nucmag.com

atw

International Journal
for Nuclear Power

2022

3

Die Deutsche Energiepolitik nach dem 24. Februar 2022

Perspektiven der Energieversorgung in Deutschland

Nuclear Threat Resulting from Russian Military Occupation of Chornobyl Exclusion Zone

ISSN · 1431-5254
32.50 €

Programmvorschau
KERNTECHNIK 2022

Ausgabe 3
2022

Mai

Inhalt

Cover:

Reaktordruckbehälter KKI2 beim Entladen während der Revision 2021 (© PreussenElektra GmbH)

Nuclear Threat Resulting from Russian Military Occupation of Chornobyl Exclusion Zone

Anatolii V. Nosovskyi, Vyacheslav M. Shestopalov, Iurii Shybetskyi, Jürgen Krone

The paper provides an overview and assessment of major nuclear threats arising from Russian military occupation of the Chornobyl Exclusion Zone (ChEZ). After an overview on the ChEZ nuclear facilities and on its accumulated radioactive waste and spent nuclear fuel (SNF), the paper presents a record of relevant events and corresponding incidents since February 24, 2022. Next, the paper provides an assessment of the resulting major nuclear threats that cannot be limited to ChEZ or Ukraine and its directly neighbouring countries. Finally, the conclusion identifies and specifies how the Russian Federation and its military forces have violated the basic principles of international law and nuclear safety and security.

Introduction

In the early morning of February 24, 2022, following Russian Federation President Putin's order to attack Ukraine, Russian military forces fired missiles on cities and military targets attacking the country from three sides, in the south from the earlier occupied Crimea, in the east from southwestern Russia, and in the north from Belarus. In a clear attempt at misleading the world, the Russian Federation trivialized its war in Ukraine by naming it a "Special Operation" [1]. Furthermore, the Russian Duma passed a law criminalizing any other description of the unprovoked invasion of Ukraine by Russian military forces.

Violating basic principles of international law and of nuclear safety and security, Russian military forces entered from Belarus directly into the bordering Chornobyl Exclusion Zone (ChEZ), with the intent of using the ChEZ as a staging ground and bridgehead for attacking the Ukrainian capital, Kyiv, from the north. About 12 hours after their initial missile and air strikes on Ukraine (5 p.m. local time), Russian forces occupied all of the nuclear facilities within ChEZ.

The paper provides an overview and assessment of major nuclear threats arising from Russian military occupation of the ChEZ. After an overview on the ChEZ nuclear facilities and on its accumulated radioactive waste and spent nuclear fuel (SNF), the paper presents a record of relevant events and corresponding incidents since the invasion began on February 24, 2022. Next, the paper provides an assessment of the resulting major nuclear threats that cannot be limited to ChEZ or Ukraine and its directly neighbouring countries. Finally, the conclusion identifies and specifies how Russia and its military forces have violated the basic principles of international law and nuclear safety and security.

Overview on Nuclear Facilities at ChEZ and Accumulated Radioactive Waste and Spent Nuclear Fuel

The ChEZ was established, after the accident on April 26, 1986 at the fourth reactor unit of Chornobyl Nuclear Power Plant (ChNPP) to protect people from the threats and legacies of the accident and for managing them as safely as possible. The current ChEZ conditions are strictly regulated by law, which prohibits permanent resident population inside ChEZ and limits any activity to managing the reactor accident legacies safely [2].

The ChEZ is divided by an outer 30-kilometer (km) perimeter and an inner 10-km perimeter. Entrance to both is strictly limited and subject to special radiation protection regulations. All nuclear facilities, as well as major site contaminations, radioactive waste and spent nuclear fuel (SNF) accumulations are located within the 10 km-perimeter.

The accident released and distributed a large quantity of radioactive materials over the surrounding territory, although the majority of the materials remains inside the damaged reactor unit 4 above that the "Shelter Object" was built, and within the local area (the Shelter Object site) that surrounds the ruined unit at the ChNPP site territory.

It should be mentioned that nuclide composition of these radioactive wastes to the first approximation corresponds to the nuclide composition of irradiated nuclear fuel of RBMK-1000 reactors with average burnup of 11,000 megawatts (MW)*day/ton (t). At that the ratio of activities of gamma and beta emitting nuclides to alpha emitting nuclides is approximately 100 to 1 [3]. Table 1 provides an overview on the released activity of main radionuclides and Figure 1 provides an overview on radioactive site contamination inside the ChEZ.

Nuclide	Activity inside unit four [10^{15} Bq]		Released activity by May 6, 1986
	April 26, 1986	May 6, 1986	
^{133}Xe	185	1.665	up to 100%
^{85m}Kr	5.6	—	up to 100%
^{85}Kr	—	33.30	up to 100%
^{131}I	167	270	20%
^{132}Te	148	48	15%
^{134}Cs	5.6	18.5	10%
^{137}Cs	11	37	13%
^{99}Mo	17	111	2.3%
^{95}Zr	17	141	3.2%
^{103}Ru	22	118	2.9%
^{106}Ru	7	59	2.9%
^{140}Ba	19	159	5.6%
^{141}Ce	15	104	2.3%
^{144}Ce	17	89	2.8%
^{89}Sr	9	81	4%
^{90}Sr	0.56	8.14	4%
^{238}Pu	0.004	0.030	3%

Tab. 1
Activity of main radionuclides inside damaged Unit 4 between April 26 and May 6, 1986 and part of the released activity by May 6, 1986.

Waste composition	Waste characteristics	Waste category	Waste Amount	
			(m³)	(t)
Inside Shelter Object				
Liquid Waste	Free water in Shelter rooms	LLW	2,500	
		ILW	500	
Fuel-containing materials	Pieces of the core and lava-like fuel containing materials	HLW		3,000
Containers with HLW behind the pioneer walls	Pieces of the core and other high-level materials	HLW	1,700	
Constructional materials and structures	Concrete, concrete plates and units	L/ILW		300,000
		HLW		90,000
Metal materials	Metal equipment and metal structures	L/ILW		20,000
		HLW		22,000
Concurrent non-metal materials	Filling material, serpentinite, construction wastes	HLW		9,000
	Burnable waste Compactable waste	L/ILW	200 5,000	
Shelter Object Site				
Non-metal materials	Ground (crushed stone, sand, gravel)	LLW	137,000	
		ILW	2,000	
		HLW	600	
Metal materials	Metal structures	LLW		1,440

Tab. 2
Radioactive waste volumes inside the Shelter Object and at Shelter Object site.
LLW = low-level radioactive waste ILW = intermediate-level radioactive waste
HLW = high-level radioactive waste

Most recently, in April of 2019, a team of experts led by the National Centre for Nuclear Robotics (NCNR) spent two weeks surveying the ChEZ. Using LIDAR technology to measure the landscape and gamma-ray spectrometers for radiation levels, the team flew unmanned aerial vehicles (UAVs) in patterns, mapping about 15 square kilometres within the zone. At the most contaminated location within the Exclusion Zone, Rudyy Lis (Red Forest), measured gamma dose rates reached 0.1 to 10.0 mSv/h. [4] Just directly before submitting this paper, details

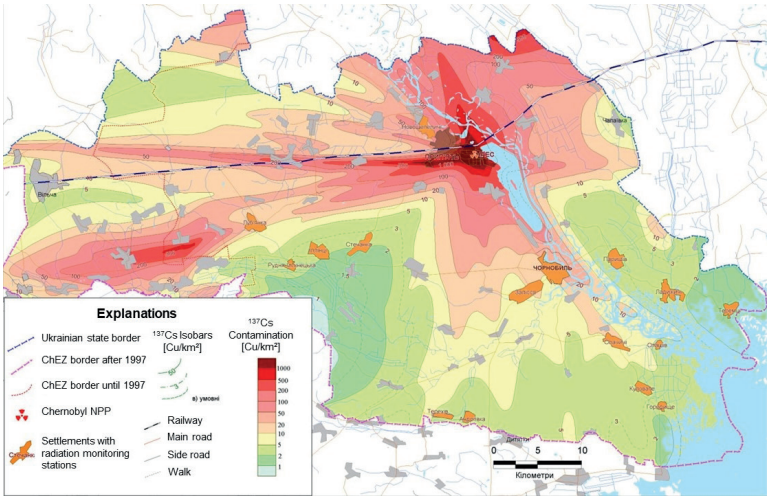

Fig. 1
^{137}CS Site contamination inside Chornobyl Exclusion Zone as of 2007.

became public that Russian soldiers had been ordered to dig trenches in contaminated areas of the ChEZ [5].

Radiological calculations performed within the safety analyses of the Buriakivka repository confirmed the dose rate due to inhalation of radioactive aerosols of a bulldozer driver that compacts contaminated soils would exceed the expected gamma dose rate more than by an order of magnitude [6].

In the case of trench digging the ratio between both dose rates can be significantly higher due to the higher exposure by radioactively contaminated dust and small SNF particles. Thus, at locations within the Red Forest doses significantly higher than 1 mSv/h or even 100 mSv/h could have been received. According to unconfirmed press releases, new trenches were found in the Red Forest as well and several tens of Russian soldiers have been directed from ChEZ to a radiological hospital in Gomel (Belarus) for treating their radiation symptoms [7]. Due to the relatively dry weather conditions, several tens of hours exposure to dust in highly contaminated areas could have been sufficient for receiving a total dose of 250 mSv or more from which deterministic radiation syndromes have been observed in the past. By 2005, the total activity that remained at the Shelter Object had been assessed at 4.17×10^{17} becquerel (Bq). Corresponding waste volumes vary (according to different estimations) – from 530 to 1,730 thousand cubic meters (m³). Table 2 provides an overview of these volumes.

The aging and hastily constructed original shelter, i.e., the Shelter Object, above reactor Unit 4 raised serious structural instability and radionuclide release concerns. Thus, a new, unique shelter, the New Safe Confinement, financed by numerous sponsor countries was completed and operationally

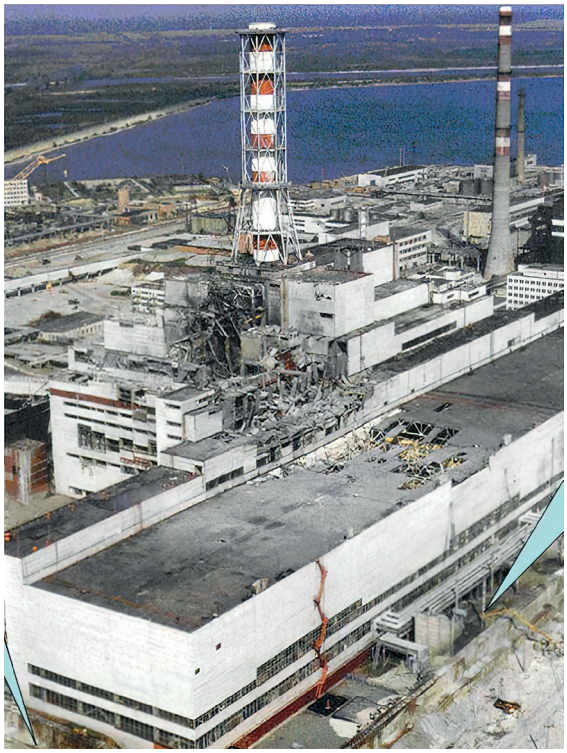

Fig. 2
Destroyed reactor building of Unit 4 with indications of storage places for HLW containers.

Waste Category	Waste Dump	Volume (m^3)	Weight (t)	Waste Nature	Activity (10^{12} Bq)
Low, intermediate and high level	Rudyy Lis	50,0000	250,000	Stones, metal scrap, ground, wood	374
Low and intermediate level	Pischane plato	57,300	91,700	Solid waste, sand	6.8
	Naftobaza	102,000	181,000	Stones, metal scrap, ground, wood	40
	Yaniv Station	30,000	15,000	Stones, metal scrap, ground, wood	37
	Stara Budbaza	171,000	316,000	Reinforced concrete, metal structures	1,100
	Nova Budbaza	150,000	70,000	Reinforced concrete, metal structures	185
	Kopachi	110,000	90,000	Wood, household rubbish and constructional wastes	33.3
	Pripiyat	16,000	11,000	Reinforced concrete structures, stones, metal scrap	25.9
	Chystohalivka	160,000	150,000	Equipment, transport facilities, etc.	3.7

Tab. 3
Major radioactive waste dumps inside ChEZ.

commissioned in 2020. This new structure was constructed and moved over the original shelter to provide safe containment and conditions over the next one hundred year to support the required decommissioning activities for this nuclear legacy site.

A considerable quantity of radioactive substances is contained in the ChNPP cooling pond (see background of Figure 2). Based on their low mobility, the radionuclides were localized in sludge deposits under a massive water layer, which served as powerful barrier preventing atmospheric release. However, after the shutdown of the last power unit, the recharge of the cooling pond was turned off, as a result of which the water level in the pond dropped. This led to the exposure of radioactively contaminated areas of the cooling pond, which in turn increased the risk of wind-driven transfer of radioactive contamination. In 2002, cooling pond sludge deposit concentrations were estimated to be $(16 \pm 3) \times 10^{13}$ Bq for ^{137}Cs, $(2.4 \pm 0.9) \times 10^{13}$ Bq for ^{90}Sr, and $(5.3 \pm 1.9) \times 10^{11}$ Bq for Pu [3].

In addition to the tremendous number of radionuclides contaminating the surrounding area accumulated in soils, groundwater, and vegetation, there is approximately 2,000,000 m^3 of radioactive waste resulting from early intervention and decontamination activities. This waste is stored in numerous waste dumps and three engineered storage facilities that are well below state of the art. An overview is provided in Tables 3 and 4 and Figures 4 – 6 [8].

Following international agreements, operation of reactor Units 1 through 3 were terminated and await decommissioning. From all three power units, nuclear fuel has been unloaded and moved to

Fig. 3
New Safe Confinement for safe containment of the destroyed reactor unit 4.

Waste Category	Waste Storage	Volume (m^3)	Weight (t)	Waste Nature	Activity (10^{12} Bq)
Intermediate and high level, long-lived	Pidlisnyi	7,040	14,080	Metal, wood, waste	1.0
		3,960	7,920	Reactor pieces	2,500
Low and Intermediate level, long-lived	3rd line of ChNPP	26,200	41900	Ground, metal scrap (partially in containers)	391
Low and intermediate level, short-lived	Buryakivka	554,000	1,048,600	Ground, scrap metal, concrete, equipment in containers, transport facilities	2,460

Tab. 4
Engineered radioactive waste storages inside ChEZ.

Fig. 4
Sections of Pidlisny Waste Storage with ILW.

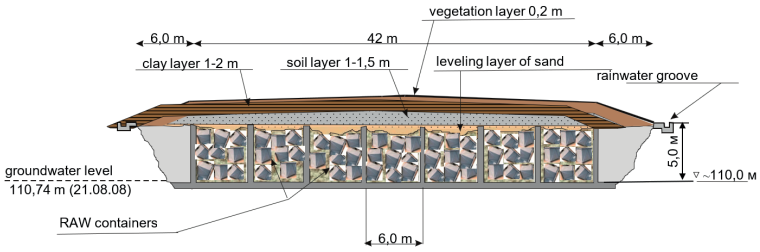

Fig. 5
Stylized cross section of radioactive waste storage 3rd Line of ChNPP.

Fig. 6
Trench-type near surface repository Buriakivka.

the wet/pool type Spent Nuclear Fuel Storage Facility 1 (SNFSF-1), located at ChNPP site. Based on its original design capacity, SNFSF-1, commissioned in 1986, can store most but not all of the 21,297 SNF assemblies with a total heavy metal equivalent of 2,415 t. Therefore, a technical solution was adopted, and its safety was justified, to allow storage placement of the SNF according to a "compacted scheme" that included using the reserve compartment.

Each RBMK-1000 SNF assembly consists of two fuel bundles settled vertically on a central rod. A bundle consists of 18 fuel elements, each of which is 3,640 to 3,644 mm long and a 13.57 to 13.9 mm external diameter and a nominal cladding thickness of 0.975 mm.

The ChNPP used standard fuel assemblies with ^{235}U with initial enrichments of 1.8 ± 0.05%, 2.0 ± 0.05%, and 2.4 ± 0.05%. Spent fuel plutonium concentration produces 4 kg/t of uranium. Table 5 provides the main radionuclide activities 20 years after reloading from the reactor for an initial enrichment of 2.4% and burnup of 24 MWt·day/kg U.

Recently, the internationally financed dry storage facility SNFSF-2 was commissioned to replace SNFSF-1 at the end of its designed lifetime in 2026. In 2021, SNFSF-2 became operational and reloading SNF from SNFSF-1 into the concrete modules of SNFSF-2 began.

Although the design, construction, and commissioning of several dedicated facilities for safely managing and disposing this radioactive waste and SNF is ongoing, due to significant delays, practically all waste and SNF remains in existing facilities.

Radionuclide	Activity [Bq]
^{85}Kr	5.80×10^{12}
^{90}Sr	7.82×10^{13}
^{90}Y	7.82×10^{13}
^{134}Cs	2.01×10^{11}
^{137}Cs	1.11×10^{14}
^{137m}Ba	1.05×10^{14}
^{154}Eu	1.17×10^{12}
^{155}Eu	1.89×10^{11}
^{238}Pu	1.65×10^{12}
^{239}Pu	3.43×10^{11}
^{240}Pu	9.64×10^{11}
^{241}Pu	5.64×10^{13}
^{241}Am	3.19×10^{12}
^{244}Cm	9.87×10^{11}

Tab. 5
Activity of main radionuclides in RBMK-1000 SNF assemblies at initial enrichment of 2.4% and burnup of 24 MWt·day/kg U, 20 years after reloading from the reactor.

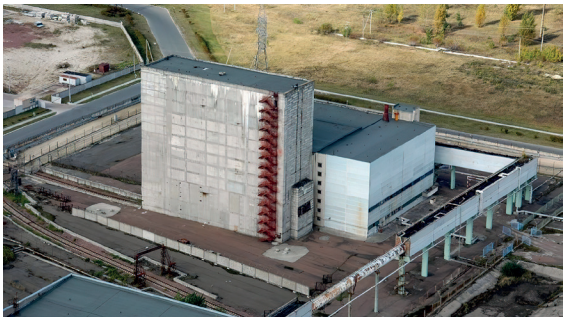

Fig. 7
Pool-type Spent Nuclear Fuel Storage Facility 1 (SNFSF-1) at ChNPP.

Fig. 8
Dry SNF storage SNFSF-2 at Chornobyl NPP.

Fig. 9
Central Storage for Spent Sealed Sources.

Furthermore, two Ukrainian-wide centralized storage facilities have been commissioned in the ChEZ – the central storage for WWER-1000 SNF built in cooperation with the United States of America (USA) and the central storage for spent sealed sources (see Figure 9), built in cooperation with United Kingdom (UK). Approximately 24,000 spent sealed sources have been loaded at the central storage facility so far (see Table 6), whereas SNF from WWER-1000 reactors has yet to be delivered to the ChEZ. It was planned that the first spent nuclear fuel from Ukrainian nuclear power plants (NPP) would be loaded into a centralized storage facility in April 2022.

Location	Main Radionuclides	Pieces	Activity (Bq)
Chamber 3, Row 2	^{60}Co	58	5.75 E+13
Chamber 3, Row 4	^{239}Pu	19100	3.53 E+09
Hot cell B	^{60}Co	16	1.22 E+09
Hot cell C	^{241}Am ^{226}Ra ^{60}Co	2 4 1	9.60 E+06 3.23 E+07 1.062 E+10
Radiation protection box	^{239}Pu	1,272	
Chamber 18, Row 7	^{239}Pu + Be	24	4.497 E+11
Chamber 18, Row 8	^{238} Pu + Be	509	5.708 E+12
Chamber 18, Cell 01/K	^{137}Cs	198	3.19 E+12
Chamber 18, Cell 04/K	^{137}Cs	388	6,45 E+12
Chamber 18, Cell 10/K	^{60}Co	14	1.88 E+12
Chamber 18, Cell 06/I	^{137}Cs	43	5.19 E+13
Chamber 18, Cell 01/A	^{90} Sr + ^{90}Y	70	3.1 5E+10
Chamber 18, Cell 12/K	^{60}Co	179	1.3 2E+10
Chamber 18, Cell 06/K	^{137}Cs	552	8.697 E+12
Stored sources in total		***22,430***	***1.36 E+14***
Free storage places		***19,100***	

Tab. 6
Inventory of the Central Storage for Spent Sealed Sources by June 30, 2021.

Record of Major Events and Corresponding Incidents at ChEZ since February 24, 2022

The following record summarizes primarily the information published by the State Nuclear Regulatory Inspectorate (SNRIU) at its website [9].

Thursday, February 24, 2022
5:00 a.m. The State Agency of Ukraine for the Management of the Exclusion Zone (SAUMEZ) orders the rapid evacuation of all nonessential employees from the ChEZ. SAUMEZ directed the National Guard of Ukraine military staff that were on duty protecting ChNPP nuclear facilities and on duty employees at these facilities to remain at their duty stations to continue performing essential tasks, recognizing but taking into account the enormous threat to these workers safety, health, and lives.
5:00 p.m. The Russian military takes control of all nuclear facilities and captures all Ukrainian staff remaining within the ChEZ. Their mobile phones were confiscated and the guard staff disarmed.
9:30 p.m. SNRIU informs the International Atomic Energy Agency (IAEA) that it had lost control of all nuclear ChEZ facilities.

Friday, February 25, 2022
Numerous SAUEMZ radiation monitoring stations identify unusual high radiation levels up to 7.6 higher normal values (see Figure 10) obviously caused by military activities. Subsequently monitoring station access was lost and remains unrecoverable.

Sunday, March 6, 2022
Several Shelter Object neutron detectors are lost and cannot be repaired, thereby, adversely affecting reliable control of potential criticality conditions.

Wednesday, March 9, 2022
11:11 a.m. The ChNPP 750 kilovolt (kV) power line is disabled, and electric power is lost at all facilities. The power line cannot be repaired due to shelling. Available diesel generators are activated to provide emergency power to safety-relevant equipment but these are designed for only 48 hours of continuous operation.

Friday, March 11, 2022
Forest fires break out in the central and western parts of the ChEZ and continue uncontrolled until March 18, 2022. During this time the Russian military prevented access of firefighting personal to the fires.

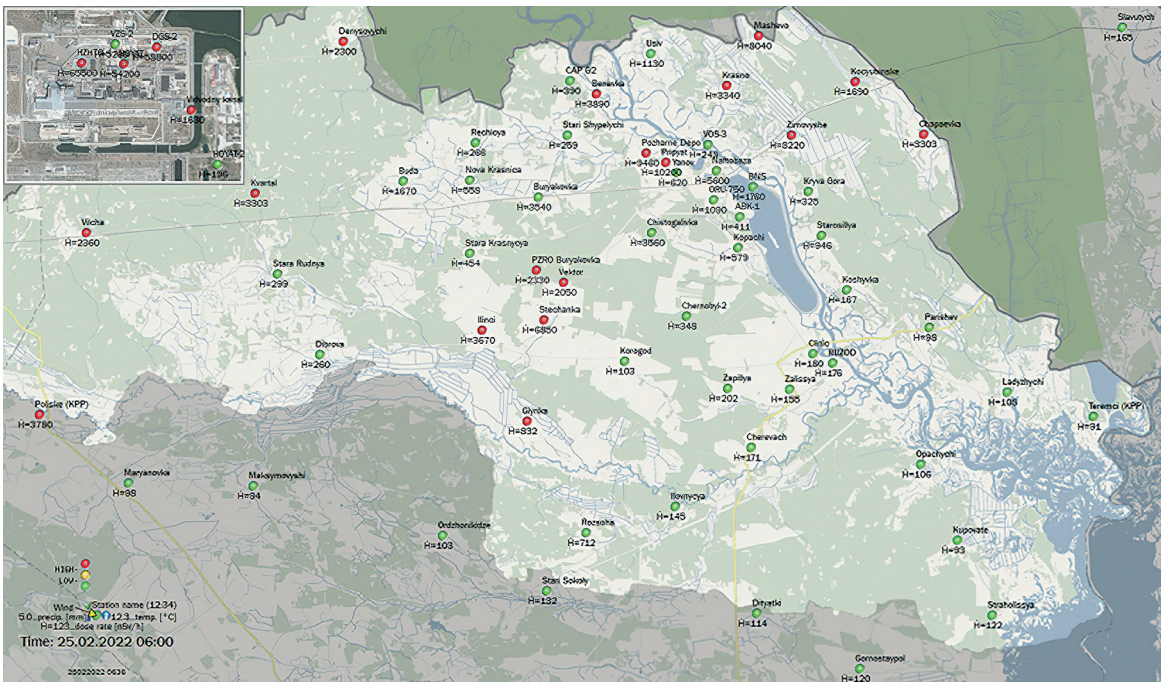

Fig. 10
Status of gamma radiation monitoring levels at ChEZ February 25, 2022.

Monday, March 14, 2022
Electric power is restored due to completed repair works at 5:45 p.m. All diesel generators are shut down.

Sunday, March 20, 2022
After 24 days, the Russian military finally allows 48 volunteers to replace 104 of the extremely exhausted employees who had remained on shift at their ChNPP duty stations since 24 February 2022. However, the larger day shift personnel, including the repair staff, did not return to ChNPP after its evacuation February 24th, 2022.

Thursday, March 31, 2022
At about 8:00 p.m., the Russian occupiers left the ChNNP territory. The radiation conditions at the site and the parameters of the equipment controlled by the operational personnel are within the limits set by the relevant technological regulations of nuclear installations. However, the day shift, including repair and contractor personnel have not been able to return to the site. The SNRIU started analyzing the possibility of resuming regulatory control over the state of nuclear and radiation safety and of nuclear materials at the ChNPP site and the Exclusion Zone.

Assessment of the Resulting Major Nuclear Threats

By occupying the ChEZ by its military, Russian President Putin caused and risked purposely and recklessly high nuclear threats, caused by:

- Inappropriate working conditions and staffing
- Loss of electric power
- Forest fires
- Shelling and explosions.

The following sections provide a first assessment of the resulting major nuclear threats.

Inappropriate working conditions and staffing

Starting on February 24, the remaining ChNNP staff was taken as hostage and forced to work under the close supervision of armed Russian soldiers. Operational personnel constantly worked under conditions of occupation, ensuring nuclear and radiation safety of all elements and systems of the nuclear facilities. The psychological state of the workers who were taken hostage deteriorated daily, with every hour of being under the constant supervision of the occupiers without mobile communications, which were confiscated by the Russian military in the first days of the occupation.
Throughout the stressful and difficult conditions at the ChNPP, its staff demonstrated a high level of solidarity and responsible attitude in performing their duties. It is very difficult to be in conditions of total control by the occupier and the available information about the plans of the Russian military to arrange a terrorist attack at the ChNPP.

These undue working conditions could have led to major mistakes and, consequently, to serious incidents or accidents. Moreover, the significantly reduced staffing and impossibility of calling for help by other specialized staff made it impossible to respond to arising repair needs and to implement emergency response measures. Altogether, it has to

Location	Fire Square [km²]	Average Activity [kBq/m²]		Concerned Inventory [Bq]	
		^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
March 11					
Stechanka	0.7	36	11.0	2.7E+10	8.0E+09
Poliske	0.8	540	8.6	4.3E+11	6.9E+09
Bober	8.5	1,400	5.7	1.2E+13	4.8E+10
Pukhove	3.8	950	4.1	3.6E+12	1.6E+10
March 16					
Korolivka	2.0	160	2.6	3.3E+11	5.2E+09
Poliske	2.9	420	8.1	1.2E+12	2.4E+10
Kotovske	2.4	460	5.4	1.1E+12	1.3E+10
March 17					
Rudnya-Grezlyanska	5.0	390	10.6	2.0E+09	5.33E+07
March 18					
Tarasi	2.3	310	7.0	7.1E+08	1.6E+07
Rudnya-Grezlyanska	0.9	350	11.9	3.0E+08	1.0E+07
Khristinivka	4.9	312	8.1	1.5E+09	4.0E+07

Tab. 7
^{137}Cs and ^{90}Sr inventories concerned by forest fires March 11 – 18, 2022.

be considered as great luck that such did not occur as far as known so far.

Loss of electric power

In the case of complete loss of electric power, the staff lose the ability to control the Chornobyl NPP nuclear facilities safety parameters, in particular the radiation state of both spent nuclear fuel storage facilities and the SNFSF-1 spent fuel pool water level and temperature. Moreover, fires cannot be identified, alarms cannot be raised, water cannot be added to maintain sufficient water levels, and permanent cleaning of the spent fuel pool water stops. Also, the ventilation systems will fail with no possibility to take compensatory measures. Thus, explosive hydrogen concentrations may be formed due to the radiolysis reaction.

For the Shelter object, a blackout will cause the loss of control over the parameters characterizing the state of nuclear and radiation safety, as well as the state of unstable structures. Additionally, under a blackout scenario the operation of the ventilation systems, which are important for safety, and the integrated control system will cease. In particular the neutron absorber injection system would cease to function. Ventilation system interruptions can cause the New Safe Confinement to lose its negative pressure, which could result in the release of gaseous radionuclides. In this situation radioactive aerosols can neither be captured, monitored, nor retained by HEPA filters.

Because of the loss of electric power at the ChNPP nuclear facilities and the limited capabilities of the stressed and exhausted operational personnel, the control of the safety parameters at the facilities cannot be guaranteed. Consequently, impacting the ability of the staff to effectively respond to both potential internal and external emergency events. This inability of the staff to effectively respond to these events could lead to severe radiation consequences.

Thankfully, additional diesel reserves at ChNPP and reliable functioning of the diesel generators electric power was not completely lost, although the external electric power supply was interrupted for almost 125 hours from March 9 – 14, 2022.

Forest fires

Due to high soil and vegetation contamination, forest fires are a permeant safety concern at ChEZ. Thus, the State Specialized Enterprise (SSE) Ecocenter operates a dedicated radiation monitoring system for directing firefighting and monitoring fire-related radionuclide distribution inside the ChEZ.

However, for unknown reasons, the system service terminated several hours after the Russian occupation making atmospheric radioactive pollution data unavailable and making it impossible to adequately respond to threats of the deteriorating radiation situation inside the ChEZ. Even worse, the military occupation conditions eliminated firefighting efforts. It is uncertain when these capabilities can be fully restored.

Forest fires in the cold season are an atypical phenomenon for the ChEZ, but there was a high probability of the intensity forest fires exceeding such limits in the spring and summer that could lead (in the absence of any firefighting measures) practically to completely burning the radioactively contaminated forests in ChEZ. Such a total destruction by fire could accordingly lead to a significant deterioration of the radiation situation in Ukraine and possibly throughout Europe.

According to the website of the Fire Information for Resource Management System (FIRMS) [10], fire areas in the period from March 11 to 18, 2022 were observed mainly in the western and central parts of the ChEZ. On March 11, 2022, the main fire areas were recorded near settlements of Poliske, Stechanka, Bober, and Pukhove. From March 12 to 15, no major fires were recorded. On March 16, forest fires resumed in the Poliske - Kotovske district, and broke out near the village of Korolivka. On March 17, a fire in the Poliske region spread northeast to the village of Rudnya-Grezlyanska and continued the next day. In addition, new cells have emerged in the area of village Tarasy and in the radioactively contaminated area outside the ChEZ

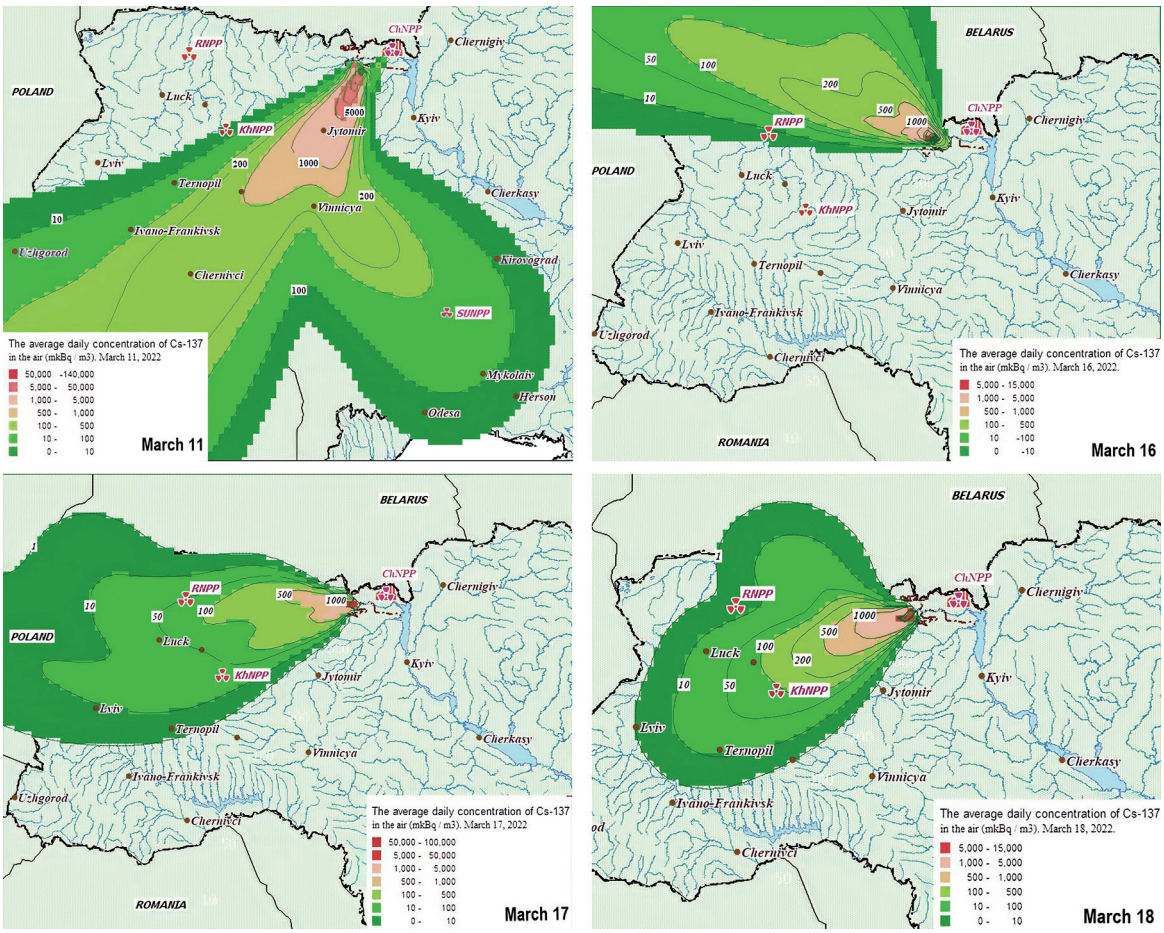

Fig. 11
Average daily ^{137}Cs activity concentration [μBq/m^3] in the surface air layer resulting from combustion products for certain days from March 11 to 18, 2022.

near the village of Novomoskovsk. Table 7 summarizes the concerned areas and ^{137}Cs and ^{90}Sr inventories.

The Department of Radiation Ecology of the ISP NPP of the National Academy of Sciences of Ukraine prepared a preliminary assessment of the spread of ^{137}Cs using additional input from the Weather Research and Forecasting (WRF) Model. Figure 11 presents the model calculation results.

During the first half of March 11, radioactive distribution drifted to the southwest and, by the end of the day, to the southeast and it was possible it would reach Moldova, Romania, and Black Sea via the central and southern of Ukraine.
The calculated average daily ^{137}Cs activity could reach 1 mBq /m³ at up to 150-200 km from the ChEZ. On March 16, the transfer direction changed to west and north-western Ukraine polluting the territory of Belarus, and subsequently transferring to the Baltic Sea. From March 17-18, the distribution continued west.
According to the FIRMS homepage on March 19, 2022, fires continued within the ChEZ (near Rudnya-Grezlyanska and Tarasy / Vlodimirovka / October), as well as in the radioactively contaminated area outside the Exclusion Zone near the village Khristinivka, Zhytomyr region. A new intensive fire center was formed in the 10-km zone of the CHNPP near the villages of Tilsty Les and Buda in an area with high levels of ^{137}Cs and ^{90}Sr pollution. Further spread of fire was recorded almost in the same areas March 20 to 21. In addition, less intense fires occurred in the southwestern part of the Exclusion Zone and in the Zhytomyr region near the boundaries of the zone.
During March 26, 2022, only a small fire near Poliskex was recorded and fires resumed near the Shelter Object on March 27. The cessation of rain showers in the late afternoon and evening of March 27 led to more intense fires in this area the next day. A new fire was also recorded in the “Rudyy Lis” approximately 2.5 – 4 km west of the ChNPP. The following day the burning stopped in this area, but fires continued in the Tarasov and in the Naroditsky regions. The resumption of heavy rainfall in the evening of March 29 led to an almost complete cessation of fires March 30 – 31, 2022.
According to the Institute for Safety Problems of Nuclear Power Plants (ISP NPP) modelling results, combustion products were transferred in the

southeast direction on March 27, and March 28 – 29 in the east. The daily average activity concentration of ^{137}Cs in surface air reached outside ChEZ up to 200 – 500 µBq/m^3 on March 28, but March 27 and 29 it did not exceed 10 µBq/m^3. From March 30 – 31, when Russian soldiers left, practically no additional radioactive surface air contamination within the territory of Ukraine was observed as a result of fires in ChEZ.

Although all modelling results suggest the Ukrainian regulatory limit for ^{137}Cs air pollutions of 0.800 mBq/m³ have not been exceeded, significantly more undue consequences could have occurred particularly due to the reasons mentioned earlier, as well as in the case of fires affecting waste dumps and/or waste storages. In the worst case, forest fires could directly impact the nuclear facilities at ChNPP which could result in practically unpredictable consequences.

Shelling and Explosions

Considering the nuclear threats of military battles near nuclear facilities and trusting basic international conventions and common sense, the Ukrainian armed forces headquarters was not prepared to defend the ChEZ territory against the Russian invaders and ordered Ukrainian defence personnel to stand down and not respond with military force. Shelling and explosions at ChEZ were most likely prevented thanks to this precaution.

However, satellite images confirmed that Russian military forces, several hundred at a minimum, brought significant amounts of ammunition into ChEZ which under the military operation and resulting occupation of the territory could have led to severe explosive damage affecting, in worst cases, the nuclear facilities.

Neither the New Safe Confinement nor the original Shelter Object, containing the damaged fourth reactor, nor other ChEZ nuclear facilities are hardened against military attack or for that matter designed to withstand an aircraft crash or similar accident.

Significant radioactive releases, similar to those after the 1986 accident, could occur from the instantaneous loss of negative pressure within either of the shelters due to shelling, explosions, or another event, such as an aircraft crash. Moreover, broken parts could fall on the original shelter and cause its collapse due to its limited stability.

Irrespective of high fissile materials amounts, criticality accidents are excluded reliably by ensuring sufficient spacing between SNF assemblies. However, in the case of shelling or explosions, this condition cannot be guaranteed which could result in an unplanned configuration/spacing of the assemblies with unpredictable consequences. If the SNFSF-1 or SNFSF-2 storage facilities are affected by explosive events from artillery shelling or missile strikes, the consequences might even exceed the those of the original reactor unit four accident, as the inventory of fissile materials in these facilities is several orders of magnitude higher.

Finally, as mentioned previously, the long-lasting electrical power loss could result in a concentration increase of radiolysis gases and possible explosions at the SNFSF-1 wet/pool-type storage.

Conclusions

Nuclear power plants and other nuclear facilities of Ukraine are for peaceful use of nuclear energy and, in accordance with Article 56 of the Additional Protocol to the Geneva Conventions of 12 August 1949 on the Protection of Victims of International Armed Conflict (Protocol I) of 8 June 1977, they are not intended for hostilities and must not be attacked [11].

Furthermore, the Russian Federation's military actions in ChEZ are in direct violation of treaty agreements. Specifically, Article 7 of the Convention on the Physical Protection of Nuclear Material, as amended (hereafter referred to as "the Convention") [12], which herein states:

The intentional commission of:

...

(e) an act directed against a nuclear facility, or an act interfering with the operation of a nuclear facility, where the offender intentionally causes, or where he knows that the act is likely to cause, death or serious injury to any person or substantial damage to property or to the environment by exposure to radiation or release of radioactive substances, unless the act is undertaken in conformity with the national law of the State Party in the territory of which the nuclear facility is situated;

...and...

(j) an act of any person who organizes or directs others to commit an offence described in sub-paragraphs (a) to (h);

...

shall be made a punishable offence by each State Party under its national law.

The Convention, to which the Russian Federation is signatory, entered into force in February 1987. and its subsequent Amendment in May 2016. The Convention and its amendment are seen as *"...crucial milestones in the development of the international legal framework for nuclear security, as they remain the only internationally legally binding undertakings in the area of physical protection of*

nuclear material and of nuclear facilities used for peaceful purposes."

The military occupation of the ChEZ, the holding hostage of the staff, the disruption of power lines and loss of power to the facilities within the ChEZ, the destruction of the radiation monitoring network, the hinderance of access of emergency response firefighting personnel are all clear violations of the Convention. The aggressive actions, ordered by the Russian President, have at a minimum resulted in substantive damage to the environment and injury to human health, and potentially may contribute to the premature death of individuals.

Considering the continuing attacks from the Russian forces on Ukraine, IAEA Director General (DG) Grossi outlined the following seven indispensable pillars of nuclear safety and security at an IAEA Board of Governors meeting on March 2 [13].

- The physical integrity of the facilities – whether it is the reactors, fuel ponds, or radioactive waste stores – must be maintained;
- All safety and security systems and equipment must be fully functional at all times;
- The operating staff must be able to fulfil their safety and security duties and have the capacity to make decisions free of undue pressure;
- There must be secure off-site power supply from the grid for all nuclear sites;
- There must be uninterrupted logistical supply chains and transportation to and from the sites;
- There must be effective on-site and off-site radiation monitoring systems and emergency preparedness and response measures; and
- There must be reliable communications with the regulator and others.

Specific to ChNPP and the waste storages and supporting facilities and infrastructure within the ChEZ, it can be seen from the discussion presented in this paper that the Russian military forces have violated each of the seven pillars outlined by DG Grossi.

It is important to note that already in the night from March 3 to 4, Russian forces shelled and attacked the Zaporizhzhya Nuclear Power Plant (ZNPP), setting fire to a training facility on the power plant's grounds, not only a clear violation of these pillars but of the above-mentioned conventions, as well.

The Russian Federation, as a signatory to these conventions, therefore, is obligated to charge, punishable by their law, the responsible individuals who ordered and instigated in their capacities at highest state duties the occupation of the ChEZ and attacks on other Ukrainian nuclear facilities, which resulted in the aforementioned violations. Failure of the Russian Federation to pursue appropriate charges as foreseen under the treaty would be a clear violation of their obligations under the Convention in intent and act and cannot be tolerated by the international community.

The highest-ranking representatives of the Russian Federation willfully and recklessly accepted and ignored the high risk of unpredictable nuclear accidents and the potential for catastrophic consequences to the population in many European countries. While it is extremely fortunate that such accidents have not already occurred, due to other fortuitous circumstances, such actions remain completely inexcusable.

Moreover, the criminal behavior of the highest-ranking representatives of Russian Federation and their willful violation of international conventions ratified by the Russian Federation raises the urgent question of how much longer the international community can tolerate their official position, which is to blame other for their own criminal actions. The Russian Federation's repeated misrepresentations and abuse of privileges, entrusted to them by international organizations, such as IAEA and the United Nations, cannot be tolerated and appropriate actions are required by the international community to address these abuses.

Acknowledgement

We would also very much like to thank Mr Terry Tetreault who assisted with editing the manuscript on very short notice, as well as other contributors who are not explicitly mentioned.

References

[1] United Nations General Assembly Resolution ES-11/1 adopted on 2 March 2022 at the eleventh emergency special session of the United Nations General Assembly.

[2] Law of Ukraine "On legal regime of territories affected by radioactive contamination result of the Chornobyl nuclear power plant."

[3] TACIS PROJECT – U4.03/04 Development of the National Strategy and Concept for State Program for Radioactive Waste Management in Ukraine (Part 1), including a Strategy for NNEGC Energoatom Radwaste Management (Part 2) (WMS-UA), TECHNICAL REPORT Task 1.1 Current situation of the legal matters and available institutional framework in the radioactive waste management in Ukraine, DBE TECHNOLOGY GmbH, Peine, October 2006.

[4] https://chernobylx.com/the-red-forest-the-most-radioactive-outdoor-environment-on-the-planet/

[5] https://www.unian.ua/ecology/chaes-rashisti-ne-tilki-rili-okopi-v-rudomu-lisi-a-y-tam-zhili-video 11775091.html?fbclid=IwAR0ICQrke3ah_czAlhz3h9HQbovxKCGjhdY-nOoGtT8Ta2umq3EVitCCUl50

[6] INSC PROJECT – U4.01/08-B Improvement of the infrastructure for radioactive waste management in the Chernobyl Exclusion Zone. Phase I: Safety assessment TASK REPORT 5.2 PRELIMINARY SAFETY ASSESSMENT REPORT FOR THE EXTENDED BURYAKOVKA DISPOSAL FACILITY, DBE TECHNOLOGY GmbH, Peine, June 2012

[7] https://telegraf.com.ua/ukraina/2022-04-01/5701140-budut-pit-chay-i-svetitsya-ot-radosti-okkupanty-poluchili-obluchenie-na-chaes-no-raduyutsya-chto-nagrabili-posudy

[8] INSC PROJECT – U4.01/09 B Disposal Concepts for Radioactive Waste in Ukraine, Technical Report Task 2, DBE TECHNOLOGY GmbH, Peine, October 2013.

[9] https://snriu.gov.ua/timeline?&type=posts&category_id=15

[10] https://firms.modaps.eosdis.nasa.gov/

[11] Protocol Additional to the Geneva Conventions of 12 August 1949, and relating to the Protection of Victims of International Armed Conflicts (Protocol 1)

[12] INFCIRC/274/Rev.1/Mod. 1 (Corrected) Date:18 October 2021.

[13] https://www.iaea.org/newscenter/pressreleases/iaea-director-general-grossis-initiative-to-travel-to-ukrain

[14] https://www.iaea.org/newscenter/statements/iaea-director-generals-introductory-statement-to-the-board-of-governors-7-march-2022

Authors

Anatolii V. Nosovskyi

Member, Academy of Science of Ukraine

Director, Academy of Science of Ukraine Institute of Safety Problems of Nuclear Power Plants

Anatoly Nosovsky, born in 1954, graduated from the Polytechnic Institute in Leningrad. Nosovsky researched nuclear submarine radiation protection for the I. Kurchatov branch of the Institute of Atomic Energy in Sosnovy Bor. In 1986, he ensured employee radiation safety during the construction of the Chornobyl nuclear power plant (ChNPP) shelter facility and associated restoration efforts.

In 1988, he served as the ChNPP Deputy Chief Engineer and later as the Deputy General Director for Radiation Protection. After decommissioning ChNPP, he was the deputy director for science at State Scientific and Technical Center for Nuclear and Radiation Safety in Slavutich. In 2004, he was a department head and, since 2015, a director at the National Academy of Sciences of Ukraine Institute for Safety Problems of Nuclear Power Plants.

Nosovsky's former positions and awards include: Doctor of Technical Sciences, Professor of the Department of Nuclear Power Plants and Engineering Thermal Physics, Academician of the National Academy of Sciences of Ukraine, Honorary Worker of the Nuclear Energy of Ukraine, Laureate of the State Prize of Ukraine in Science and Technology, Member of the National Commission for Radiation Protection of the Population of Ukraine, Member of the Board of the Ukrainian Nuclear Society, Expert Council of the Ministry education and science of Ukraine; scientific and technical councils of NNEGC "Energoatom," and the Ministry of Energy of Ukraine.

Vyacheslav M. Shestopalov

Member, Presidium of the Academy of Science of Ukraine

Director, Academy of Science of Ukraine Radioecological Centre

Vyacheslav Shestopalov, born in 1936, graduated from Kyiv University in 1959 majoring in hydrogeology. In 1971 Shestopalov earned his PhD in 1971 and Doctor of Science in 1983 at the Kyiv Institute of Geological Science. He served in 1991 as a teaching professor, in 1995 he became Academician of National Academy of Sciences of Ukraine, in 2004-2015 as the Academician-Secretary of the Department of Earth Sciences of National Academy of Sciences of Ukraine, and Advisor to the Presidium of National Academy of Sciences of Ukraine in 2015, and currently is Director of State Enterprise at the Radioenvironmental Centre of National Academy of Sciences of Ukraine.
He has over 30 years of experience with radioactive waste disposal and eliminating the consequences of the Chornobyl NPP catastrophe. Professor Shestopalov has authored more than 600 publications, including 28 books. He was also awarded three Orders of Ukraine "For Merit" in 2002, 2008, and 2016 and the State Prize of Ukraine in the field of science in 2004.

Iurii Shybetskyi

Principal scientist, Academy of Science of Ukraine Radioecological Centre

Iurii Shybetskyi was born in 1960 and graduated in 1983 from Kyiv University and earned his PhD in isotopic geochemistry at the Kyiv Institute of Geochemistry and Mineral Physics in 1994. He has 25 years of experience in the field of radioactive waste disposal as a Principal Scientist at State Enterprise "Radioenvironmental Centre of National Academy of Sciences of Ukraine" and as a Member of the National Commission for Radiation Protection of Ukraine. His main areas of expertise include radioactive waste disposal siting; safety assessments; national legislation development of norms and programs for radioactive waste management; and scientific project management. Iurii Shybetsky has authored more than 100 publications, including six books. He also helped develop the following Laws of Ukraine: "On State Ecological Program for Radioactive Waste Management in Ukraine" (2008), "On radioactive waste management" (2019), of the Decree of Cabinet "On Radioactive Waste Management Strategy in Ukraine" (2009), of the Regulations "General safety provision for geological disposal of radioactive waste" (2007), and "Siting Requirements for Radioactive Waste Disposal" (2008).

As leading Ukrainian Expert, he was responsibly involved in several EU-funded international cooperation projects e.g., U4.01/08-C, "Improvement of the Waste Classification System in Ukraine" (2011-2012); U4.01/09-B, "Disposal concepts for Radioactive Waste Management in Ukraine" (2012-2017); and U4.01/14-B, "Development of a National Plan for Radioactive Waste Geological Disposal in Ukraine" (since 2018).

Dr. Jürgen Krone

Before retirement 2018 CEO of DBE TECHNOLOGY GmbH

Jürgen Krone was born 1955, graduated with a degree in computer science in 1979 and earned his PhD in 1981 from Kharkiv Polytechnical Institute. He has held various industrial management positions focusing on engineering and applied research, including several production atomization and environmental protection projects. In 1996, Krone's professional and scientific focus became radioactive waste disposal. From 2001 until retirement in 2018, he led the newly founded DBE TECHNOLOGY GmbH. 2001 – 2021 he led a consortium of prominent European radioactive waste management organizations that implemented numerous internationally funded cooperation radioactive waste management projects in Eastern Europe and, in particular, Ukraine.