been employed against Mariupol shelters—regarded as an effective propelled weapon. Considering the specs of the latter, a ZNPP building could resist the blow, thus preventing an enormous amount of radioactivity from being released.

A major risk of a nuclear disaster is related to the dry storage [50] facility installed at the ZNPP site which guards 167 casks of 144-ton each. Their protecting shield is in the range specified by radiation protection regulations, but not made to resist the BETAB's [49] impact. Therefore, those containers could release massively their content.

A smaller amount (700 tons) of spent fuel is temporarily stored in a water pool inside the reactor building, that would be damaged, if targeted by a higher-caliber weapon, possibly the KAB-1500L [51], a Russian-made precision-guided weapon designed to penetrate above 2-m thick concrete. Other self propelled weapons [52] are powerful enough to reach the radioactive core. An unfortunate hit by one of those traveling off-target, could render inaccessible the plant, disrupting maintenance or emergency equipment, thus leading to a chain of unexpected deleterious events.

Most likely, bunker-busters like BETAB and KAB, are those that pose major risk to an NPP. The foreseeable consequences can be estimated from radioactive material released by the Fukushima Daiichi (2012) accident.

In any risky circumstances, the most advantageous plan to follow is considering a cold shutting down of a reactor near a war zone. Such an action could decrease or prevent a large radioactive contamination.

After shutdown, the radioactive fuel remains a sizable heat generator. The decay rate diminishes exponentially due three main general factors [53,54]: (a) fission from delay neutrons, (b) decay of radioactive fission products, and (c) decay of U-239, Np-239, Pu-239, Pu-241. Some contributions are short-lived, fractions of a minute to minutes, others last years or thousands of years.

To highlight the importance of maintaining the emergency cooling integrity and operability after the shutdown for a given period of elapsed time t (s), we give an estimate of power-production applying the Wigner-Way formula [49]:

$$\frac{P_s}{P_0} = 0.1\left\{(t_s+10)^{-0.2} - 0.87\left(t_s + 2\times 10^7\right)^{-0.2}\right\} - 0.1\left\{(t_s+t_0+10)^{-0.2} - 0.87\left(t_s+t_0+2\times 10^7\right)^{-0.2}\right\}, \tag{2}$$

where P_s = rate of heat during shutdown, P_0 = rate of heat during operation, *e.g.* for ZNPP [55] is 3000 MWth, t_0 = operation time in seconds, *e.g.* $\sim 10^{10}$ or $\sim$ 3 y 94608000 s, t_s = time since operation in seconds.

Figur 3 displays the rate-of-heat decay which includes U-239 and Np-239 in the range of 10 to 10^6 s. Equation (2) is an experimental approximation [53] with best accuracy between 10^4 and 10^6 s.

Let us suppose that the errand missile hit the VVER-1000/V-320 reactor protecting wall, instead of the center training building and the shutdown occurred one day after. The decay heat can be estimated by Eq. (2).

Considering Fig. 3 above, the 3 GWth plant with three year old fuel at the shutdown moment, has a heat decay about 1.6% after about 1 h, about 1.3% after 2 h. Then after 1 day it is down to about 0.6% and down to about 0.35% after one week, the equivalent of 10.5 MWth.

In spite of a fast decay rate, a Loss-of-Coolant Accident (LOCA) or a fail of the emergency cooling system has serious consequences. After two hours the power is still considerably high, about 39 MWth at the reactor core. Meltdown is an inevitable consequence. A large mass of fuel, fission products and other radioactive matter can escape from a melted casing.

FIGURE 3. Log-log rate-of-heat decay in %, estimated using equation (2), for a single NPP at Zaporizhzhya.

A direct military strike inducing a LOCA on a nuclear reactor core or spent fuel clusters, has the potential to cause serious public health damage, together will all its environmental ramifications.

It could be added that the possibility of self-sabotage, *i.e*. caused by Ukrainian technicians themselves, although possible, is also considered by the authors to be highly unlikely.

NPP's operators are well-trained personnel that understand the consequences of driving the reactor into a dangerous condition—if that were the target of self-sabotage. The situation would evolve to the disadvantage of the Ukrainian population, needless to say, including the operators themselves. Possibly, the least dangerous consequence of self-sabotage would be the shutdown of a reactor, which at the same time would be direly expensive if done wrong.

We emphasize that the perspective here presented is historical and technical, and certainly not the only one [1]. Our perspective, was inspired by the recent events in Ukraine and the ever present concern of safety which is in the mind of all those involved in nuclear technology. With the latter in mind we include some references about detailed technical studies that seek to understand and improve the performance of NPPs [14, 15, 50, 56].

7. Conclusions

Nuclear plants for energy production or research, and in general, any civilian nuclear facility in a war zone, is exposed to potential damage. Release of radioactive matter is thus one of the consequences. To this day we have not witnessed the destruction of an operating NPP, and nobody wishes that event to ever materialize. In this document we have attempted to sketch a possible outcome, and to highlight potential risks that could follow the Russia-Ukraine military conflict. Past experiences like the Chernobyl disaster serve as a gauge for a possible scenario—the reactor was loaded with 190 ton of nuclear fuel, 5% of which was released. The outcome may not be too dissimilar for any of the 13 VVER-1000 NPPs, if hit by a suitable damaging missile. Clearly, a weak element of safety could be posed by radioactive material contamination due to spent fuel, improperly stored outside the NPP. Unlike material at the core that is well shielded. Most 1000 MWe GEN III^{+} units have been constructed to stand ordnance's impact. However, low power 440 MWe, have been designed with a military-proof lower-safety grade, and often times they are also near the end of their operational life.

Despite NPPs' sturdy design—to aircraft crash or earthquake—the risk of radioactive release increases if a military conflict happens in their vicinity. A reactor's concrete structure becomes more vulnerable with time, in an accelerated fashion due to long-term radiation exposure. Clearly, an important aspect during risk assessment of an NPP immersed in a war zone.

Needless to state, a purposeful military action against an NPP will cause damage to all parties involved in a conflict, possibly with disastrously unforseeable consequences.

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