Deliverable 8.13: Analysis of the conditions of the state-of-emergency radioactive wastes packages contained SNF, FCM or HLW/LLW generated due to ChNPP accident

Work Package 8

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EURAD Deliverable 8.13 – Analysis of the conditions of the state-of-emergency radioactive wastes packages contained SNF, FCM or HLW/LLW generated due to ChNPP accident

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EURAD Deliverable 8.13 – Analysis of the conditions of the state-of-emergency radioactive wastes packages contained SNF, FCM or HLW/LLW generated due to ChNPP accident

29.

Executive Summary

The main objective of Subtask 4.2 of the WP8 "Spent Fuel Characterisation and Evolution until Disposal" of the EURAD programme "Analysis of the conditions of the state-of-emergency radioactive waste packages containing SNF, FCM or HLW/LLW generated due to ChNPP accident " is to describe how the handling of spent nuclear fuel (SNF), including damaged SNF, fuel containing materials (FCM), High Level or Low Level Waste (HLW/LLW) is carried out at the Chornobyl nuclear power plant (ChNPP) and in the Chornobyl exclusion zone.

Brief information about the nuclear power industry of Ukraine is given, indicating the types of reactors at each Ukrainian NPP and short characteristics of these reactors.

Some specific characteristics of the nuclear fuel of the RBMK-1000 reactor type, which were used at the Chornobyl nuclear power plant are provided.

Next, general solutions for spent nuclear fuel management in Ukraine (sub-chapter 4.1 and 4.2) and the specific implementation of these solutions at the Chornobyl nuclear power plant is described, taking into account that the Chornobyl NPP is currently shut down and is in a state of decommissioning.

The deliverable contains description of both the old "wet" SNF storage facility at the Chornobyl nuclear power plant - Independent Storage Facilities -1 (ISF-1), and the new, "dry" storage facility - ISF-2. The deliverable sets out in detail the main aspects of the technologies used at the ChNPP for both “wet” and “dry” SNF storage, including damaged SNF handling.

The deliverable also provides description of the main approach for monitoring the SNF condition in the Independent Storage Facilities in Ukraine and some details concerning SNF conditions monitoring at ChNPP ISF-1 and ISF-2 in the process of long-term storage.

Since during the operation of the Chornobyl nuclear power plant a certain amount of damaged SNF (DSNF) was formed, it was also necessary provide some DSNF handling procedures in the technological chains of the SNF handling at ISF-1 and ISF-2.

The deliverable describes the main aspects of the management of damaged spent nuclear (DSNF) fuel at the Chornobyl NPP.

The deliverable discusses probable accident scenarios for SNF packages, the accident initial events that can lead to such accidents and corresponding consequence analysis. In addition, design measures to prevent accidents and eliminate the consequences of accidents are described.

Also, this deliverable provides information on the situation with post-accident high-level radioactive waste (HLW) containing damaged nuclear fuel, fuel fragments and fissile materials in radioactive waste disposal facilities in the Chornobyl exclusion zone.

Finally, the deliverable describes special installations at ChNPP for radioactive waste processing.

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Glossary

ALARA	As Low As Reasonably Achievable (principle)
ANSI	American National Institute of Standardization
AR	Absorber rods
CE CPS	Control elements of control and protection systems
ChEZ	Chornobyl Excluding Zone
ChNPP	Chornobyl Nuclear Power Plant
CHTS	Canister handling and transportation system
CSM	Concrete storage module
DBE	Design basis event
DSC	Dry Storage Canister
DSNF	Damaged spent nuclear fuel
DWC	Double walled canister
FA	Fuel assembly
FAT	Factory acceptance testing
FCM	Fuel containing materials
FE / FR	Fuel element, fuel rod (part of FA)
FFD	Fuel failure detection
FGD	Forced gas dehydration system
FR	Fuel rod
FSFA	Fail Spent Fuel Assembly
FR	Fuel Rod
FT	Fuel tube
HGTO	Russian acronym for Storage for Solid and Liquid Radioactive Waste (ХЖТО)
HI-TRAC-H	OSTC, On-site transport container for ISF-2
HLW	High-level waste
HTO	Russian acronym for temporary storage facility of solid radioactive waste
ISF-1	Interim/Independent Spent Fuel storage facility No.1 of Chornobyl NPP
ISF-2	Interim/Independent Spent Fuel storage facility No.2 of Chornobyl NPP
ITS	Important to safety (equipment or systems)
LLW	Low-level waste
MCC	Metal Concrete Container/Cask
MCT	Maximum cladding temperature (fuel element)
MDE	Maximum design basis earthquake
MLW	Medium level waste
NDT	Non-destructive testing
NF	Nuclear fuel
NM	Nuclear materials
NUHOMS	NUTECH Horizontal Modular Storage

OSTC	HI-TRAC-H, On-Site Transport Container
PVLRO	Russian acronym for temporary repository point of radioactive waste
PZRO	Russian acronym for repository point of radioactive waste
RC	Reactor core
RD	Regulatory document
RF	Reactor facility
RU	Reactor unit
SCR	Spontaneous chain reaction
SFA	Spent fuel assembly
SFP	Spent fuel pool
SFPF	Spent Fuel Processing Facility
SFSA	Spent fuel storage area
SLW	Short lived radioactive waste
SNF	Spent nuclear fuel
SNRIU	State Nuclear Regulatory Inspectorate of Ukraine
SSE	State specialised enterprise
TS	Technical specification
TTB	Transport transfer basket
TUC	Transport Utility Cask
UDDS	Unified design documentation system
US NRC	United States Nuclear Regulatory Commission
VHTVAO	Russian acronym for temporary repository of high level of radioactive waste
VVSM	Vertical Ventilated Storage Module

1. Introduction

The main objective of the Subtask 4.2 of the WP8 "Spent Fuel characteristic and Evolution until Disposal" of the EURAD project "Analysis of the conditions of the state-of-emergency radioactive waste packages containing SNF, FCM or HLW/LLW generated due to ChNPP accident " is to describe how the handling of packages with spent nuclear fuel (SNF) from ChNPP reactors, including damaged SNF, is arranged at ChNPP and provides information on the situation with post-accident high-level radioactive waste (HLW) containing damaged nuclear fuel, fuel fragments and fissile materials in radioactive waste disposal facilities in the Chornobyl exclusion zone.

2. Nuclear power industry in Ukraine

Nuclear power industry is an important branch of the Ukrainian economy. In Ukraine, there are 4 nuclear power plants with 15 power units, one of which, Zaporizhzhya NPP, with 6 VVER power units with a total installed capacity of 6,000 MW, is the largest in Europe. By number of power reactors (all of VVER type), Ukraine ranks eighth in the world and fifth in Europe in terms of installed capacity (total 16680 MW as for 01.01.2022) of nuclear power plants.

Ukraine inherited twelve power units from the USSR, three more were commissioned after its collapse - in 1995 and 2004. All power units with RBMK reactors operating in Ukraine were part of Chornobyl NPP. As a result of the Chornobyl accident, the power unit No.4 was destroyed, the rest of power units were alternately shut down between 1991 and 2000. Thus, all remaining reactors in the country are of VVER type, 2 - VVER-440 and 13 - VVER-1000. Brief characteristics of power units of the Ukrainian NPPs are given in Table 1.

In 2017, the contribution of nuclear power amounted to 55% of the total electricity production in Ukraine, the total capacity of NPPs was 13107 MW.

Figure 1 – Zaporizhzhya NPP

Name	**Power unit**	**Reactors**	**Capacity, MW**	**Start of construction**	**Commissio-ning**	**End of operation**	**End of design lifetime**	**Lifetime extension**	**Fuel**
Zaporizhzhya NPP	1	VVER-1000	1000	1980	1984		23.12.2015	23.12.2025	TVEL
	2	VVER-1000	1000	1981	1985		19.02.2016	19.02.2025	TVEL
	3	VVER-1000	1000	1982	1986		05.03.2017	05.03.2027	TVEL
	4	VVER-1000	1000	1983	1987		04.04.2018	04.04.2028	TVEL
	5	VVER-1000	1000	1985	1989		27.05.2020		TVEL and Westing house
	6	VVER-1000	1000	1986	1995		21.10.2026		TVEL
Rivne NPP	1	VVER-440	440	1973	1980		22.12.2010	22.12.2030	TVEL
	2	VVER-440	440	1973	1981		22.12.2011	22.12.2031	TVEL
	3	VVER-1000	1000	1980	1986		11.12.2017	11.12.2037	TVEL
	4	VVER-1000	1000	1986	2004		07.06.2035		TVEL
Khmelnytskyi NPP	1	VVER-1000	1000	1981	1987		13.12.2018		TVEL
	2	VVER-1000	1000	1985	2004		07.09.2035		TVEL
	3	VVER-1000	1000	1986	frozen construction				
	4	VVER-1000	1000	1987	frozen construction				

Name	**Power unit**	**Reactors**	**Capacity, MW**	**Start of construction**	**Commissio-ning**	**End of operation**	**End of design lifetime**	**Lifetime extension**	**Fuel**
South Ukrainian NPP	1	VVER-1000	1000	1977	1982		02.12.2013	02.12.2023	TVEL
	2	VVER-1000	1000	1979	1985		12.05.2015	31.12.2025	TVEL
	3	VVER-1000	1000	1985	1989		10.02.2020		TVEL and Westing house
	4	VVER-1000	1000	1987	mothballed				
Chornobyl NPP	1	RBMK-1000	1000	1970	1977	1996			
	2	RBMK-1000	1000	1973	1978	1991			
	3	RBMK-1000	1000	1976	1981	2000			
	4	RBMK-1000	1000	1979	1983	1986			
	5	RBMK-1000	1000	1981	cancelled				
	6	RBMK-1000	1000	1981	cancelled				

Table 1 – Brief information on power units of Ukrainian NPPs

3. Nuclear fuel

Until 2011, all nuclear fuel for Ukrainian for Ukrainian nuclear power plants (both for VVER and RBMK reactors) was supplied from Russia by TVEL Company. Supplies of fuel for RBMK reactors were stopped in 2000 due to the final shutdown of the Chornobyl nuclear power plant.

In 2008, Ukraine embarked on a diversification of fuel supplies, concluding a contract with the American company Westinghouse Electric Company for the supply of at least 630 fuel assemblies during 2011-2015 for the phased replacement of Russian fuel at three power units with VVER-1000; in 2011, Westinghouse began supplying its FAs to Ukraine.

In April 2012, at the 3rd power unit of South Ukraine NPP, which was operated in a pilot industrial mode using Westinghouse fuel, breakdowns in the FAs of this company were detected and their use was suspended. According to the results of investigation of the Ukrainian commission, a conclusion was made about the design errors of these FAs. Subsequently, the design of the fuel assembly was improved and Ukraine is currently purchasing FAs from Westinghouse for power units with VVER-1000 reactors.

As of 2015, the Russian company TVEL continued to be the main supplier of nuclear fuel for Ukrainian nuclear power plants, providing more than 90% of Ukraine's needs. Fuel from Westinghouse was supplied only for the 3rd power unit of the South Ukrainian Nuclear Power Plant.

At the end of 2018, Westinghouse already supplied 46% of nuclear fuel to Ukraine, the remaining 54% was supplied by the Russian concern TVEL.

According to NNEGC Energoatom, for six months of 2019, Russian-made fuel for $ 47 million 173.1 thousand was purchased for the Ukrainian nuclear power plants (NPPs), and Swedish-made fuel (Westinghouse) – for $ 51 million 228.9 thousand.

In addition, Ukraine extended the agreement expiring in 2020 on the purchase of Russian nuclear fuel for another five years.

After the start of Russia’s war against Ukraine (February 2022), Energoatom reported that Ukraine was completely abandoning the purchase of Russian fuel for nuclear power plants and intended to completely replace it with Westinghouse assemblies from the beginning of 2024. In March 2023, the press service of the Ministry of Energy of Ukraine announced its intention in three years to establish its own production of nuclear fuel for nuclear power plants, which could replace Russian fuel on the European market.

3.1. Characteristics of nuclear fuel of Chornobyl NPP

3.1.1. Fuel assemblies of RBMK reactors

The RBMK-1000 reactors (High Power Channel Reactor) were operated at Chornobyl nuclear power plant.

Upon reaching the design (maximum) burnup value, the SFAs were removed from the reactor using refuelling machine (REM) and placed in separate water-filled canisters in the at-reactor spent fuel pools. Each of three reactors of the Chornobyl NPP has two spent fuel pools with a capacity of 900 SFAs each.

The spent fuel pools were filled with water and had special heat exchange units for removing heat generated during the radioactive decay of fission products. To prevent corrosion of fuel elements claddings, the water of spent fuel pools underwent special chemical treatment.

SFAs were kept in these pools for at least 2 years, after which they were transported to the spent nuclear fuel storage facility located on the territory of power plant - ISF-1. The design of ISF-1 sections, in which the SFAs are stored, is close to the design of at-reactor spent fuel pools. The capacity of ISF-1 is 21,900 SFAs. More information on ISF-1 is given in chapter 4.3.1

Currently, all ChNPP reactors are shut down and nuclear fuel is unloaded from them. All SFAs are placed in the existing “wet” SNF storage facility - ISF-1.

Since ISF -1 has a limited service life (up to 2022), a new dry SNF storage facility, ISF-2, has been built at the ChNPP site. This storage facility was commissioned in 2021. A detailed description and characteristics of ISF-2 are given in chapter 4.4.1.

After the start of Russia’s war against Ukraine (February 2022), ISF-2 storage loading has been stopped.

Brief characteristics of fuel assemblies (FA) of RBMK-1000 reactors are given below with main parameters in Table 2.

The RBMK fuel assembly consists of two identical fuel rod bundles - the upper (TFB) and the lower (LFB), which are placed vertically one above the other in the reactor core channel. Each bundle includes 18 fuel rods located around a frame tube (FT) in two rows - 6 fuel rods in the inner row and 12 fuel rods in the outer row. Structurally, the RBMK fuel rod consists of a fuel pellets in a protective shell (fuel cladding), sealed at the ends with a plug and a tip using 33 contact butt welding. On the side of the tip there is a free volume - a gas collector with a fuel tablet column clamp placed in it. The fuel rod tips are fixed in the end grids using crimp rings. In each bundle, the fuel elements are spaced by ten spacer grids (SG) made of stainless steel or zirconium alloy. The spacer grids are fastened by pressing the walls of their guide bushings into the grooves on the SG. Both bundles are connected into a single fuel assembly using a central rod or pipe for the gamma camera, passing inside the TFB and LFB frame pipes. In the TFB, the fuel rods are located with the tips up, and in the LFB - down. The end caps of the TFB and LFB fuel elements are located in the centre of the RBMK reactor core and are spaced from each other at a distance of ~30 mm to compensate for the elongation of the cladding tubes. The alloy Zr-1%Nb (E110) is used as a material for shells and end parts of fuel rods. The fuel is sintered tablets and bushings made of uranium dioxide or a mixture of UO_2 + Er_2O_3 with 2.4-3.0% enrichment in U-235 (the percentage of Er_2O_3 depends on the enrichment of the fuel in U-235). To reduce the energy release at the junction of the LFB and TFB, screen tablets with less enrichment are used. The movement of fuel pellets along the length of the fuel rods is prevented by clamps

Two types of fuel assemblies are used: - type 49 and type 50. FAs with central supporting rod of 12 mm in diameter (assemblies of type 50). FAs with a hollow supporting tube that is of 12x2.75 mm in diameter for gamma-camera (assemblies of type 49).

Each fuel bundle contains 18 fuel rods with a length of 3640 mm and an external diameter of 13.6 mm (Figure 2). In the upper part of the assembly, a suspension rod with a protective plug is welded for sealing the technological channel of reactor, in which FA is located.

The total weight of uranium in the fuel assembly is 107-117 kg, dependent of the type of the SFA.

Object	Unit of measurement	Numerical value, description
SFA length with suspension rod	mm	10014-1033 (type 50 SFA), 10034-10054 (type 49 SFA)
Length of bundle (cassette) of FR	mm	3642
SFA outer diameter (by spacer grid)	mm	79 ± 0.4
SFA weight	kg	185 ± 4
Number of FR in one FA bundle	pieces	18
Configuration of assembly with FR	pieces	6 on a diameter of 32 mm; 12 on a diameter of 62 mm
Outer diameter of FR cladding	mm	13.57 – 13.90
Inner diameter of FR cladding	mm	11.7-12.1
Outer diameter of fuel pellet	mm	11.52
Enrichment: • minimum • maximum	wt. %	1.8 ± 0.05 2.4 ± 0.05
Cladding material		Zr + 1% Nb
Length of active part of fuel	mm	3460
Size of expansion gap	mm	20 - 27
Fuel density	g/cm^3	10.4 – 10.7
Dimensions of central rod (inner/outer diameter)	mm	12.5/15
Central rod material		Zirconium alloy E-125
Mass of UO_2 in FA	kg	135

Table 2 – Parameters of RBMK-1000 fuel assembly (FA)

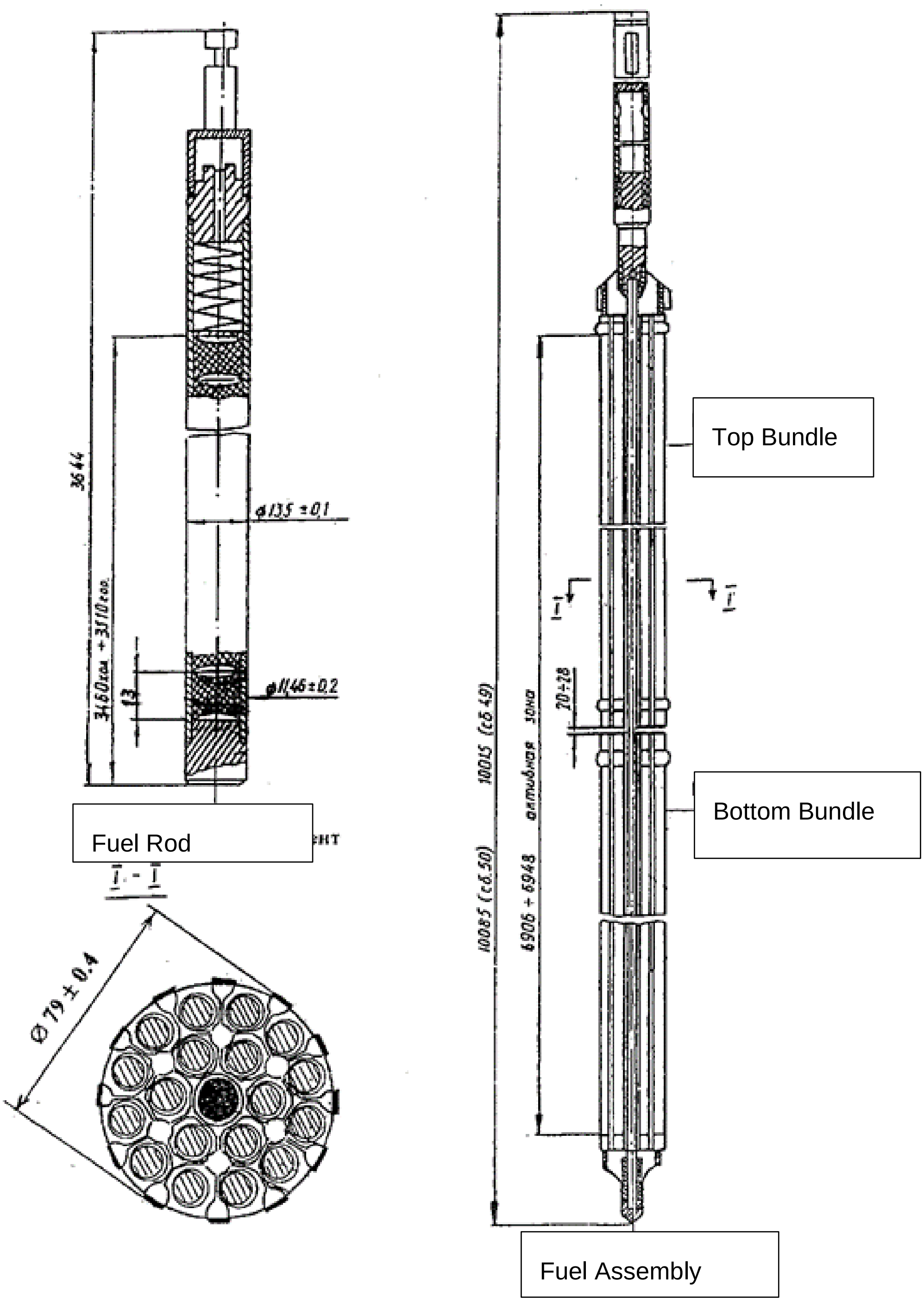

Figure 2 – Fuel rod. RBMK-1000 fuel assembly

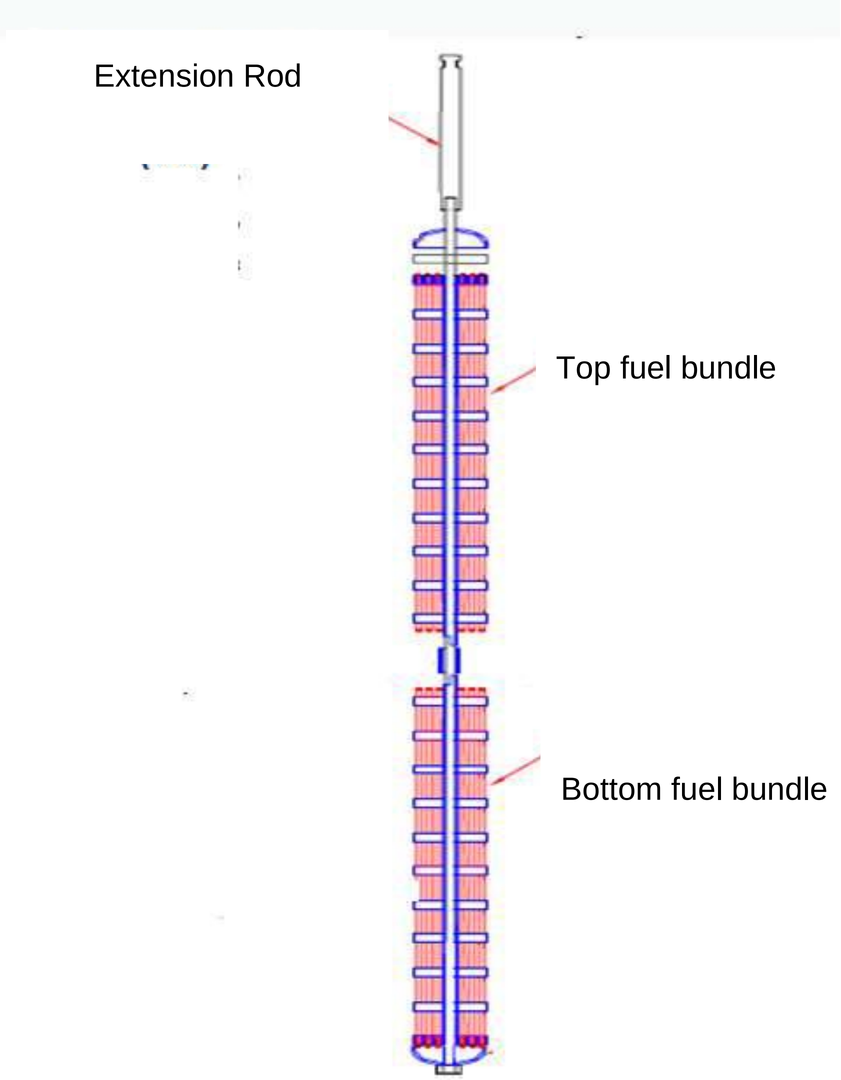

Figure 3 – RBMK-1000 fuel assembly

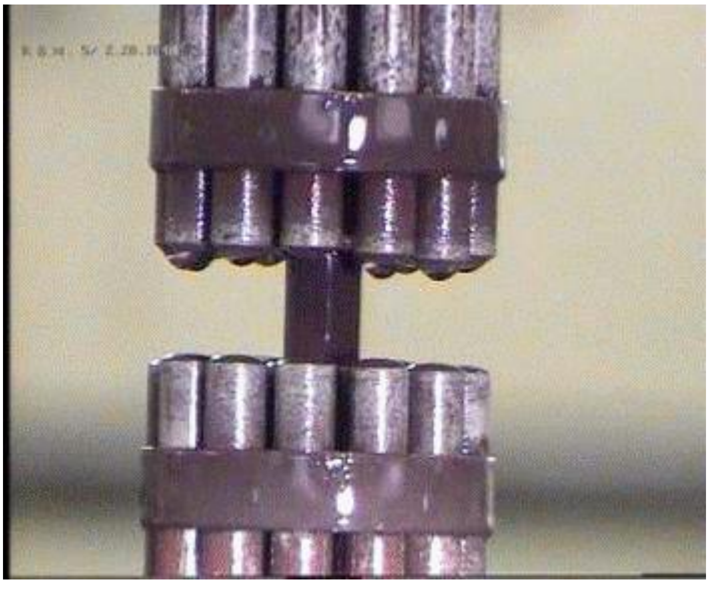

Figure 4 – Expansion gap between the fuel element bundles

At Chornobyl NPP, FAs with initial enrichment in uranium-235 of 1.8, 2.0 and 2.4% were used.

Table 3 presents data on the average and maximum burnup of RBMK-1000 SFAs with various initial enrichment.

Initial enrichment, %	Average	Maximum
1,8	15170	21900
2,0	17260	22940
2,4	18580	23550

Table 3 – Maximum burnup of RBMK-1000 FA

4. Spent Nuclear Fuel Management in Ukraine

4.1. Prospects for SNF long-term storage

Spent nuclear fuel storage is a necessary stage in the nuclear power plant fuel cycle. After unloading from the reactor, holding (storage) of SNF in an aqueous medium in the at-reactor spent fuel pools ensures a decrease in residual heat release (up to 2-10 kW per SFA) and decay of the most active short-lived radionuclides, such as iodine-131, xenon-133, etc. The time required for this is usually 1-3 years, depending on the type of nuclear fuel. Initially, it was assumed that after the end of the required holding period, the spent nuclear fuel would be transported to the radiochemical reprocessing plant. Currently, only a few countries with a developed nuclear power industry are reprocessing SNF - England, France. Some countries are preparing to start reprocessing SNF - Japan, China. The United States has abandoned the massive reprocessing of fuel unloaded from reactors and stores it in special storage facilities. However, most countries with a nuclear power industry pursue a policy of the so-called "deferred solution", which means storing spent nuclear fuel for a long time (50-100-300 years).

The increase in the SNF storage time led, in turn, to a change in the technological requirements for the storage process and, in general, to a change in the storage technology itself: at present, a transition from a "wet" method of SNF storage to a "dry" method is under way.

Each SNF storage technology has its own advantages and disadvantages, but in practice, as a rule, a combination of the two technologies is implemented. First, the SNF freshly unloaded from the reactor is sent for storage to the spent fuel pools, and then, after a certain holding time, it is transferred (or is planned to be transferred) to dry storage.

The total storage period of spent nuclear fuel after unloading from the reactor before its processing and/or disposal, taking into account the permissible wet storage period (~ 5-40 years) and the currently assumed dry storage period (50-100 years), can be up to 300 years. With such a storage period, the issues of ensuring safety during SNF storage are especially critical, as well as issues related to the study of SNF behaviour under conditions of wet and then dry storage.

4.1.1. Requirements for SNF storage facilities

The main requirements for all types of SNF storage facilities are as follows:

- Ensuring nuclear safety during storage, transport and processing operations with spent fuel;
- Ensuring the integrity (leak tightness) of fuel elements;
- Ensuring radiation safety of personnel and environmental protection;
- Monitoring the removal of residual heat, guaranteeing the integrity of fuel cladding and the safety of fuel in storage facility;
- Elimination of radioactive substances release outside the storage facilities into the environment;
- Possibility of fuel retrieval (removal) from storage facilities;
- Rational organization of storage of defective spent fuel (with defective spent fuel assemblies and fuel elements).

In addition, in accordance with the safety regulations in force in Ukraine, the following technological requirements are imposed on SNF storage facilities:

- Ensuring physical safety (protection) of spent nuclear fuel;
- Compliance with Safeguards (non-proliferation of nuclear materials).

Furthermore, the additional requirements are imposed on each type of storage facility depending on the type of storage facility and storage technology.

4.1.1.1. Requirements for wet SNF storage facilities

Long-term experience of wet storage of spent nuclear fuel in different countries has proven its reliability and convenience, especially for reduction of radiation loads level and removal of residual heat release of spent fuel immediately after unloading from the reactor. Wet storage allows direct monitoring of SNF condition, its presence. Cooling water parameters in wet storage are maintained using simple and reliable technologies. Water provides both the necessary biological shielding during SNF storage and process operations for fuel loading and it's unloading from pools, as well as residual heat removal.

All "wet" SNF storage facilities in Ukraine are reinforced concrete structures lined with stainless steel. The fuel is stored in them either at the bottom of the pool (in racks - spent nuclear fuel from VVER), or suspended on a metal ceiling (spent nuclear fuel from RBMK).

In Ukraine, only one separate "wet" SNF storage facility has been built at ChNPP (see 4.5). The rest of the "wet" SNF storage facilities are VVER 440 and VVER 1000 at-reactor spent fuel pools.

Along with general requirements, specific additional requirements are imposed on wet SNF storage facilities:

- Ensuring the cooling of water in the storage facility to a temperature not exceeding 50°C, with the removal of residual heat from the spent nuclear fuel;
- Ensuring water purification from radioactive substances entering the water with surface contamination of fuel elements by corrosion products, as well as from fission products from damaged (leaking) fuel elements;
- Ensuring the necessary transparency of the pool water when conducting remote reloading operations under water;
- Preventing the possibility of water leakage from pools into the environment and organised collection of possible leaks;
- Ensuring radiation safety and environmental protection;
- Collection and removal of liquid and solid radioactive waste.

When designing and operating "wet" storage facilities in accordance with the requirements of regulatory documents, possible emergencies are taken into account, associated with both the impact of external factors (earthquake, hurricane, flood, etc.), and arising from failures of equipment of systems important for safety, personnel errors, etc. Particular attention, from the point of view of ensuring nuclear and radiation safety, is paid to emergency situations associated with the so-called "freezing" of the fuel (i.e., when the fuel is in a state not foreseen by the storage technology and caused by equipment failure during time that exceeds the time established by the regulations), or its fall when carrying out operations for loading, moving and unloading fuel from the pool. The consequences of beyond design basis accidents are also considered: occurrence of SCR in the storage facility, complete dehydration of storage facility, fall of process equipment and building structures on the ceilings of storage compartments and stored fuel.

Wet storage of spent nuclear fuel is carried out in the at-reactor spent fuel pools, freestanding intermediate SNF storage facilities located on the territory of NPP, as well as in buffer storage facilities at radiochemical plants (storage facilities of the latter type were not built in Ukraine).

Common to all types of power reactors is the placement of spent fuel assemblies unloaded during refuelling in the at-reactor spent fuel pool. In the process of holding, the radioactivity and heat release of SNF decrease, which facilitates the further SNF management and makes it safer. For SNF sent to radiochemical plants, the minimum holding time is, as a rule, 3 years (VVER), for SNF sent to an intermediate in-plant storage facility (RBMK-1000), the minimum holding time was assumed to be 1 year. During the reactor operation and during the SNF reloading, the leak tightness of fuel elements is monitored. Fuel assemblies, the leakage of which is recorded by the standard fuel element cladding leak detection systems (CLD) during refuelling or after removal from the reactor, are installed in sealed canisters and are kept in the at-reactor pool during the entire power unit operation period.

Interim storage facilities have been built at all NPPs with RBMK reactors for accumulating and storing spent fuel for a longer period of time - at least 10 years. Such storage facilities are located at the NPP site in separate buildings. The experience gained in Russia and Ukraine in the operation of water-cooled storage pools shows that leaktight fuel elements with an average burnup level (for fuel assemblies of VVER-1000 reactors - 50 MW•day/kgU, for fuel assemblies of RBMK reactors - 30 MW•day/kgU) are not subject to destruction and show high corrosion resistance in pool water for a long time (up to 40 years). For defective fuel elements after several years of storage, no noticeable deterioration of their condition was also observed.

4.1.1.2. Requirements for dry SNF storage facilities

Dry storage of spent nuclear fuel is an alternative to the "wet" technology, but it does not exclude preliminary holding of fuel in water to reduce the level of radioactivity and heat release. During dry storage, there is no cooling water, which excludes leaks of radioactive water, storage conditions are improved (since water is a more aggressive storage medium compared to air and inert gases), ensuring the integrity of fuel elements. Maintenance of storage facilities is simplified, especially when cooling by natural convection, since the use of pumps is not required, and the share of electrical equipment is reduced. Dry storage leads to a decrease in the volume of secondary radioactive waste generation in comparison with wet storage. With dry storage technology, it is easier to implement the modular principle of commissioning, the storage facility construction time and operating costs are reduced, and the procedure for decommissioning storage facilities is simplified.

In general, during storage of spent nuclear fuel in dry storage facilities, the integrity (leak tightness) of fuel cladding must be ensured until the end of the storage period. However, in some cases, a small percentage of leaky fuel elements are allowed. In this case, Ukrainian legislation requires the provision of multi-barrier protection of spent nuclear fuel.

To prevent the release of radionuclides, it is necessary to seal the defective fuel elements. The design of dry storage facilities should provide for measures to prevent personnel exposure and environmental contamination in unforeseen situations.

The most important characteristics for dry storage are the following:

- Adopted heat removal method (forced or free cooling);
- Ways to protect personnel from overexposure;
- Prevention of environmental contamination during normal operation and in case of unforeseen situations, accidents;
- Placement relative to ground level (on the ground, partially recessed storage, completely below ground level);
- Ability to retrieve SNF (mobility);
- Degree of independence of individual storage modules;
- Modularity, that is, the ability to increase storage capacity by adding modules;
- Construction parameters (.module dimensions, wall thicknesses, storage parameters control systems, etc.).

The key characteristic for SNF integrity in this storage method is the temperature of fuel element cladding. Under an inert gas and under the condition of fuel dehydration to remove residual moisture trapped from the water pool, it is usually allowed to store leak-tight fuel elements at a temperature of 380-400°C (for example, in the USA). In Ukraine, it is legally established that the maximum temperature of undamaged spent nuclear fuel should not exceed 300°C.

It is conservatively assumed that fuel elements/fuel rods with defects in the cladding are not lost their structural integrity under an inert gas pressure up to a temperature of ~200°C. When storing spent nuclear fuel in a gaseous environment containing oxygen, the storage temperature shell be lowered for to avoid chemical reactions of fuel oxidation.

In Ukraine, when deciding on the organization of dry storage facilities for spent nuclear fuel from power reactors, several options for dry storage were considered:

- On-site storage facility at each NPP;
- Centralised storage facility for all nuclear power plants in Ukraine.

The technical implementation of dry SNF storage facilities was assumed in one of the following options:

- Container storage facilities of various types,
- Modular storage facilities,
- Chamber storage facility, storage facility of NUHOMS type.[1]

The following main aspects were identified as criteria for choosing a storage technology and technical solutions for designing the SNF storage and handling system:

- Non-exceedance of limits for external and internal exposure of personnel and population during normal operation and in case of design basis accidents;
- The principle of defence-in-depth, based on the use of a system of barriers to the spread of ionizing radiation and radioactive substances into the environment: fuel matrix; fuel elements cladding; sealed canister; storage facility building structures.
- Comprehensive justification of technical and organisational solutions, their compliance with national and international norms and rules adopted for the nuclear power industry;
- Use of design solutions and technical means aimed at preventing design basis accidents and measures limiting the consequences of beyond design basis accidents;
- Design of equipment and building structures important for safety[2], taking into account external impacts and possible emergency situations;
- Storage of spent nuclear fuel assemblies in honeycomb design basket/grid in sealed canisters that provide confinement;
- Ensuring nuclear safety under normal conditions and in emergency situations due to the placement of SNF in canisters with a certain pitch[1] and the use of special neutron-absorbing materials;
- Ensuring leak tightness monitoring of canisters with SNF;
- SNF residual heat removal during storage due to natural air circulation around the storage canisters;
- All operations on SNF reloading from the TUC cask into sealed canisters are carried out in a specially equipped protective chamber;
- Use of special lifting devices that exclude spontaneous detachment of items containing SNF;
- A possibility to carry out tests, maintenance, dosimetry control and checks for contamination with radioactive substances of equipment involved in the technological process of SNF storage and handling;
- Decontamination of equipment and premises of the system is provided;
- Accounting and control of VVER-1000 and RBMK-1000 SFAs is ensured in the processes of SNF reloading, storage and transportation.

At present, the dry technology of SNF storage has been implemented or planned to be implemented in almost all countries that have nuclear power plants and carry out SNF storage.

All the above-described requirements for SNF management were taken into account when choosing technologies for various types of SNF storage facilities that had been built or are being built in Ukraine.

The current situation regarding SNF management in Ukraine is described below.

4.2. Current situation with SNF management in Ukraine

Spent nuclear fuel is fuel elements or their groups, extracted from nuclear reactors of nuclear power plants and other installations. The fuel is classified as spent if it is subsequently unable to effectively maintain a chain reaction.

Spent nuclear fuel from Ukrainian power reactors includes SNF from RBMK-1000, VVER-1000, and VVER-440 reactors.

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[1] Grid spacing

[2] Important to Safety - Structures, systems and components that provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public (NRC, 10 CFR 50).

For VVER-440 SNF, the initial design envisaged the implementation of so-called “closed” fuel cycle. After unloading from core, SNF was stored for 3 years in at-reactor spent fuel pools, and then removed from the territory of NPP for processing at the Mayak Production Association (Russia).

For SNF of remaining reactors (VVER-1000, RBMK-1000), the so-called “deferred decision” was accepted. In this case, SNF storage is carried out in at-reactor spent fuel pools, on-site storage facilities, in the centralised storage facility at the “MCC” (VVER-1000). RBMK-1000 SFAs (in Ukraine only at Chornobyl NPP) are stored at NPP in wet storage at-reactor spent fuel pools and freestanding ISF.

At present, SFAs with burnup from several hundreds of MW•day/tU to ~ 28 GW•day/tU are stored at ChNPP ISF-1.

With regard to VVER-1000 SFAs, the design envisaged the following scheme: after operation in reactor, the SFAs should be put into at-reactor spent fuel pools for storage, and then, after a certain holding time, transported to the wet storage facility SFSF-1 of FSUE “MCC” (Russia). Basically, VVER FAs with initial fuel enrichment in uranium-235 (3.53; 3.90; 4.23) wt.% with a burnup of 34–47 GW•day/tU are currently unloaded from reactors. The technical conditions for new types of FA set the maximum allowable fuel burnup equal to 55 GW•day/tU. According to design data for new types of FA, fuel enrichment in uranium-235 can reach 5.0 wt.%, burnup - 68 GW•day/tU, fuel mass in FAs - 549.3 kg.

Further, the SNF was supposed to be sent to the SNF reprocessing plants in special transport containers.

However, after Ukraine gained independence, the originally envisaged by design chain of SNF management turned out to be subject to such political decisions on the part of Russia, which could cause a stoppage of SNF dispatch to Russia and, as a result, a shutdown of Ukrainian NPPs due to overfilling of at-reactor spent fuel pools. To solve the problem of SNF management, a so-called “deferred decision” strategy was accepted. In the framework of implementation of this strategy, it was planned to build long-term (50-100 years) SNF storage facilities at NPPs sites and a centralised SNF storage facility for all NPPs in Ukraine.

At present, Ukraine has built and operates on-site dry SNF storage facility at Zaporizhzhya NPP, and wet SNF storage facility (ISF-1) at ChNPP. The construction of a dry SNF storage facility at ChNPP (ISF-2) and centralised storage facility for SNF from VVER-type reactors (CSFSF) is underway.

Further in this review describes the main aspects of the management of spent nuclear fuel at the Chornobyl NPP with special attention on failed and damaged spent fuel (DSNF).

4.3. Existing SNF storage facility at Chornobyl NPP (ISF-1)

During the period of electricity generation, from 1977 to 2000, the Chornobyl NPP used 21284 fuel assemblies.

All of these assemblies are now in the “wet” type spent nuclear fuel storage facility (hereinafter - ISF-1). The assemblies are stored under water. Storage in such conditions allows controlling the condition of fuel, providing the necessary biological shielding and removing residual heat.

The storage facility is intended for acceptance and storage of SFAs after preliminary, no less than 1.5-year, holding them in spent fuel pools or reactors of power units 1, 2, 3.

The site of spent nuclear fuel storage facility (ISF-1) is located within the 30-kilometer exclusion zone on the territory of ChNPP industrial site.

ISF-1 was put into operation in 1986. This facility is not designed for long-term storage of spent fuel (more than 100 years) and its lifetime (by design) is limited to 2028. Operation beyond this period requires significant amounts of reconstruction and strengthening of building structures. In addition, the wet storage method is not rational for long-term storage of spent nuclear fuel. Therefore, all spent fuel assemblies (hereinafter - SFA) will be moved to a new dry-type spent nuclear fuel interim storage facility (hereinafter - ISF-2). Today, SFAs from three units of Chornobyl NPP are located in ISF-1 - more than

21 thousand assemblies. As of 01.01.2020, all construction and installation works at ISF-2 have been completed. On April 26, 2021, the Chornobyl NPP received a license for the right to carry out activities at the stage of the life cycle "operation of a nuclear installation – Independent Spent nuclear fuel Storage Facility" of dry type (ISF-2).

Figure 5 – "Wet" storage facility ISF-1 at ChNPP

4.3.1. Brief characteristics of ISF-1

The ISF-1 storage facility is a separate building located at the ChNPP industrial site - (see Figure 14).

The ISF-1 building (Figure 15) consists of three units combined into one space:

- transport and technological unit, which in turn consists of two spaces: SFA spent fuel pool section (items 1-3 in Figure 15) and transport container acceptance and reloading section (items 4-11 in Figure 15);
- chemical unit with premises of facility for treatment and cooling water of spent fuel pool, canyon and transfer basket storage compartment, unit for desorbing solution preparation, transformer, collection and pumping of sewage, and other premises;
- administrative and household unit with premises of changing room and sanitary locks, ventilation centre with filter station, electrical switchboard and other auxiliary rooms.

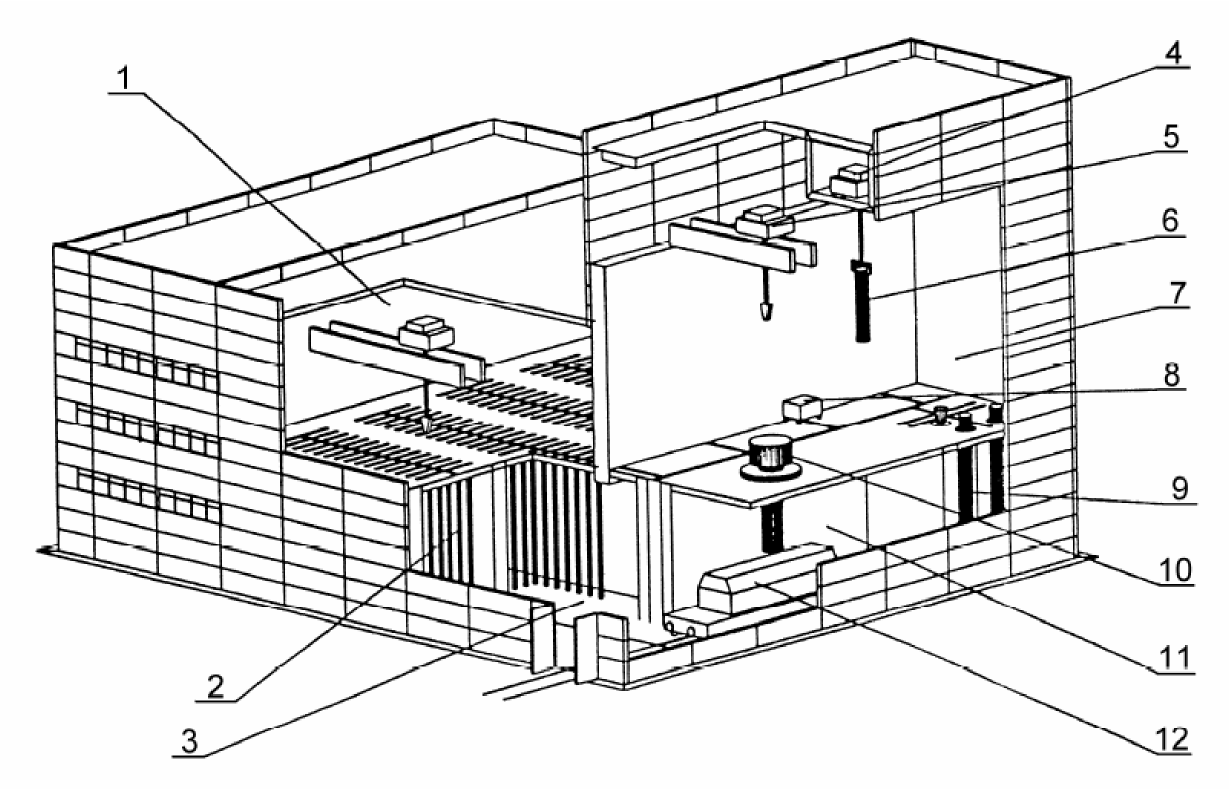
In the spent fuel pool (SP) section, there are five separate independent pools (compartments) with a capacity of up to 4380 SFAs each. Four compartments are operational and one compartment is a backup.

SFAs are placed for permanent storage in canisters filled with water (Figure 16), in one SFP compartment - up to 4380 SFAs, in the canyon - up to 420 SFAs. (The canyon is a small pool in the main hall of ISF-1 (item 7 in Figure 15), designed for temporary storage of canisters with SFAs during acceptance/transfer of SFAs from power units). The canyon is intended for storage (placement) of SFAs, as well as for ensuring the movement of canisters with SFAs to SFP compartments of ISF-1.

It is permitted to store SFAs in no more than four out of five SFP compartments (SFP1-5). One of SFP compartments is a backup for the possibility of accepting SFAs from the compartment that is being repaired. SFP compartments, canyon and TBSK are filled with water to a nominal level. Canisters with SFAs are filled with water to overflow.

To move the SFA from the power units to ISF-1, a TK-8 rail car (item 12 in Figure 15) with a transfer basket is used. The transfer basket (Figure 18) is designed to transport 9 SFAs with grapple-plugs or 9 SAAs with grapple-plugs in the protective container of TK-8 transport rail car.

The rail car (Figure 16) is a vehicle, including an eight-axle railway transporter, a body with equipment, and a protective container. The rail car is intended for transportation in a protective container of baskets with SFA and SAA at the ChNPP industrial site between power units and ISF-1. At present, a more advanced TK 700 rail car has been put in operation. It will be used to transport SFAs from ISF-1 to the new dry storage facility of ISF-2.



1. Storage pools hall
2. SFA thimbles
3. Spent fuel pool
4. Cable cart
5. Bridge crane
6. Basket

7. Main hall
8. Transfer cart
9. Reloading compartment
10.Guiding device
11 Transport corridor
12. Container rail car

Figure 6 – Design of ISF-1 wet storage facility at ChNPP

4.3.2. Main transport and technological operations for spent nuclear fuel acceptance/transfer for storage at ChNPP ISF-2

The main transport and technological operations for spent nuclear fuel acceptance/transfer for storage at ChNPP ISF-2 are:

- Preparation and loading of transfer basket with SFAs in rail car at NPP power unit.

At this stage, rail car (Figure 7) with empty transfer basket (TTB) - (Figure 9) is delivered into the transport corridor of NPP power unit (Figure 8). Roof of rail car opens, container is moved from horizontal to vertical position, protective cover is removed and, through the protected shaft inside the building structures of power unit, TTB is delivered to central hall of reactor compartment and installed in a special slot in spent fuel pool. Then, 9 SFAs to be transferred to ISF-1 are placed into TTB (Figure 9).

Loaded TTB through the protected shaft inside the building structures of power unit is lowered into rail car, protective cover is put on container, container is lowered to horizontal position, and rail car roof is closed.

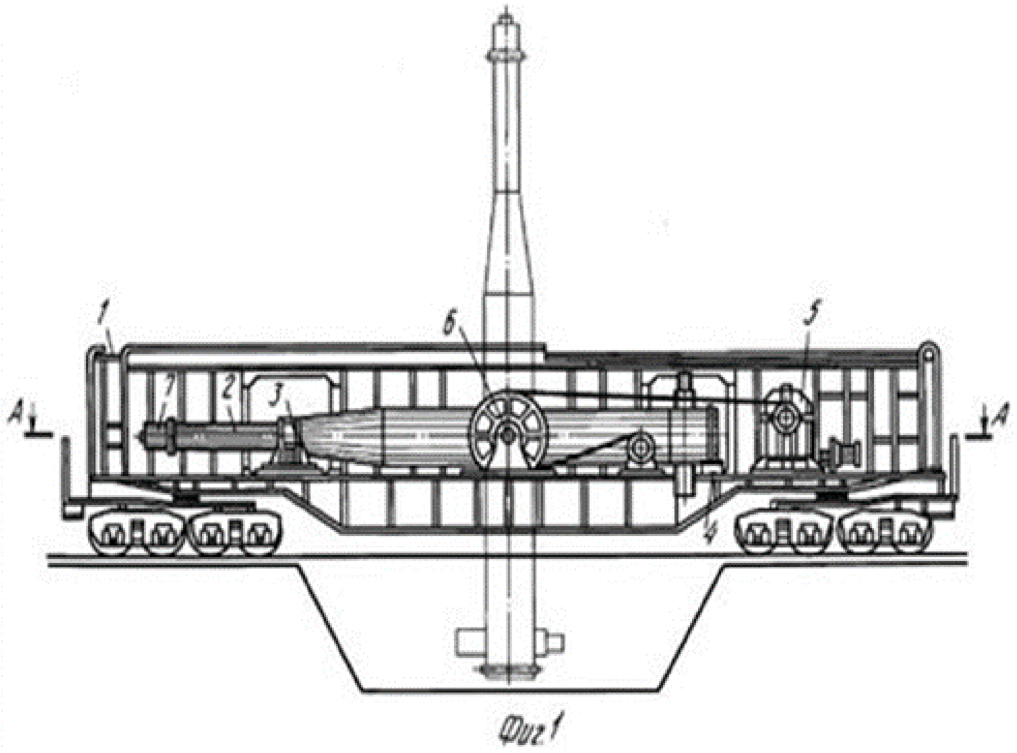
Next, rail car is moved to the transport corridor (item 11 of Figure 6) of ISF-1.

- The following main technological operations are carried out at ISF-1:
  - Acceptance of TK-8 rail car.
  - Delivery, acceptance and transfer of transfer basket with SFAs to transfer basket storage compartment of ISF-1 (item 9 of Figure 6).
  - SFAs reloading from transfer basket to canisters.
  - Transfer of canisters with SFAs from acceptance compartment to SFP compartments (item 2, 3 of Figure 6.
  - Arrangement of canisters with SFAs in SFP compartments for storage.

A general view of SFAs storage site in ISF-1 SFP is shown in Figure 19.

As of 01.01.2020, all SFAs from spent fuel pools of ChNPP power units have been transferred to ISF-1. In the future, a gradual transfer of all SFAs from ISF-1 to a new dry storage facility ISF-2 is envisaged.

The description of ISF-2 is given in chapter 4.4.1 below.



Rail car roof and bottom are opened and, with the help of special hydraulic drives, the container is installed from horizontal to vertical position and fixed by special devices for loading.

Figure 7 – Design of TK-8 rail car for transportation of SFAs at ChNPP ISF-1

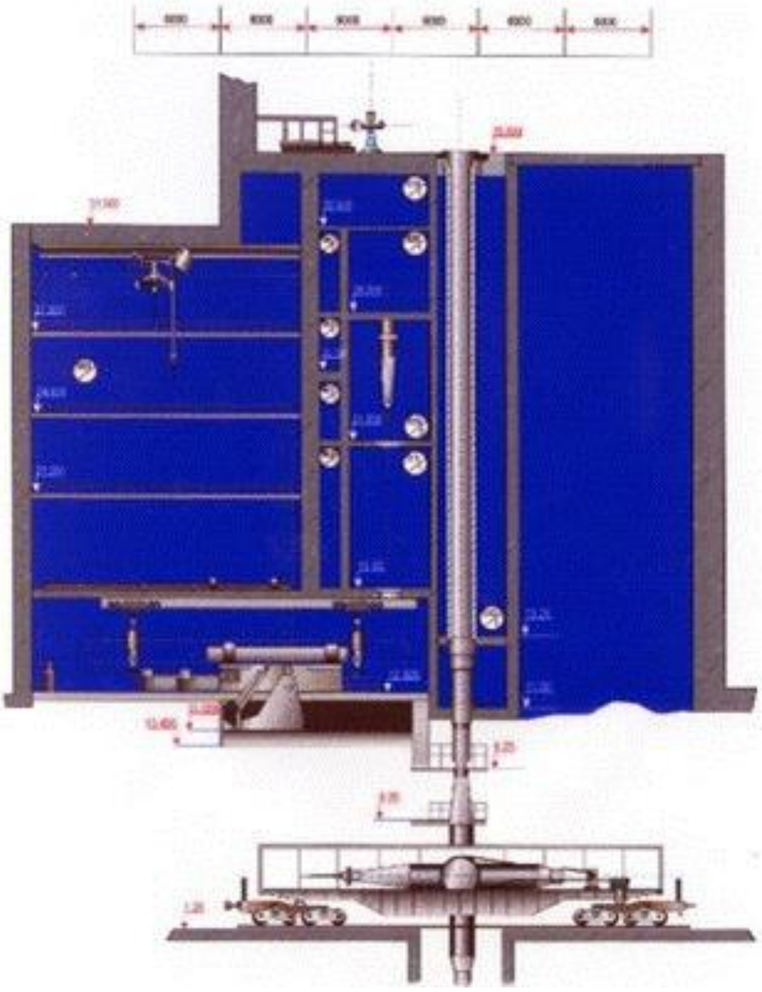
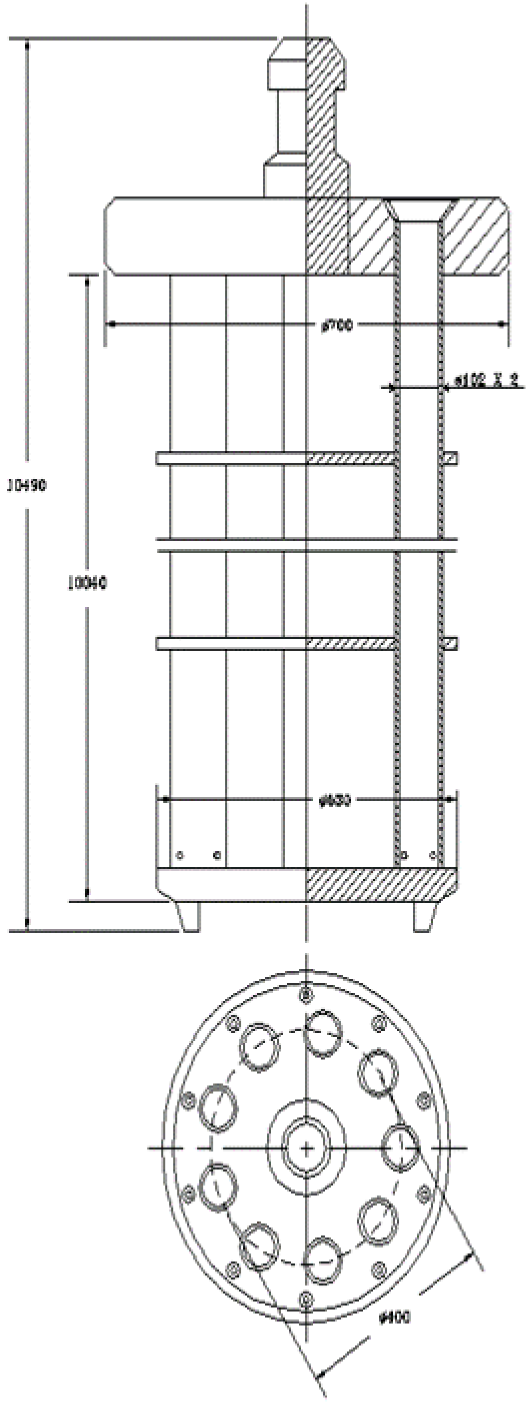


Figure 8 – Scheme of loading of transfer basket into TK-8 rail car at ChNPP power unit for transportation of SFAs to ChNPP ISF-1



Characteristics of TTB

1.	Weight of basket:	1200 kg
2.	Total weight of loaded items:	1800 kg
3.	Total weight of basket with items, no more than:	3106 kg
4.	Length of basket, considering eye-bolts:	10552 mm
5.	Top plate diameter:	700 mm
6.	Bottom plate diameter:	530 mm
7.	SFA (SAA) capacity:	9

Figure 9 – Transport transfer basket

Figure 10 – Storage of RBMK-1000 SFAs in ISF-1 “wet” storage facility

4.4. Dry-type spent nuclear fuel storage facility (ISF-2) at Chornobyl NPP

ChNPP (Independent spent nuclear fuel Storage Facility #2) - ISF-2 is a dry-type spent nuclear fuel storage facility designed for preparation for storage and storage of SFAs for 100 years.

In ISF-2, fuel will be stored in special canisters placed in concrete storage modules (CSM) - Figure 13). Before storage, the fuel will be processed and dried in the spent fuel processing facility (Figure 11). After the end of the 100-year storage life, the fuel will be transferred to another storage facility or, if the necessary technologies are available, reused.

The Spent Nuclear Fuel Storage Facility (ISF-2) design was developed in 1999 by the French company FRAMATOME within the framework of international financial and technical assistance provided to Ukraine on the basis of “Memorandum of Understanding between the governments of the G7 countries, the Commission of the European Community and the Government of Ukraine on closure of the Chornobyl NPP” concluded on 12.20.95 and the Grant Agreement (Chornobyl NPP Nuclear Safety Project) signed on 12.11.96 by the European Bank for Reconstruction and Development, the Government of Ukraine and the Chornobyl NPP.

For ChNPP spent nuclear fuel (SNF), in accordance with the design, a dry storage system in leak-tight containers (canisters) placed in ventilated concrete modules (NUHOMS®) was selected.

The construction of ISF-2 was started by FRAMATOME in 2000; the third quarter of 2004 was determined by the date of commissioning.

However, in 2003, significant design flaws that affect reliability and safety were identified, which led to the need to adjust technical solutions and, consequently, the inability to complete construction on time. Construction works were suspended. According to experts, works were completed by 70%. Since the parties did not find acceptable ways to solve the problems identified, in April 2007, the State Specialized Enterprise Chornobyl Nuclear Power Plant (SSE ChNPP) terminated the contract with the French consortium AREVA NP (FRAMATOME). The company HOLTEC International (USA) (hereinafter referred to as HOLTEC) was selected as the company responsible for modifying the design and completing construction, which for two years participated in the discussion of technical approaches to solve ISF-2 problems. At the same time, it was taken into account that the already constructed structures have the necessary quality and can be used, taking into account the technology proposed by HOLTEC, to complete the construction.

The HOLTEC technology adopted for ISF-2 provides for the use of a double-walled dry shielded canister (DWC). Its design (two consecutive independent leak-tight welded shells - Figure 15) provides long-term storage of fuel due to isolation from the environment. The removal of residual heat generated by SNF occurs due to the transfer of this heat from fuel rod to the shell of DWC as a result of use of helium as a coolant inside the DWC.

DWC leak-tight canisters loaded with SNF will be placed horizontally in concrete storage modules (CSM) - Figure 22. This storage facility configuration is a variant of the NUHOMS® type SNF interim storage system.

Accordingly, there will be no radiation impact on the environment during normal storage in concrete modules. One DWC contains 93 spent fuel assemblies.

As of 01.01.2020, all construction and installation works at ISF-2 have been completed. The so-called “cold” testing of facility, on SFA simulators, have been carried out and preparation for commissioning being performed. The commissioning stage involves the processing (preparation for storage) of 196 SFAs and the loading of 2 DWC (double-walled dry shielded canister) with SNF to CSM (concrete storage modules).

On April 26, 2021, the Chornobyl NPP received a license to carry out activities at the stage of the life cycle “operation of a nuclear installation - spent nuclear fuel storage facility” of dry type (ISF-2). On June 8, 2021, the long process of transporting spent nuclear fuel from the Chornobyl nuclear power plant to the ISF-2 began.

But it didn't last long.

Since the beginning of Russia's war against Ukraine, on February 24, 2022, Russian troops invaded Ukraine from the territory of Belarus through the exclusion zone of the Chornobyl nuclear power plant and by the end of the day, without fighting, they captured the Chornobyl nuclear power plant and took control of the territory of the cities of Pripyat and Chornobyl.

For this reason, all activities at the Chornobyl NPP, including transportation of spent fuel to ISF-2, were stopped.

4.4.1. Brief description of ISF-2

ISF-2 consists of two main parts, namely:

- Spent Fuel Processing Facility (SFPF) - Figure 11, intended for acceptance and packaging of spent fuel assemblies (SFA) for storage for hundred years. This facility is also used for management of solid radioactive waste (SRW) obtained during the operation of the ISF-2 [2, 3, 4].
- Spent Fuel Storage Area (SFSA) - Figure 13, intended for storage during one hundred years of spent nuclear fuel in the form of FR bundles, placed in DWCs, which, in turn, are placed in CSM. 58 Concrete Storage Modules, arranged in two rows, each module contains 4 cells for DWC storage, were built at SFSA site, a total of 236 cells.

The design of facility provides for the annual productivity of processing and placing for storage of 2500 SFAs coming from ISF-1. Spent fuel assemblies are delivered from ISF-1 to the SFPF in transport container designed for transportation of SFA/SAA of ChNPP RBMK-1000.

Figure 11 – Spent Fuel Processing Facility (SFPF)

4.4.2. Technological process of SNF management at ISF-2

The SNF management scheme at ISF-2 is shown in Figure 12.

SFAs at ISF-1 will be loaded into a special transport transfer basket (TTB) - Figure 9 by 9 SFA at one TTB, and then into TK 700 special transport protective container (Figure 7).

Further, transport container will be delivered to the ISF-2 SFPF.

At SFPF, TTB will be moved to the “Hot chamber”, where SFA will be separated into three parts: an extension rod and the upper and lower bundles of fuel elements characteristics of RBMK 1000 FA see 3.1.1 and Figures 2, 3, 4).

The SFA extension rod will be sent back to the ISF-1 in the same TTB, and the upper and lower bundles of fuel elements will be packed one at a time in so-called fuel tube (FT) (see Figure 14).

Then, the FTs, each containing one bundle of fuel elements (half of SFA) will be placed in special metal double-walled shielded canisters (196 halves for each canister). A schematic representation of DWC is shown in Figure 15.

During operations on installation of FTs loaded with FR bundles, DWC will be located in a special On-Site Transport Container (OSTC) - Figure 16. During loading, OSTC is placed vertically on a special transport carriage inside the SFPF.

Characteristic*	**DWC**	**FT**	**OSTC**
Length, mm	4 440	3 820	5 120
Outer diameter, mm	1 870	110	2 540
Weight of empty, kg	15 700	10	75 000
Weight of loaded, kg	31 000	80	110 000

* The approximate value is given

Table 4 – Characteristics of main elements of SNF storage system at ChNPP ISF-2

Fuel tube is made of Metamic type boron-aluminium alloy (Al + 10% B_4C). The use of boron in the composition of tube material ensures the maintenance of a subcritical state in DWC under any conditions - both during normal operation and in case of any design basis accidents.

According to the patented technology of HOLTEC Company DWC is made entirely of stainless steel, including intra-canister structural elements and spacer grids. Each canister holds 196 FTs containing FR bundles.

After all 196 FTs are placed in DWC, operations are carried out to install and weld the DWC internal protective lid.

Further, the procedure of draining DWC and SNF located in it is performed.

It should be noted, that ChNPP SNF is currently stored in the so-called “wet” storage facility - in water (water serves to remove residual heat from SNF). In some fuel elements, as a result of high thermal loads during operation in the reactor core, micro cracks are formed on fuel rod cladding, through which cooling water penetrates into the internal cavity of fuel rod. Since all SFAs in ISF-1 were stored in the water environment for at least 20 years, it should be conservatively expected, that a significant number of fuel elements can be leaking - i.e. being filled with water.

Based on this assumption, the use of standard method of vacuum drainage of SNF in DWC could be ineffective. HOLTEC proposed using a variant of Forced Gas Dehydration System (FGD) developed by them [1].

In the variant of the FGD implemented at ChNPP ISF-2, nitrogen gas heated to a high temperature is used as a drying agent. The dry nitrogen heated in the heater passes through DWC, removes moisture from SFA (tubes containing FR bundles are un-tight and allow the drying gas to pass through the internal cavity, taking moisture from SFA). The drainage procedure is carried out for several hours, until the moisture is no longer released on the condenser-cooler of the FGD.

Then cooling and control vacuuming of the DWC is carried out to make sure that all moisture from a SFA is removed.

Lastly, helium is pumped into the DWC through a special port in the inner lid. Helium circulating through untight fuel tube provides heat removal from the SNF to the internal walls of the DWC.

At the final stage, an external lid is installed and welded in DWC.

When a DWC is loaded, filled with helium and both lids - internal and external - are welded, the OSTC is placed in a horizontal position on the Canister Handling and Transportation System (CHTS) - Figure 25.

Transport frame (CHTS) with installed on it On-site Shielding Transport Container (OSTC), in which Double wall container (DWC) loaded with spent fuel assemblies SNF is located, moves along the rail track in Spent Fuel Storage Aria (SFSA) to Concrete Storage Module (CSM), into which DWC is supposed to be loaded.

Then DWC, with the help of a hydraulic ram, moves into the open empty CSM. At the end of the operation, the entrance aperture of CSM with DWC inside is closed with a concrete cover plug.

In this configuration, it is supposed to store DWC with SNF for 100 years.

During the storage period, the state of DWC is monitored in accordance with a special control and monitoring program.

For more details on control and monitoring of DWC during the storage period, see section 4.5.4.

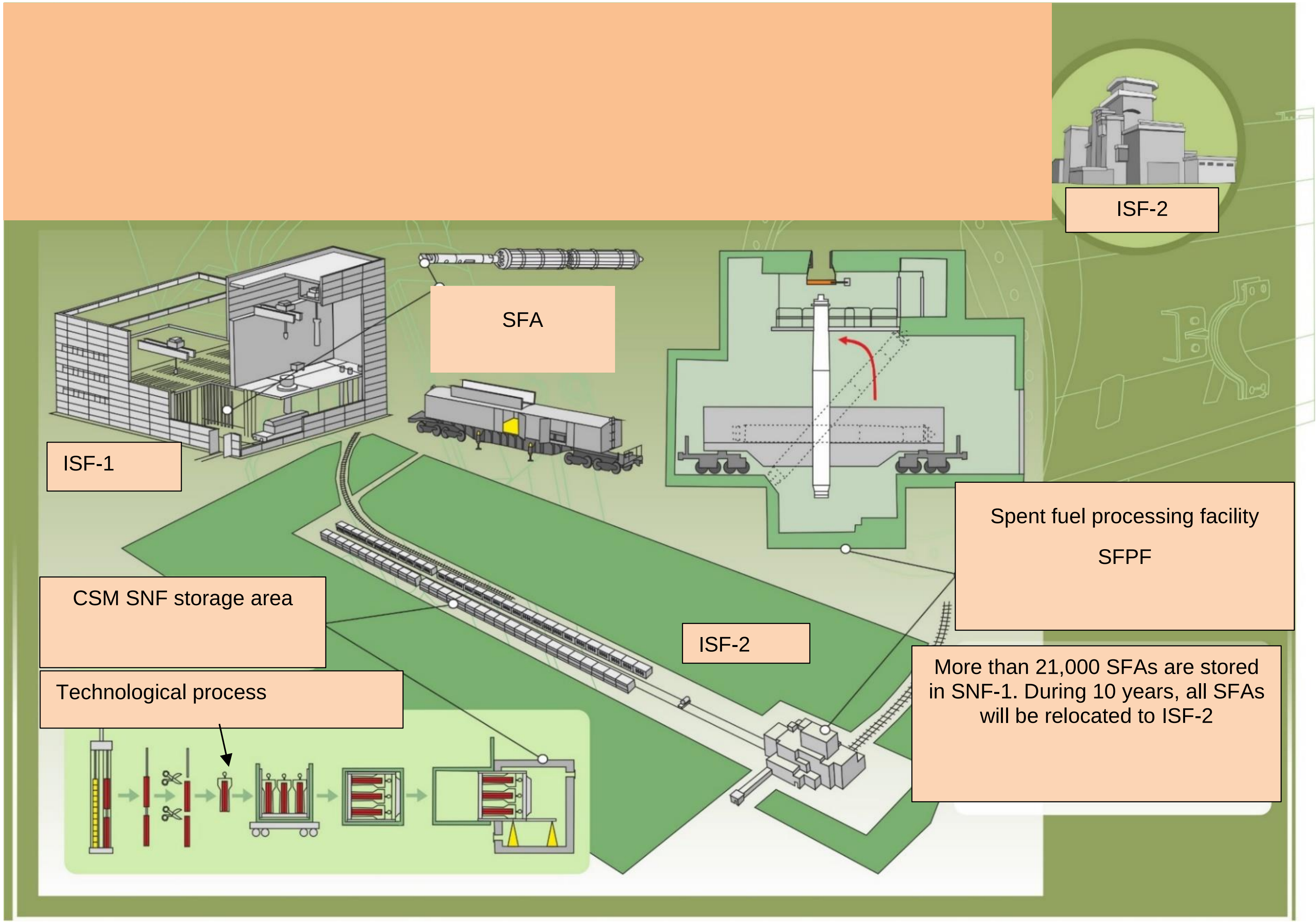


Figure 12 – Block diagram of SNF management at ChNPP

Figure 13 – Area of SNF storage in CSM (SFSA) in ChNPP ISF-2 storage facility

Figure 14 – Fuel tube in which FR bundles will be stored

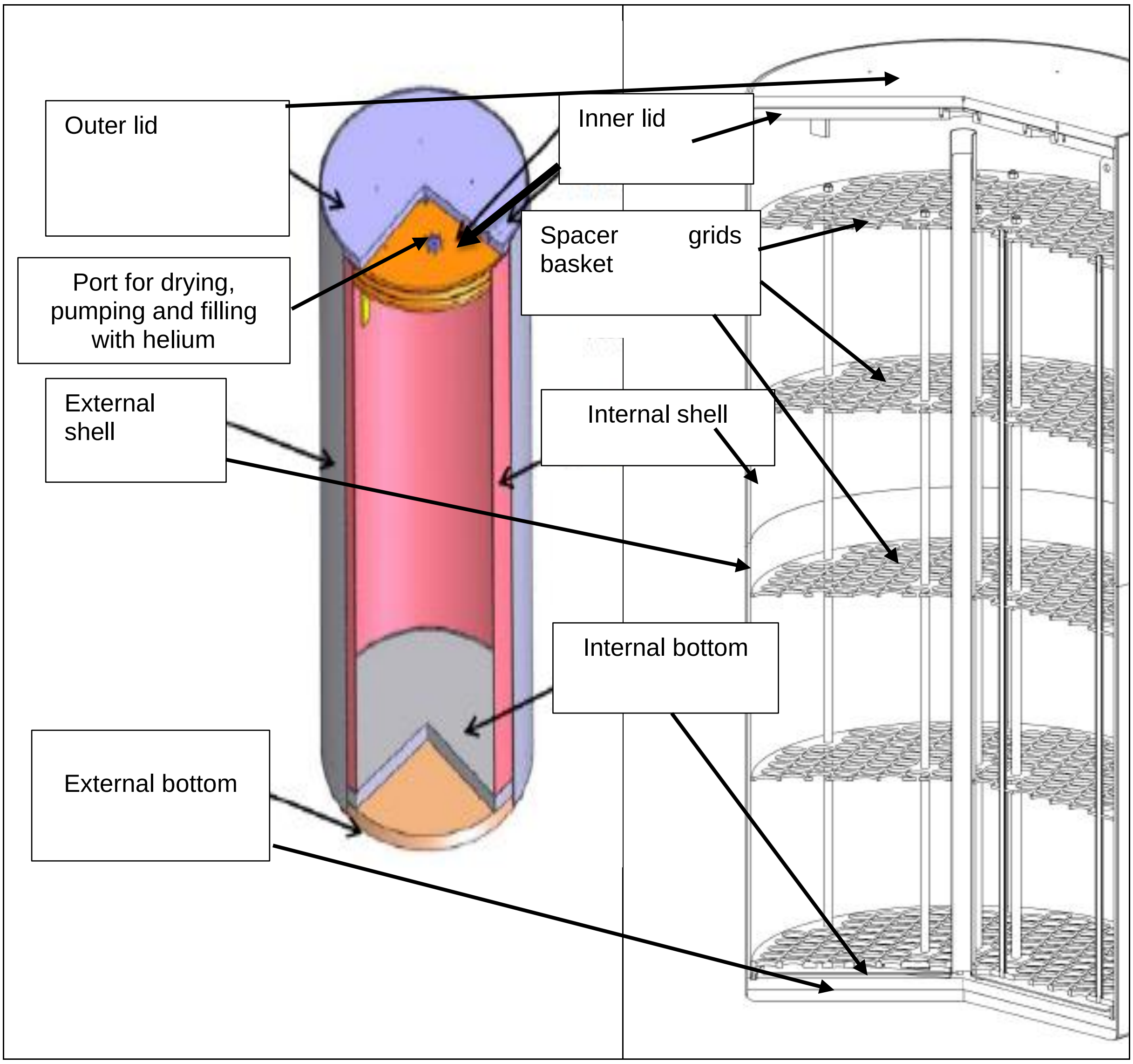


Figure 15 – Double-walled shielded canister (DWC)

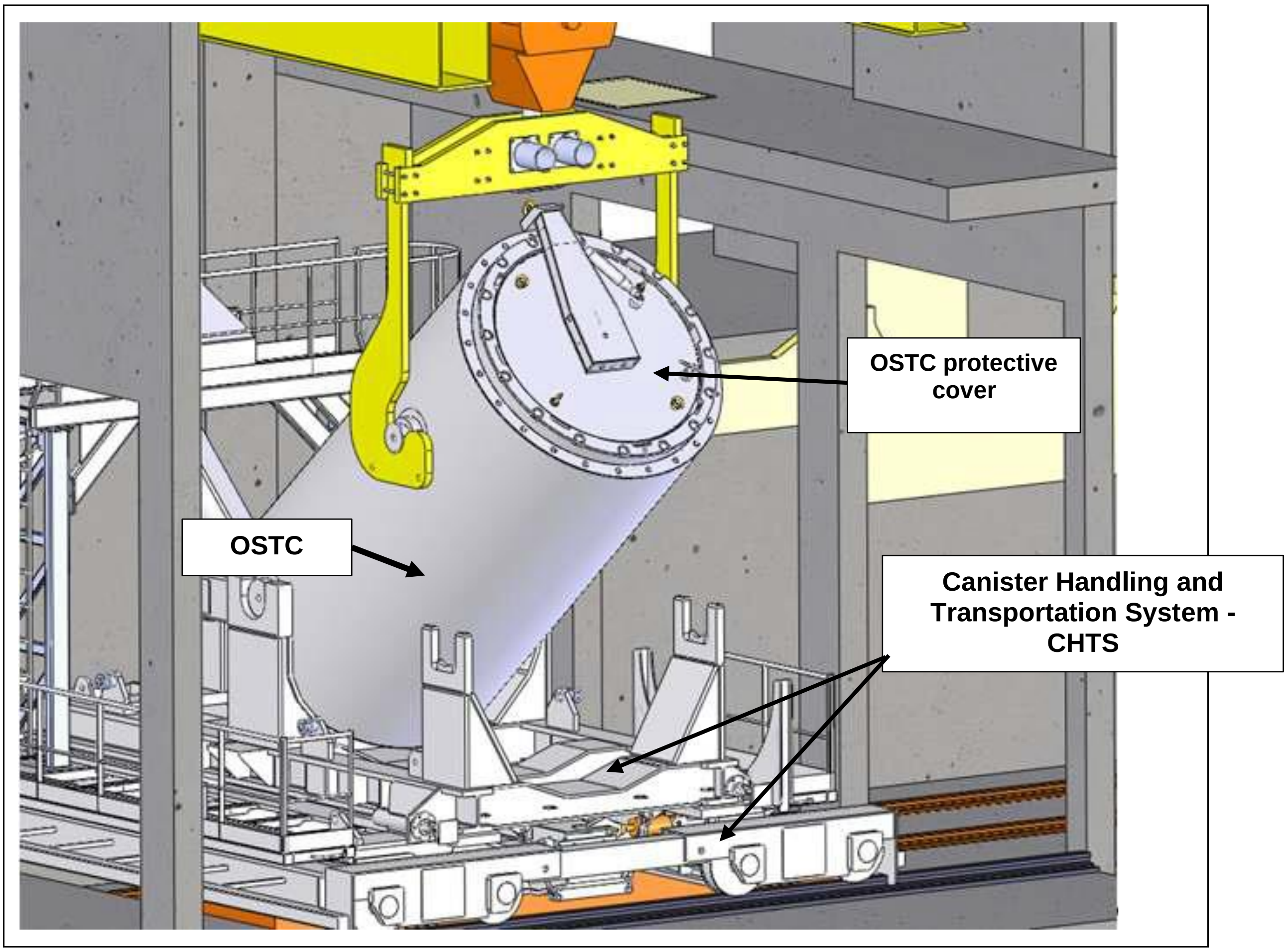


Figure 16 – On-site transport container (OSTC), installation on CHTS

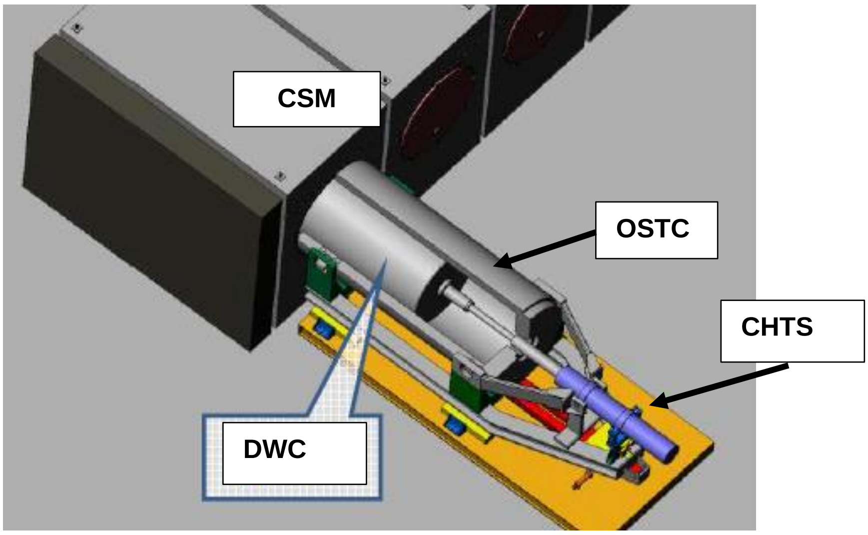


Figure 17 – Installation of DWC loaded with SNF in concrete storage module – CSM

4.4.3. Status of the ISF-2 project as of 01.01.2024

On April 26, 2021, the State Nuclear Regulatory Inspectorate of Ukraine issued a permit to the Chornobyl NPP for ISF-2 commission. On September 10, the transportation of first nine fuel assemblies of 21,000 began to be transported to the new “dry” storage facility. According to the State Specialized Enterprise “Chornobyl Zone” the use of ISF-2 is safer and cheaper.

Within the framework of the “Commissioning” stage (“hot tests”), 286 spent fuel assemblies were transported from the old “wet” type ISF-1 storage facility to the Spent Fuel Processing Facility (SFPF). These SFAs were disassembled into fuel bundles (FB), which, then, were placed in double-walled dry shielded canisters - DWC. Then, the FBs were dehydrated in DWCs, the sealing lids were welded, and the DWCs were filled with helium. The sealed DWCs were placed in Concrete Storage Modules (CSM).

On November 18, 2020, as part of the “hot” tests, the first canister loaded with spent nuclear fuel was placed at the dry-type spent nuclear fuel storage facility (ISF-2). It was placed in a concrete module for long-term storage for 100 years. In total, within the framework of “hot tests”, 186 SFAs - 2 DWCs were prepared for storage and placed in CSM (see Figure 18 and Figure 19).

“Hot tests” of ISF-2 were completed in December 2020. Based on the results of the “hot tests”, the Operating Organization (ChNPP) prepared a Report on ISF-2 Commissioning (i.e., on “hot tests”) and a Final Safety Analysis Report (FSAR). On the basis of these documents, the Ukrainian Regulator (State Nuclear Regulatory Inspectorate of Ukraine) issued a permit to the SSE “Chornobyl NPP” for the normal operation of ISF-2 nuclear facility.

Figure 18 – Loading of the first DWC with SNF into ISF-2 concrete storage module #1 (CSM -1).

Figure 19 – Loading of the first DWC with SNF into ISF-2 concrete storage module #2 (CSM – 2).

4.5. Monitoring the SNF condition in the Independent Storage Facilities in Ukraine

During long-term SNF storage, it is necessary to monitor the condition of SNF and packages with SNF and the compliance with the requirements for wet and dry SNF storage facilities. In different variants of SNF storage technology, it is technically possible to monitor a certain limited amount of SNF parameters. Based on the requirements for SNF storage facilities given in Section 4.1.1, it is possible to establish a list of the main characteristics of SNF that are important to ensure reliable and safe long-term SNF storage. Some of these characteristics/parameters can be monitored only during SNF loading for storage, while during the storage period itself it is technically possible to monitor only a limited set of parameters.

In this section, on the example of SNF storage facilities existing in Ukraine, the issues of monitoring of main characteristics of SNF, which are important for ensuring reliable and safe long-term SNF storage, are considered.

4.5.1. Parameters of SNF packages to be monitored during storage

The main characteristics of SNF that are important for ensuring reliable and safe long-term SNF storage are usually the following:

1. Nuclear safety (sub-criticality) of packages with SNF, during storage and carrying out transport and process operations with spent fuel under normal conditions, violation of normal conditions and during accidents;

2. Structural integrity of SFAs and FEs;
    Note: In some variants of storage systems, it is required to ensure the leak tightness of fuel elements.
3. SNF storage medium parameters (chemical neutrality, non-aggressiveness in relation to SFA materials);
4. Radiation safety of personnel and environmental protection;
5. Residual heat removal;
6. Elimination of radioactive substances release outside the storage facilities into the environment;
7. Possibility of retrieval (removal) of fuel from storage facilities;
8. Rational organisation of storage of defective spent fuel (with defective SFAs and FEs);
9. Provision of physical safety (protection) of spent nuclear fuel;
10. Compliance with IAEA Safeguards (non-proliferation of nuclear materials).

4.5.2. SNF conditions monitoring at ChNPP ISF-1

This section provides brief descriptions of methods for technical implementation of monitoring the parameters of SNF and SNF packages listed in subsection 4.5.1 at existing SNF storage facilities.

The ChNPP Independent Spent Nuclear Fuel Storage Facility No. 1 (ISF-1) is a “wet type” storage facility and is intended for the acceptance and storage of SFAs from RBMK-1000 reactors after preliminary, not less than 1.5-year, storage in the SFP of reactors of power units 1, 2, 3, as well as for the operations of SFAs unloading from the ISF-1 with its subsequent transfer to the “dry-type” ISF-2.

ISF-1 is the so-called active storage system, and to ensure safety during the SNF storage period, it is required to monitor a significantly larger number of parameters than the so-called passive storage systems.

Monitoring of SNF condition at the ChNPP ISF-1 (i.e., ISF-1 safety) is based on ensuring the following basic technical requirements and criteria, which are at the same time the design basis for ISF-1:

1. **Nuclear safety** (sub-criticality) of packages with SNF during storage and transport and process operations with spent fuel under normal conditions, violation of normal conditions and during accidents is ensured by the design of storage canisters, placement of canisters in the storage pools of ISF-1 with a safe pitch, procedure for carrying out transport and process operations with spent fuel under normal conditions, violation of normal conditions and during accidents.
2. **Structural integrity of SFAs and FEs**; It is provided by the design of storage canisters, placement of canisters in the storage pools of ISF-1, procedure for carrying out transport and process operations with spent fuel under normal conditions, violation of normal conditions and during accidents. Damaged SFAs and fuel fragments are stored in special canisters, separately from normal SFAs.
3. **SNF storage medium parameters** (chemical neutrality, non-aggressiveness towards SFA materials); It is provided by measures (process operations) aimed at maintaining the water-chemical composition and monitoring the temperature of water in spent fuel pools.
4. **Radiation safety of personnel and environmental protection**; It is provided by:
    a. storage of SFAs in SFP under protective layer of water;
    b. carrying out estimations of radiation fields in ISF-1 under normal conditions, violation of normal conditions and during accidents;
    c. development of process operations for SNF management at ISF 1, taking into account the ALARA principle;
    d. carrying out estimations of the impact of ISF-1 (discharges, releases) on the environment in case of violation of normal conditions and in case of accidents.
5. **Residual heat removal**; It is ensured by the use of the technology of SFAs storage in SFP water, by keeping water temperature in SFP within the design limits in case of violation of normal conditions and in case of accidents.

6. **Elimination of radioactive substances release outside the storage facilities into the environment**; It is provided by design solutions of ISF-1 process systems and special organisational and technical measures:
    a. ISF-1 ventilation system is equipped with an effective system of filters that prevent the release of untreated air into the atmosphere;
    b. Solid radioactive waste management is carried out in accordance with the agreed and approved by the Ukrainian Regulator scheme for the SRW management at ChNPP, according to the procedure established by the “Regulations for solid radioactive waste management at SSE “Chornobyl NPP”;
    c. Liquid radioactive waste (LRW) and radioactive water management is carried out in accordance with the agreed and approved by the Ukrainian Regulator scheme for their management at ChNPP, according to the procedure established by the “Regulations for liquid radioactive waste management at SSE “Chornobyl NPP”.
7. **Possibility of retrieval (removal) of fuel from the storage**; It is provided by design solutions and organizational and technical measures.
8. **Rational organisation of defective spent fuel** storage (with **defective SFAs and fuel elements)**. It is provided by design solutions - the use of special canisters designed for safe storage of damaged spent fuel assemblies and spent nuclear fuel fragments. A conceptual solution for DSNF management has been developed, the implementation of which is postponed.
9. **SNF physical protection (security) provision**; It is provided by:
    a. ISF-1 design;
    b. Physical protection/security of the storage facility site, as an object on the territory of ChNPP.
10. **Compliance with Safeguards (non-proliferation of nuclear materials)**. It is provided by:
    a. IAEA monitoring during SNF loading into ISF-1;
    b. Physical protection/security of the storage facility site;
    c. IAEA monitoring at all stages of placement for storage and monitoring during storage.

The organisational and technical methods of SNF monitoring during storage applied at the ChNPP ISF-1 ensure safe storage of spent nuclear fuel for the entire period of time until the transfer of all SNF to a new dry-type SNF storage facility - ISF-2.

4.5.3. SNF condition monitoring at ChNPP ISF-2

A system for long-term storage of SNF placed in DWC, in turn loaded into the CSM (version of the NUHOMS system) (see 4.5.1) is a passive storage system and during the storage period requires monitoring only of a few safety relevant parameters (see. 4.7.3.1). However, when preparing spent nuclear fuel for storage, to ensure reliable and safe storage of spent nuclear fuel during the estimated storage period (100 years), it is necessary to monitor a significantly larger number of parameters - when selecting fuel for storage, performing a number of process operations during loading and transfer DWC loaded with SNF for storage in CSM.

Operational limits and reference parameters are established based on the conditions for safe operation of DWC system in CSM both under normal and abnormal conditions, as well as in case of design basis accidents.

Table 16 shows the main types of process operations and other activities carried out during the placement of SNF for storage, for which it is necessary to comply with the reference parameters and limits in order to ensure the safe operation of DWC system in CSM. The list of reference parameters and limits, as well as the types of periodic checks of the system condition, necessary from a safety point of view, are shown in Table 6.

Table 7 provides a brief description of the ways to monitor the SFAs condition in the SNF storage facility at Chornobyl NPP.

As of 01.01.2021, in the ChNPP ISF-2, during trial operation, two DWC loaded with SNF have been placed for storage.

Stages of technological process at which operational limits and monitoring are established		**Conditions or parameters to be monitored**
1.	Fuel characteristics	Burn-up and time after irradiation or content of fission products, residual heat release, intensities of γ-radiation sources and neutrons
2.	Operations with DWC	Preparation of DWC for SNF loading, check of the permeability of inner basket of DWC. Check and preparation of CHTS, OSTC and concrete storage module.
3.	Preparation for fuel loading	Selection of a set of SFAs for loading in accordance with burn-up, residual heat release (no more than 6.8 kW in total) per DWC that meet the criteria for acceptance at ISF-2. Loading, welding of the first (protective) lid.
4.	Fuel loading	Separation of SFA into two bundles and an extension rod (suspension rod). Loading of FE bundle into FT and FT into DWC.
5.	Welding of the inner lid of DWC	Colour (capillary) flaw detection of the protective (inner) lid of DWC.
6.	Dehydration	Dehydration of the inner cavity of a DWC using FGD. Vacuuming the DWC, depressurize reaching a pressure of 3 mm Hg and holding it for 30 minutes.
7.	Injection of helium into DWC	Helium pressure is 140 kPa absolute during storage.
8.	Welding of the outer lid of DWC	Colour (capillary) flaw detection of DWC outer lid.
9.	Inspection of welds of DWC outer lid and inner lid for the absence of welding defects and leaktightness	The rate of helium leakage is smaller than 1.0 x 10^{-7} atm-cm^3/s when testing for leak tightness with a helium leak detector. Colour (capillary) flaw detection of DWC outer lid and inner lid.
10.	Radiation protection	Dose on the surface of DWC lids before and after welding.
11.	CHTS (Transporter)	CHTS readiness
12.	Inspection of CSM condition	Inspection of integrity of the entire CSM, inlets and outlets of air ducts (protective grids). Assessment of radiation dose to personnel. Dose rates on the front surface of CSM, inlets and outlets of air ducts.

Note. Numerical values of the parameters are the approximate/rounded design value and can slightly differ from actual data.

Table 5 – Stages of technological process of SNF placement for storage in ChNPP ISF-2, at which the application of operating limits and monitoring is mandatory

№	**Name**	**Limit parameter**
1. Functional and operational limits and limit parameters		
1.1	Monitoring of solidity and leaktightness of welds of inner and outer lids.	The maximum permissible values of helium leakage rate from DWC are not more than 1.0 x 10^{-7} atm-cm^{3}/s. The presence of defects in welds during capillary monitoring and solidity monitoring by the method of helium leak detector is not allowed.
1.2	Maximum permissible outlet air temperature	Temperature difference at the inlet and outlet of ventilation ducts ≤ + ΔT 60^{o}C (Estimated maximum temperature difference at a maximum outside temperature is 48^{o}C). Exceedance of this value will indicate a violation of air passage through the ventilation duct.
1.3	Maximum dose rate on the surface of front wall of CSM after loading the DWC with SFAs	≤6.7 µSv/h on average at a distance of 10 cm from the front wall of CSM ≤ 8 µSv/h at the inlets and outlets of air ducts
2. Limit operation conditions		
2.1	Parameters of fuel to be stored	– Fuel element cladding - zirconium (alloy 110), no more than 2 leaky fuel elements per SFA are allowed; Fuel element cladding should not be considered as a radioactive substances safety (spread) barriers. – SFA defects; – residual energy release: ≤ 67 W per fuel assembly; – burnup - 23,500 MW × day/ton of uranium without using the irregularity ratio; – holding time in spent fuel pool - ≥ 20 years; – maximum initial enrichment: 2.4% U^{235}
2.2	Depression in DWC during vacuumization	< 3 mm Hg within 30 minutes
2.3	Helium pressure in the basket	170 ± 3 kPa within 30 minutes after filling with helium
2.4	Inspection of welds of outer and inner lids of DWC by colour flaw detection and by helium leakage test	Absence of cracks, delamination, burn-throughs, fistulas, sagging, shrinkage cavities, lack of penetration, accumulations and non-single inclusions. Lack of single surface inclusions larger than 2.0 mm. [3]
2.5	Average annual ambient temperature	≤ 24° C
2.6	Permissible CSM concrete temperatures	For normal operating conditions and abnormal ambient temperatures: 45°C - on average by the mass of concrete, 107°C - local. For violations of normal operation and emergencies: 93°C - on average by the mass of concrete, 177°C – local.
3. Monitoring during normal operation		
3.1	Check of radiation condition in SFPF and CSM and on SFSA storage site	Regulations for radiation monitoring of ISF-2.
3.2	Visual inspection of inlet and outlet vents of CSM	According to the Regulations for monitoring during storage (usually once a week).

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[3] In accordance with the standard procedure for assessing the quality of the weld

№	Name	Limit parameter
3.3	Temperature conditions of CSM	Permanent monitoring of temperature of air leaving the ventilation ducts.
3.4	Inspection of external surface of CSM	According to the regulations for monitoring during storage (usually once a month).
3.5	Inspection of outer surface of DWC using a borescope	According to DWC monitoring program at the stage of long-term storage.
3.6	Inner cavity of CSM	According to DWC monitoring program at the stage of long-term storage.
3.7	Monitoring of base metal and welds of DWC by examining the surveillance specimens	According to DWC monitoring program at the stage of long-term storage.
3.8	Monitoring of radioactive aerosols presence in the air of CSM	According to DWC monitoring program at the stage of long-term storage.
3.9	Monitoring of gamma radiation dose rate from CSM	According to DWC monitoring program at the stage of long-term storage.
3.10	Monitoring of neutron radiation dose rate from CSM	According to DWC monitoring program at the stage of long-term storage.

Note. Numerical values of the parameters are the approximate/rounded design values and can slightly differ from actual data.

Table 6 – Operational limits and monitoring ChNPP ISF-2

No.	Parameter	Implementation methods	Possibility of monitoring during storage
1	Nuclear safety (sub-criticality)	DWC design. Storage of FE bundles in FT, made of neutron-absorbing material	During storage, the parameters of DWC design do not change. Internal monitoring is not carried out.
2	Structural integrity of spent fuel assemblies and fuel elements	DWC design and inner basket design	During storage, the parameters of DWC design do not change. Internal monitoring of SNF condition is not carried out. Monitoring of fuel elements bundles is impossible without opening the DWC.
3	SNF storage medium parameters (chemical neutrality, non-aggressiveness in relation to SFA materials)	DWC dehydration, filling with helium, sealing by welding.	During storage, the parameters of internal medium do not change. Internal monitoring is not carried out. Monitoring of parameters of internal medium is impossible without opening the DWC.
4	Radiation safety of personnel and environmental protection	Leak tight DWC structure. Storage module (CSM) with concrete biological shielding.	Permanent monitoring of the intensity of gamma and neutron radiation is carried out on the outer surface of CSM and on the territory of the storage facility.
5	Residual heat removal	DWC design, ventilated storage module (CSM).	Internal monitoring of fuel element temperature is not carried out. The

No.	Parameter	Implementation methods	Possibility of monitoring during storage
		The internal medium of DWC is inert gas helium with high heat transfer.	temperature of the air leaving the storage module (CSM) is permanently monitored.
6	Elimination of radioactive substances release outside the storage facilities into the environment	Leak tight DWC structure.	During the entire storage period, permanent monitoring of the presence of radioactive substances in the air cooling the storage module (CSM) and on the territory of storage facility is carried out.
7	Possibility of fuel retrieval (removal) from storage facilities	Design of DWC, storage module (CSM).	Only after opening the storage module (CSM).
8	Rational organization of defective spent fuel storage (with defective spent fuel assemblies and fuel elements)	DWC design provides for the storage of defective / damaged SNF.	The DWC design assumes that the leak tightness of storage is ensured by the double-walled design of canister. The fuel element cladding is not considered as the first leak-tight constructive barrier for SNF confinement.
9	Provision of SNF physical protection (security)	Design of DWC and storage module (CSM). Physical protection/security of the storage facility site.	Storage facility site security is performed continuously during the entire storage period.
10	Compliance with Safeguards (non-proliferation of nuclear materials)	Design of DWC and storage module (CSM). IAEA monitoring during DWC loading. Physical protection/security of the storage facility site.	IAEA monitoring at all stages of placement for storage and monitoring during storage.

Note. Numerical values of the parameters are the approximate/rounded design values and can slightly differ from actual data.

Table 7 – Methods for SNF condition monitoring in ISF-2 at ChNPP

4.5.4. Monitoring SNF packages condition in ISF-2 at the stage of long-term storage

To ensure reliable DWC monitoring at the stage of SNF long-term storage in ChNPP ISF-2, a special “Program for DWC monitoring at the stage of long-term storage” was developed (hereinafter referred to as the Program).

The Program determines the procedure and scope of monitoring of storage conditions for double-walled dry shielded canister (DWC) loaded with SNF and stored for a long time in concrete storage module (CSM) of ISF-2, namely:

1. Scope and procedure for monitoring the radiation situation in the SNF storage area (SFSA);

2. Scope and procedure for in-service monitoring of condition of base metal and welded joints of the DWC outer shell;
3. Scope and procedure for monitoring of DWC leak-tight barrier.

The procedure and the scope of DWC monitoring determined in the Program were established by HOLTEC (as an equipment designer) in accordance with safety and operational requirements.

The first revision of the Program was prepared and agreed on by the customer (ChNPP) and the regulator (national Regulatory Body of Ukraine, SNRIU) in 2013, at the stage of ISF-2 Project implementation, when many details of equipment and technological operations in ISF-2 were not yet fully developed. The last, currently valid version of the Program (Rev.4) was agreed and put into effect in 2016.

Since the mentioned Program has been implemented into the ISF-2 loading technology, and the actual loading of the storage facility has just begun, the results of using the Program will be known after some time. Estimated time for evaluation of results and revision of the Program is 3 - 5 years.

At present (January 2024), all ISF-2 equipment has been manufactured, passed individual factory acceptance tests, on-site tests, comprehensive tests and so-called “hot” tests with real SNF. In April 26, 2021 ChNPP got the licence for ISF-2 operation from the national Regulatory Body of Ukraine (SNRIU).

The latest version of the Program takes into account the actual state of ISF-2 Project implementation.

The Program is typical in accordance with the requirements of the Ukrainian regulatory documents (RD) in the field of nuclear energy and determines the procedure and scope of the double-walled dry shielded canister (DWC) storage conditions monitoring, operational monitoring of condition of base metal and welded joints of the DWC outer shell and monitoring of leak-tight barrier of DWC loaded with SNF and stored for a long time in the ISF-2 concrete storage module (CSM).

In accordance with the requirements of RD, the Program contains:

- Main technical measures to prepare DWC for monitoring;

DWC monitoring determined in the Program were established by HOLTEC (as an equipment designer) in accordance with the requirements (RD). List of monitored zones;

- List and places of installation of the irradiated surveillance specimens with an indication of the characteristics determined by these surveillance specimens;
- Requirements for surveillance specimens and their parameters;
- Types of monitoring and scope of monitoring;
- Description of monitoring methods;
- Frequency of monitoring;
- List of special means of monitoring;
- Requirements for the resolution of special means of monitoring;
- Norms for assessing the results of monitoring;
- Safety requirements during monitoring.

Detailed descriptions and guidelines for certain types of monitoring are set out in the detailed procedures for monitoring, a list of which is given below:

- DWC leaktightness monitoring using a helium leak detector at the ISF-2 site;
- Procedure for visual inspection of the DWC outer surface in CSM;
- Monitoring of radioactive aerosols volumetric activity;
- Monitoring of inert radioactive gases (IRG) volumetric activity in the air of loaded cells of CSM;
- Determination of radionuclide composition of air contamination in loaded cells of CSM;
- Monitoring of ambient dose equivalent rate of gamma radiation in CSM area;
- Monitoring of neutron radiation dose rate during storage of DWC in CSM;

- Monitoring of total radioactive contamination of exhaust ventilation ducts of CSM cells;
- Procedure for periodic cleaning of CSM ventilation grids;
- Procedure for cleaning of DWC and HI TRAC-H (OSTC);
- Procedure for monitoring changes in the characteristics of base metal, metal of welds and metal of welded joints of the outer shell of DWC.

The described Program must be approved by the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) in accordance with RD. During the operation of ISF-2, as well as a result of DWC monitoring, this Program may, if necessary, be amended. In this case, the modified version of the Program must be submitted to the SNRIU for approval.

The results of DWC monitoring at the stage of long-term storage in CSM should be used to reassess the safety of DWC storage and extend the validity period of the license for the ISF-2.

5. Damaged nuclear fuel

5.1. General description of damaged SNF

According to the definition in the Ukrainian regulatory documents [2]: Damaged nuclear fuel (DSNF) is a nuclear fuel that has mechanical damage that does not allow its intended use, and the management of which requires additional and/or other design solutions in comparison with management of nuclear fuel without damage.

As a rule, DSNFs are spent nuclear fuel assemblies (SFAs), which during their residence in the reactor were deformed or got cladding defects (flaws, cracks, etc.), due to which direct contact of fuel with water became possible. Also, defects of spent fuel assemblies can be formed during transportation of SFAs and process operations when handling them (when unloading from the reactor, moving from the reactor hall to the spent fuel pool hall, etc.) or during storage of fuel assemblies in the spent fuel pools.

Damaged fuel management is a more complicated and time-consuming technological process. The safety of this process, both from the point of view of nuclear and radiation safety, and in relation to the impact on personnel, population and the environment, is ensured by appropriate measures.

It should be noted that, in general, at the NPP during normal operation, the total number of damaged fuel assemblies stored at both units is relatively small and amounts to about 0.2% - 1% of the total number of spent fuel assemblies stored at the NPP.

However, in the event of various emergencies or incidents at NPPs (ChNPP Unit 4, TMI, Packs 2003), the number of damaged fuel assemblies, or even nuclear fuel debris, can be significant.

Organisational and technical measures for DSNF management can be different, depending on the specific technical situation and the legal framework in the field of nuclear energy. A very good review by the IAEA provides information on all aspects of damage to nuclear fuel and related violations in the normal operation of NPP. Below in this document, fuel assembly monitoring, diagnostics and DSNF management at Ukrainian NPPs and in SNF storage facilities in Ukraine are briefly described.

5.2. FAs monitoring and DSNF diagnostics at Ukrainian NPPs

One of the main types of monitoring at nuclear power plant (NPP) is radiation monitoring of protective barriers condition, which includes, among other things, fuel element (FE) cladding leak detection (CLD) by measuring the volumetric activity of reference radionuclides or their groups in the coolant of the primary circuit. The main regulatory criterion for the ability to operate the reactor core fuel loading, in accordance with NSR-2008 [3], is the number of leaky (damaged) fuel elements in the reactor core. Damages in which only volatile fission products enter the coolant from under the fuel element cladding are commonly called gas leaks. Another type of damage is damage that allows fuel to come into contact with water. Regulatory requirements, limiting the number of leaky fuel elements in the core for each type of damage, look like this:

1. “The operational limits of fuel elements damage due to the creation of micro-cracks with defects such as gas leaks in the cladding should not exceed 0.2% of FEs and 0.02% of FEs in direct contact of nuclear fuel with the coolant.”
2. “Safe operation limit in terms of the number and nature of fuel elements defects is 1% of FEs with defects of “gas leakage” type and 0.1% of FEs, for which there is a direct contact of the coolant with nuclear fuel.”

In accordance with the requirements of the current regulatory documents, both the Ukrainian ones and IAEA recommendations, the main criterion is the number of leaky fuel elements in the reactor core, and the criterion - coolant activity by reference radionuclides - is the derivative value of the main criterion. The fuel failure detection (FFD) is carried out both during operation and after shutdown of the reactor facility (RF). The purpose of FFD is to identify leaky spent fuel assemblies for organising their storage in accordance with the norms and rules of nuclear and radiation safety, as well as to prevent further operation of assemblies that have exceeded the failure criterion. Some details about technology of the identification the leaky spent fuel assemblies are given in Attachment 3.

According to [8], a fuel element considered leaky, if in the it’s cladding is a penetrating crack. There are two types of such damages: the formation of micro-cracks, through which only gaseous fission products can penetrate (the so-called gas leaks), and the presence of defects, in which direct contact of the fuel with the coolant is possible, which leads to transport of other fission products into the coolant, besides gaseous.

5.3. Damaged Fuel Handling at the ChNPP

At present, the Chornobyl NPP is at the stage of termination of operation. Spent nuclear fuel (SNF) as of 01.01.2024 has been removed from the power units and placed in the ISF-1 spent fuel pools.

The SNF at ChNPP contains damaged spent nuclear fuel (DSNF) and special spent SFAs (measuring and thermometric SFA). ChNPP DSNF represents a number of SFAs, both leaky and having other types of damage. DSNF is stored in the form of SFAs and fuel elements bundles (FB) in special canisters of various configurations in the ISF-1 pools.

Currently, all the ChNPP SNF, including DSNF has been transported from the SFP of power units to the ISF-1 storage facility. Description of the DSNF management at ChNPP wet spent fuel storage facility ISF-1 is provided below in subchapter 5.3.1.

For long-term interim storage of intact SNF, accumulated during operation of ChNPP power units, new SNF storage facility of “dry type” - ISF-2 was built at the ChNPP site (see 4.4.1).

For DSNF, FSFA handling at Chornobyl NPP specific Conceptual solution was developed back in 2008 (within the framework of a separate Project for DSNF and thermometric SFAs management), which assumes dry storage of SFAs in special double-walled canisters developed by HOLTEC International without cutting along the expansion gap. Short description of this solution presented in subsection 5.3.2 below.

Currently, work on this Project is suspended.

5.3.1. DSNF management at ChNPP ISF-1

At the ChNPP spent fuel assemblies (SFA) exist in various states of integrity, ranging from intact to heavily damaged and debris. The spent fuel assemblies are RBMK type consisting of two fuel rod bundles connected by a central rod and Extension Rods.

ChNPP power units were designed to use the TK-8 transfer cask for transportation the SFA from power units to the Interim Spent Fuel Storage 1 (ISF-1) for interim storage. Under normal conditions, individual fuel assemblies are fitted with a gripper assembly and removed from at-reactor spent fuel pools individually using a shielded fuel transfer bell with a bottom shield gate and an internal fuel grapple and lifting mechanism. The fuel assemblies are placed into the TK-8 transfer cask removable basket for transport to ISF-1.

Transport of SFA from the power units into the existing ISF-1 was performed by the regular spent fuel transportation procedure. The intact SFA stored in ISF-1 storage pools will be transferred to the new dry ISF-2 after modification of the ISF-1.

After transfer, all intact and failed SFA to ISF-1, a complete inspection/status check of these SFA was carried out. Table 8 presents numbers and properties of fuel assembly defects (damage description) resulting from inspection of 1,956 fuel assemblies in the ISF-1 pools based on inspection records/reports.

At ISF-1 intact SNF is stored in standard canisters in the spent fuel pools (Figure 10), DSNF- and special SFAs - in special canisters (Figures 20 through 23).

In the ISF-1, failed spent fuel assemblies are stored in five distinct types of special canisters (Figures 24 through 27). The different types of specialized canisters are required because of the condition of the spent fuel assemblies (or bundles). Any failure of the bottom nut, bottom nozzle, extension rod or central rod results in the inability to handle the fuel assembly in a normal manner. Individual bundles have no standard means of handling necessitating the need for non-traditional means of handling such as wire rope. The RBMK fuel assembly is designed for handling only by the Extension Rod. Furthermore, the TK-8 is designed for handling intact fuel assemblies only. The basket handling shaft, shielded transfer cask and turret mechanism are designed for handling full length intact fuel assemblies into a TK-8 transfer cask. Once the diameter of the canister, length of the canister or handling means is changed from that of a normal intact fuel assembly, the existing fuel handling mechanisms are rendered ineffective.

The handling of the special canisters (namely Types 1, 2 and 5) required the specialised handling methods and specialised transfer machine to remove them from their storage locations. The water coverage in conjunction with the physical length of the canisters necessitates special grippers, a shielded handling machine and special procedures.

The Failed/Damaged SFA (FSFA) cannot be transferred from ISF-1 to ISF-2 under the normal procedure and also not processed in ISF-2 through the normal process.

Special SFA also cannot be processed in ISF-2 by normal process as disassembling of specific SFA to bundles by cutting at expansion gap is impossible due to fuel elements presence within the expansion gap. Transport of specific SFA to ISF-2 anticipates utilization of the regular procedure for transportation of spent nuclear fuel.

In the frame of ChNPP decommissioning process, special approach to handling of the FSFA was developed.

Special canisters were transferred to ISF-1 and placed in the fuel pools (Figure 24). Figure 25 shows, as an example, an overview of the special canister with damaged SFA.

5.3.2. General description of the technical solutions for FSFA

At the first stage of activities under the Project for the Safe and Long-Term Storage of the Failed/Damaged Spent Nuclear Assembly (FSFA) at the Chornobyl NPP, in 2008-2012, a “Conceptual solution. Chornobyl Nuclear Plant Modification Project Management of Damaged spent nuclear fuel and spent additional absorbers” was prepared with the choice of the optimal variant of the SNF management technology. To understand the proposed method for handling the Failed/Damaged fuel, it is essential to understand the existing fuel handling process and equipment in place to perform the fuel handling, and also to understand the challenges associated with the handling of special canisters.

Storage technologies for SNF are based on the use of a vertical ventilated storage module (VVSM) system, patented and tested by HOLTEC International [1], were chosen as the optimal option. The considered design has the following features:

1. Spent fuel assembly is stored in a vertical position, that is, the orientation of the fuel is not subject to change from the moment it is received as new fuel at nuclear power plants. Thus, the whole complex of problems that arise when storing fuel in a position other than the working state (horizontal) is eliminated.
2. SFA is placed in a dry storage canister - DSC, which, in turn, is loaded into the VVSM, without the need for fragmentation of SFAs or any other operations to process failed/damaged SFAs.
3. DSC is structurally made in the form of two sealed vessels independent of each other, while the outer wall of the inner vessel fits snugly against the inner wall of the outer vessel along the entire contour. Each of these two vessels provides an independent barrier against the release of radioactive materials. In addition, in the proposed system of two independent barriers between the container and the environment, there are no gaskets or other mechanical seals that could potentially leak.
4. Adjacent to each other double walls of the container are in macroscopic contact over the entire surface, which thus allows for heat exchange between the contents of the container and the atmosphere. Due to this, the dry storage container, despite the presence of a double wall, serves as an efficient heat exchanger and allows the heat that accompanies the radioactive decay of SNF to be removed to the environment.
5. The DSC includes a "fuel basket" capable of holding damaged SFAs with different cross-sectional dimensions in such a way that:
    a) such rigidity of the structure is ensured, in which the main vibration frequency during bending of the prefabricated structure (consisting of SFA and canister) is in the zone of elastic vibrations;
    b) the efficiency of heat transfer is ensured due to the presence of the thermosiphon mechanism;
    c) it is possible to provide an increase or decrease of the dimensions of the internal structural elements of the container depending on the temperature difference.

6. DSC provides the possibility of drying SNF to an extremely high level of dehydration (total partial pressure of water vapor does not exceed 400 Pa using the forced gas drying technology patented by HOLTEC.
7. Nitrogen is used as an inert medium during long-term storage of SNF in a container. The free volume of the container is sufficient to ensure safety in terms of total pressure (below the calculated limit for both shells) in the theoretical case when 100% depressurization of all fuel rods occurs, leading to leakage of all gases contained inside.
8. VVSM[4] used for storage provides:

a) effective ventilation of the external surfaces of the DSC with air flow;

b) an almost insurmountable barrier for gamma and neutron radiation from the container, as a result, the radiation dose outside the canister is negligible;

c) storage of fuel in a state in which, there is practically no threat of exposure/dispersion from it in the event of an aircraft accident or missile attack.

9. All external surfaces of the DSC are made of austenitic stainless steel, thereby ensuring low brittleness and high impact resistance of the structure under extremely low temperature conditions that are possible in the storage area during winter.
10. The DSC fuel basket design includes neutron absorbers to ensure system sub-criticality at k_{eff} below 0.95 even in the case of optimal multiplication capacity under the most unfavorable set of circumstances, and also taking into account the errors of the computer code used for calculations. (This methodology is an example of the application of the defense in depth principle that HOLTEC uses in the design of all containers it manufactures).
11. The system for installing the DSC inside the VVSM is designed in such a way that the DSC can be easily removed from the VVSM even if the foundation is settling. Also, the presence of corrosion on the surface of the VVSM parts, in case of maintenance problems during operation, will not entail difficulties in removing the container from the module.
12. The proposed system contributes to high efficiency of loading operations, while providing measures aimed at minimising the dose of radiation received by the service personnel.

The above main features of the proposed SNF storage system are in full accordance with the direction of long-term work to address issues of SNF management at the Chornobyl NPP.

5.3.3. Characteristics of Storage Systems for Failed/Damaged SFAs and Fuel Debris

For use at the Chornobyl NPP, the «HI-STORM 100™» [1] system was proposed. This dry storage system uses dry storage canisters (DSCs). The HI-STORM 100 system consists of the following components: interchangeable Dry Storage Canisters (DSCs) where the fuel resides, and a container storage system known as the HI-STORM 100 System, where the DSCs are located during storage.

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[4] VVSM – Vertical Ventilated Storage Module

The HI-STORM 100 system is a vertical ventilated storage module (VVSM). The HI-STORM 100 system has a thick-walled steel inner casing with a welded steel bottom and a removable reinforced concrete top cover.

The HI-STORM system is designed for installation, on-site transportation and long-term storage of Failed/Damaged spent fuel assemblies (SNF) and their fragments in an inert gas (nitrogen) environment. The main functions of the packaging are:

1. Remote installation and storage of spent fuel,
2. Removal of heat from spent fuel assemblies to the outer surfaces of the packaging,
3. Fixation of radioactive materials and inert environment.
4. The design of the HI-STORM system, the choice of materials and its manufacture will ensure the following:
    - 4.1. Compliance with nuclear safety requirements;
    - 4.2. Compliance with radiological safety requirements;
    - 4.3. Creation of at least two passive sealed barriers to prevent the release of radioactive materials into the environment
    - 4.4. Integrity of barriers throughout the storage life at the Chornobyl nuclear power plant. The design will determine and justify the probabilities of failure of one or both passive barriers;
    - 4.5. Limitation of gas leakage from the packaging must be determined by the following main parameters:
        - 4.5.1. Operating limit for fuel temperature;
        - 4.5.2. Permissible limits for the release of radioactive materials;
        - 4.5.3. Risk for personnel and the public in accordance with section 2.5 of NRBU 97/D-2000;
        - 4.5.4. The impossibility of unauthorised depressurisation of the packaging, including through covers, valves and other elements that must be closed during normal operation
    - 4.6. Sufficient mechanical, chemical and biological protection properties of the materials used to implement the functions of the packaging set under the designed storage conditions in terms of radiation resistance, physical and chemical compatibility, corrosion, swelling of fuel cladding, detection of latent defects, low-temperature effects and other factors.
    - 4.7. Integrity of at least one packaging containment barrier in case of a DBE[5] event.
    - 4.8. Since the DSC used in the HI-STORM system is designed to store SNF, it must comply with the requirements of the appropriate Ukrainian regulatory documents. Accordingly, the Safety Analysis Report (SAR) should be developed in accordance with the appropriate Ukrainian requirements.

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[5] DBE – Design Based Accident. A postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety (US NRC Glossary).

5.3.4. The main characteristics of the storage system for the Chornobyl nuclear power plant

The Dry Storage Cask - DSC (US Patent No. 5898747) consists of a sealed body and a fuel basket. The pressurised enclosure is a flat-ended cylindrical stainless steel container designed to ASME Section III Subpart NB (Class 1). The design of the DSC includes a honeycomb structure fuel basket, a bottom base, a body, a cover and a sealing ring.

The original DSC (as in US Patent) consist of the cylindrical body, the bottom base of the DSC, the top lid, the lids covering other openings in the Cask, and the sealing ring form a double sealing barrier (Figure 26). The containment barrier is a robust welded construction made entirely of stainless steel. The fuel basket inside the DSC has fuel storage cells. The DSC is a welded pressure vessel that meets the load limit requirements of ASME Boiler and Pressure Vessel Standards, Section III, Subsection NB. DSC fuel baskets are designed and tested to meet the load limit requirements in accordance with Section III, Subsection NG of ASME standards.

In terms of thermal performance, one of the most important design considerations is to ensure maximum heat dissipation in the HI-STORM system. One of the important points in the design is to determine all possible measures to improve the ability to remove heat from the fuel cans, including the optimisation of the nitrogen circulation process and the use of the thermosiphon effect. The use of the thermosiphon mechanism, along with the design of the DSC fuel basket, is the feature of the technical solution for the DSC, aimed at ensuring efficient heat removal from the SNF.

At present, HI-STORM systems are licensed for storage of damaged SFAs from PWRs, BWRs, and fuel debris in smaller than standard storage canisters. The addition of a permit for the storage of damaged fuel and fuel debris to the HI-STORM license provides confidence that other types of damaged SNF, including SNF from RBMK reactors, can also be safely and securely stored in these systems.

For safe storage of damaged nuclear fuel as well as fuel fragments, the inner basket of the spent fuel dry storage cask (DSC) will be designed in such a way that specialised canisters for SNF can be placed in it. An example of such a canister is shown on Figure 27 (canister for dry storage of damaged fuel and fuel debris from PWR reactors). In order to ensure dry storage of all damaged fuel and fuel fragments of the Chornobyl nuclear power plant, canisters of various geometric sizes will be designed for the fuel of the RBMK reactors of the Chornobyl nuclear power plant. At the feasibility study stage, a final decision will be made on the feasibility of either placing canisters of different sizes in one container, or on the location of specialised canisters for the most damaged SFAs and fuel fragments in a separate container.

5.3.5. Basic Container Loading Solutions

At the current stage of designing the dry storage system for FSFA, the following loading procedure is assumed:

1. Canisters for damaged fuel (DFC) are placed in the ISF-1 spent fuel pool.
2. Damaged fuel is remotely placed into the DFC and the DFC is closed with top plugs.
3. DFCs are transferred to the DSC located in the shielding transfer container
4. After filling the DSC, DSC lids are welded, the DSC is dried using a HOLTEC forced drying system and filled with an inert gas (nitrogen).
6. The sealed DSC is lowered in a protective shaft into a transfer container placed in the transport corridor on a specialised railway platform.
7. A protective cover is put on and secured to the transfer container.

8. The transfer container is moved to a horizontal position for transporting to the storage location.

Technical solutions for container loading will be specified and adjusted at the stage of feasibility study development in order to select the best option.

5.3.6. The main characteristics of transport operations

At the current stage of designing the dry storage system for FSFA, the following procedure for transport operations is assumed:

1. A special railway wagon with DSC placed inside the transfer container arrives at the unit.
2. Transfer container is moved from horizontal to vertical position.
3. The loaded DSC, placed inside the transfer container, is delivered to the storage site. The location of the storage site will be specified during the development of the feasibility study.
4. At the storage site, the transfer container is moved to a vertical position.
5. A specially designed gantry (bridge) crane removes the transfer container from the platform and installs it on the HI-STORM storage container. To fix the transport container on the HI-STORM storage container, the so-called an interface device that ensures the safety of operations for moving the DSC to HI-STORM.
6. The transfer container is moved to HI-STORM.
8. On the HI-STORM container an additional cover is placed, fixed on the bolts.
9. IAEA seals are affixed to HI-STORM.

Technical solutions for the transportation and reloading of DSC casks into HI-STORM storage containers will be specified and adjusted at the stage of development of the feasibility study when choosing the best option.

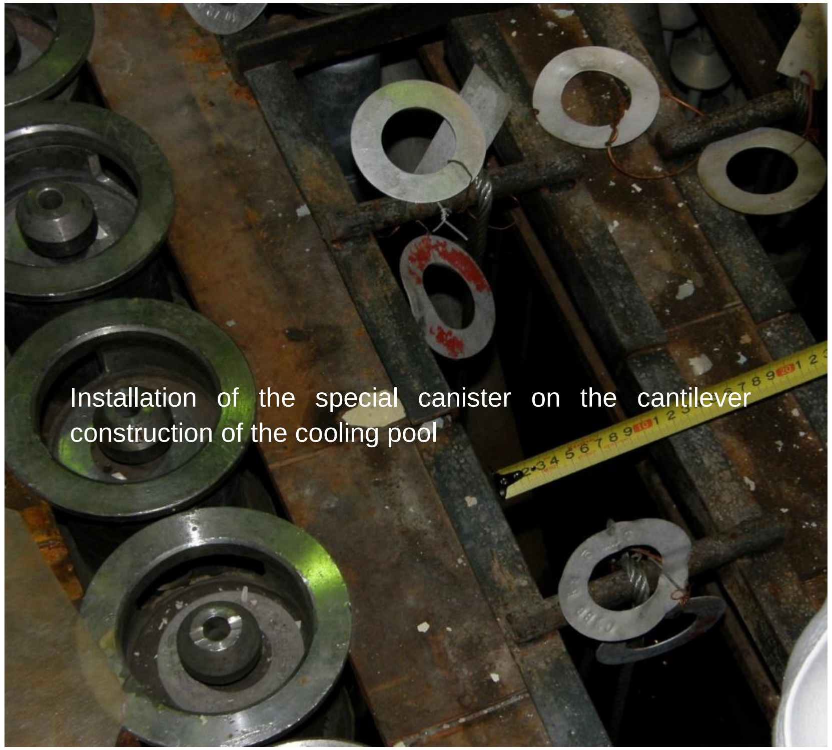
Based on above described approach, for DSNF, FSFA and special SFA (thermometric) handling at Chornobyl NPP specific conceptual solution was developed back in 2008 (within the framework of a separate Project). In this conceptual solution proposed dry storage of the SFAs in special double-walled canisters developed by HOLTEC International without cutting along the expansion gap.

Currently, work on this Project is suspended.

Table 8 Number and properties of fuel assembly defects resulting from inspection of 1,956 fuel assemblies in the pools of Units 1, 2, 3 and ISF-1 as based on inspection records/reports

No.	Defect symbol	Class type	Damage description	Total amt.
1.	Z	A3	Gap between bundles less than 18 mm	63
2.	ZS	A3	Gap between bundles less than 18 mm, foreign objects between fuel rods	1
3.	RZ	B1	Gap between bundles less than 18 mm, end pin unscrewed	1
4.	I	A3	Bent SFA	1
5.	J	B1	Fuel assembly fragmented into halves	1
6.	K	A3	Jammed in the basket	4
7.	H	B1	End piece missing	1
8.	O	B1	Fuel assembly detached from the extension rod	10
9.	B	B1	Fuel rods separated from the central rod	1
10.	V	B1	Fuel rod caps missing	1
11.	D	A3	Spacer grid damage	445
12.	DP	A3	Spacer grid and fuel rod damage	2
13.	DPS	A3	Spacer grid and fuel rod damage, foreign objects between fuel rods	2
14.	DZ	A3	Spacer grid damage, gap between bundles less than 18 mm	19
15.	DJ	B1	Spacer grid damage, SFA fragmented into halves	4
16.	DS	A3	Spacer grid damage, foreign objects between fuel rods	5
17.	S	A3	Foreign objects between fuel rods	13
Total				574

<table>
<tr><th colspan="4">Special canisters for storage of failed spent fuel assemblies at ISF-1</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Figure 20: Type 1/2 special canister for storage of failed spent fuel assemblies</td><td>Figure 21: Type 3/4 special canister for storage of failed spent fuel assemblies</td><td>Figure 22: Type 3/4 special canister lid for storage of failed spent fuel assemblies (partial cut-away view)</td><td>Figure 23: Type 5 special canister body for storage of failed spent fuel assemblies</td></tr>
</table>

 Installation of the special canister on the cantilever construction of the cooling pool	
Figure 24: Special canisters for storage of failed spent fuel assemblies in ISF-1 spent fuel pool	Figure 25: Overview of the special canister with damaged SFA

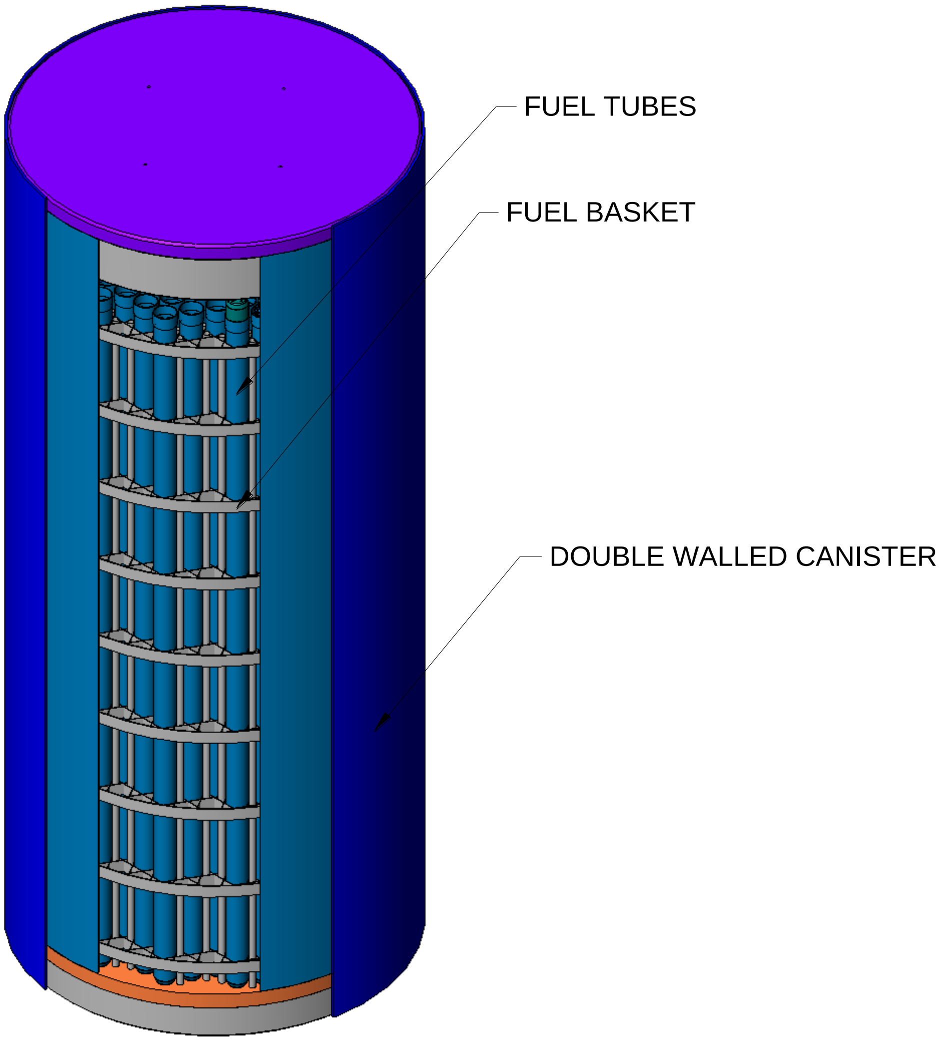


Figure 26: Dry Storage System (US Patent No. 5898747) «HI-STORM 100™»

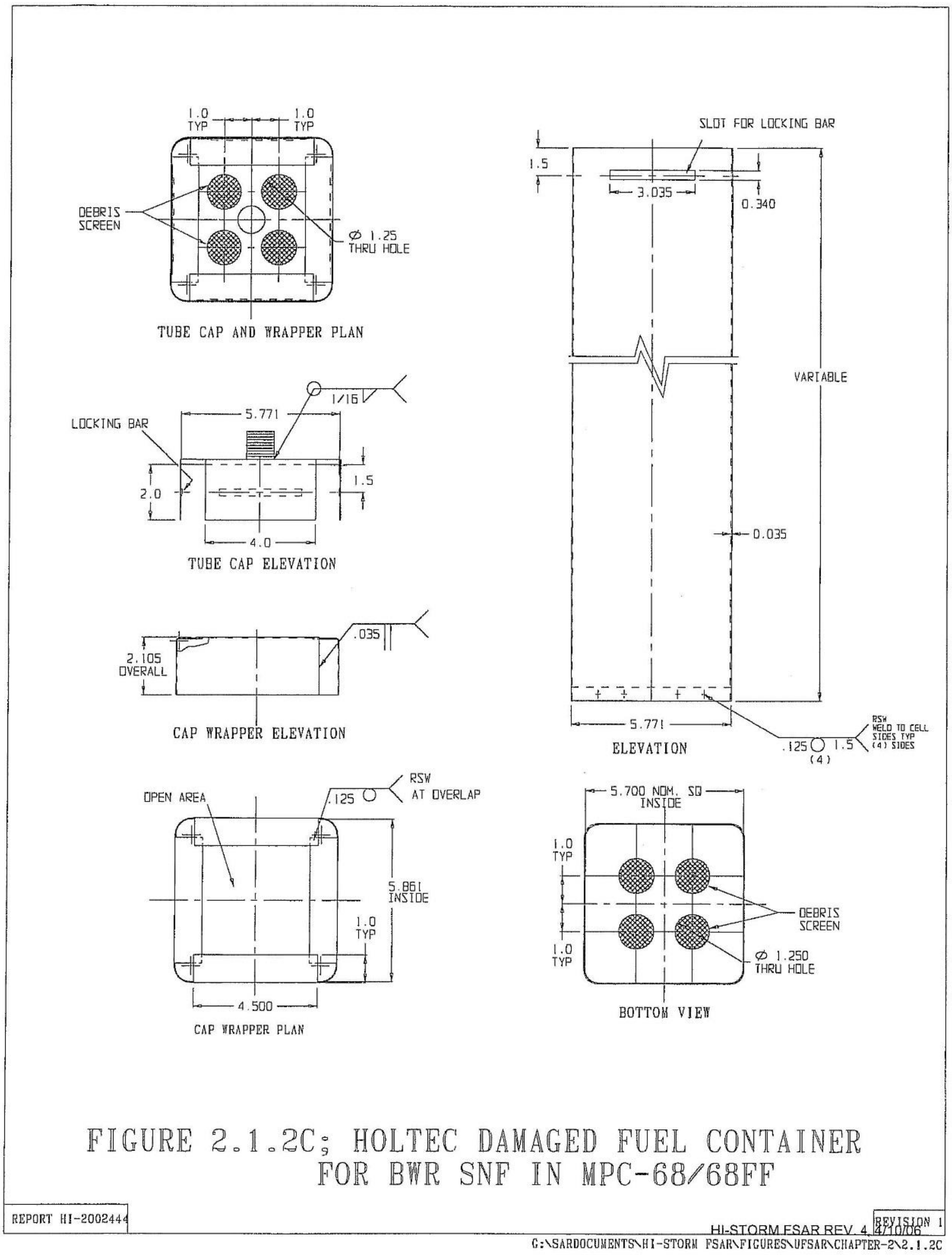


Figure 27: HOLTEC canister for dry storage of damaged fuel and fuel debris from PWR reactors)

5.3.7. DSNF management in ChNPP ISF-2

DSNF cannot be transported to the ISF-2 according to the standard scheme and processed at ISF-2 using the standard technology. Transportation of special SFAs to ISF-2 can be carried out using the standard scheme for transporting spent nuclear fuel, however, special SFAs cannot be processed at ISF-2 according to the standard technology, since cutting of special SFAs into bundles by cutting along the expansion gap is impossible due to passing of fuel elements through expansion gap. Only SFAs with certain types of defects can be transported to ISF-2, namely SFAs with defects allowing these SFAs to be placed into TTB, transported from ISF-1 to ISF-2, to separate the SFAs along the expansion gap, and to pack them in DWC.

As a preliminary list of possible damage to SFAs, in which processing and placement for storage in ISF-2 is possible, the “Minimum list of SFA damages that can be accepted for transportation from ISF-1 to ISF-2 or may occur during transportation to ISF-2 or when handling SFA at ISF-2” was adopted in accordance with the Technical Specification for ISF-2. The list was taken as a basis, since it was compiled based on the results of practical experience in spent fuel assemblies handling at ChNPP (see Table 9 below).

Also in the Technical Specification for ISF-2 it is stated that at ISF-2 it is necessary to ensure the possibility of preparation and placement for storage of spent fuel assemblies (more than 21,000 units) with any types of damage that may occur as a result of transportation to ISF-2 or handling at ISF-2, including the possibility of disassembling the spent fuel assemblies into separate fuel elements for their preparation and placement for storage.

No.	Description of defects
1.	Cracks, ruptures of FE cladding (visible)
2.	Lack of FE end plug
3.	Protruding burrs and ruptures of spacer grids
4.	Size of gap between the FE bundles is less than 8 mm (displacement of FE)
5.	Foreign objects in the volume of SFA
6.	Visually observed bending of SFA
7.	Lack of FE (one or more)
8.	Separation of SFA from extension rod
9.	Missing nut and/or bottom nozzle
10.	Cut/rupture along the expansion gap of SFA or along the fuel rod
11.	Deformation (bending, increase in overall dimensions) of SFA (bundle, fuel element) to a state that does not allow it to be removed from the transport transfer basket (TTB) analogue of TK-8 and/or placed in ISF-1.
12.	Displacement of SFA grid

* SFA with mechanical defects, which do not allow use of standard scheme of reloading and transportation using the equipment available at SSE ChNPP, and special SFAs are not included in the scope of work of the ISF-2 Project. Such SFAs will not be transported to ISF-2.

Table 9– Minimum list of SFA damages allowed for transportation and processing at ISF-2 SFPF

In order to ensure the possibility of the aforementioned operations, a special device was included in the equipment of the “hot” chamber in the Spent Fuel Processing Facility (SFPF) - the damaged fuel processing table (DFPT). It will be used for management of SFAs with defects in accordance with the abovementioned list.

It should also be taken into account that at various stages of operations with SFAs in the SFPF hot chamber, initial events that can lead to SFAs damage not mentioned in Table 9 are theoretically possible.

In order to assess the consequences of such initial events, an approach was used that assumes the determination of the most serious SFAs damage as a result of initial events (i.e., boundary, most unfavourable cases).

As a result of such assessment, in addition to the list in Table 9, and after consultations with ChNPP, a List of additional mechanical defects of SFAs that can occur as a result of operations in the SFPF was developed - Table 10.

No.	Description of defects
1.	Damage to SFA gripper plug, which does not allow carrying out operations on SFA displacement by crane in room 501 and/or reliable installation of SFA into the slot of the Holder Slide upper gripper.
2.	SFA damage during operations with it in room 501, characterised as complete destruction of one fuel element of the lower fuel bundle (MDBA).
3.	SFA geometry perturbation, which does not allow its installation on the Holder Slide or the DFPT tilting unit, due to a fall in room 501*
4.	SFA damage resulting from an initial event associated with seismic impact, equipment failure or operator error, which does not allow further operations with it according to standard technology (not characterised as MDBA).

* The initial event of SFA fall may (or may not) also lead to the appearance of other defects.

Table 10 – List of mechanical defects of SFAs that may result from operations in SFPF

It can also be conservatively assumed that the so-called multiple damage to SFA is possible, i.e. the case when the SFA has several different damages. Such a situation seems unlikely, but possible, for example, as a result of additional damage during the transport and in extreme cases as a result of a seismic event.

The availability of DFPT allows preparing all SFAs for storage, even those with damage listed in Table 9 and Table 10.

In the technological process of SFA processing in the “hot chamber” of the SFPF, various operations are provided for cutting and packing the SFA into fuel tubes and, then, in DWC, including SFA fragmentation into separate fuel elements, or even SFA fragments or spillage of fuel pellets.

The handling of defective SFAs in the ISF-2 SFPF is an exceptional procedure. Depending on the type of SFA defects, a special program for handling and packing such SFA for storage is developed for each case.

The table for DSNF with special tools is specially designed for such cases of handling DSNF with a wide range of possible SFA defects.

6. Probable accident scenarios with SNF packages

According to the requirements of Ukrainian regulatory authority documents in the field of nuclear energy use, for each project of a nuclear facility (including NPP, SNF storage facility, etc.), a “Safety Analysis Report” (SAR) of this facility must be developed. The purpose of the SAR is a convincing demonstration of the compliance of design and organisational solutions of the facility with the requirements, norms and rules of the current normative legal acts (NLA) on nuclear and radiation safety and ensuring an acceptable level of safety of the facility at all stages of its life cycle.

Each SAR necessarily includes a section devoted to the analysis of accidents that may occur at such an object. In particular, for SNF storage facilities, the regulatory document [4] defines the requirements listed in this section.

This section of the SAR provides a list and analysis of violations of the limits and conditions of safe operation and accidents, their causes, ways of development and running and possible consequences. Specifically, this section describes:

1. **Violations of limits and/or conditions for safe operation**

The initial events that can lead to violation of safe operation limits and/or conditions (including failure of elements and equipment, errors of operating personnel, etc.) are described. Methods and means of registration of initial events are indicated.

In order to determine the possibility of accidents, the analysis of chronological sequences of initial events development is carried out with the provision of a description of initial conditions and assumptions, action of protective systems and necessary actions of operating personnel (corrective actions necessary to return the system to its original safe condition).

The results of descriptions and analyses should be used to identify systems and components important to safety, assess their reliability, and to identify failures that can be initial events for accidents.

2. **Design basis accidents**

Based on the list of design basis accidents initial events, determined by the current regulations, and analysis of violations of safe operation limits and/or conditions, a list of design basis accidents initial events and their characteristics during the SNF storage facility operation is provided.

The ways of development and running of design basis accidents and their consequences are described and analysed in specific SAR chapter. The operation of systems and equipment affecting the ways of design basis accidents running is described.

The performed analysis should contain information on the assessment of the amount, composition and concentration of radioactive substances that can go beyond the protective barriers of SNF storage facility during design basis accidents, as well as on the radiation impact on personnel, population and the environment, determined by deterministic and probabilistic methods.

The sufficiency of measures and means of radiation protection depending on the predicted consequences of design basis accidents is shown.

The analysis considers the interaction and mutual influence of the accident condition and SNF storage facility systems.

3. **Beyond design basis accidents**

On the basis of the list of beyond design basis accidents initial events, determined by current regulations, a list of beyond design basis accidents initial events and their characteristics during the SNF storage facility operation is provided.

An assessment of the probability of initial events and a description of methods for its determination are given.

The ways of development and running of beyond design basis accidents and their consequences are described and analysed. The operation of systems and equipment affecting the ways of beyond design basis accidents running is described.

The performed analysis should contain information on the assessment of the amount, composition and concentration of radioactive substances that can go beyond the protective barriers of SNF storage facility during beyond design basis accidents, as well as on the radiation impact on personnel, population and the environment, determined by deterministic and probabilistic methods.

Resources (technical and human) and measures to mitigate the consequences of beyond design basis accidents are described. The possibilities of beyond design basis accidents control using the available technical means intended for normal operation, to ensure safety in design basis accidents, or specially designed to reduce the consequences of beyond design basis accidents (if available in the project) are shown.

The analysis considers the interaction and mutual influence of the AC and SNF storage facility systems.

4. Additional information

A description of the methodology and techniques for analysing accidents and their consequences is given. The used physical and mathematical models are described, their application is substantiated. The initial data, assumptions and simplifications adopted in the analysis are given. The used computer programs and codes, their input data, etc. are described.

Further, in this section, using the example of the analysis of accidents for ChNPP ISF-2, it will be shown how the above requirements of the regulatory document are implemented in practice for a specific SNF storage facility in Ukraine, which was built recently.

6.1. Analysis of initial events and their consequences

When analysing the accidents possible at ChNPP ISF-2, it is assumed that the initial events (IE) are considered to be the malfunctions (failures) of ISF-2 systems (elements) and equipment or personnel errors, as well as external and internal effects. It is understood that an IE includes all dependent failures that result from that IE.

ISF-2 design solutions, in accordance with the requirements of regulatory documents, provide for measures to prevent failures or protect ISF systems and elements from subsequent failures of safety important systems or elements that occur due to the initial single failure, personnel error, internal and external effects, and the sufficiency of such measures is substantiated.

The analysis of accidents at ISF-2 was performed in order to demonstrate the compliance of technological solutions adopted at ISF-2 with the requirements of regulatory documents on dry-type spent nuclear fuel storage facilities safety provision in force in Ukraine. When compiling the list of ISF-2 IE, the list of ISF-2 design basis events (DBE), defined in the Technical Specification (TS) for ISF-2, was taken as a basis, taking into account the recommendations of the regulatory document [9].

In the analysis of accidents for ChNPP ISF-2, the DBE are grouped by frequency of their occurrence. In such a grouping, the parameters of design basis events are laid down in the design decisions/measures to ensure the operability of ISF-2 systems and equipment in order to establish a common logical and systematic approach to safety provision.

In accordance with the TS for ISF-2, 4 groups of design basis events are considered:

- Group I. Events that occur frequently or regularly during the ISF-2 operation, such as acceptance of transport cask, retrieval of TTB, preparation of fuel for storage, RAW handling, etc. (i.e. the operations provided by technological process at normal operation of facility);
- Group II. Events that are not regular or frequent but occur with sufficient frequency or frequency equal to one event per calendar year of ISF-2 operation. (For example: short-term power outage; error of personnel with subsequent application of appropriate corrective action; minor failure of lifting mechanisms that does not lead to the need to retrieve SFAs from the storage system; spontaneous equipment actuation; insignificant leakage of pipelines flange connections of radioactive waste management system, etc.);

- Group III. Events that are not frequent, but can occur during the period of ISF-2 operation. (For example: long-term power outage; significant equipment failure, including fuel transportation equipment (without loss of biological shielding functions, but with the need to retrieve FAs from the storage system); fall of FA in a hot chamber; passive failure of the protective barrier of liquid radioactive waste treatment system, etc.);
- Group IV Hypothetical events, the consequences of which can lead to the maximum possible impact on the environment in the immediate vicinity of the facility. The analysis of these events should be taken into account in the design basis of systems that perform localization functions. Project events of group IV are the following:
    - External design basis initial events of natural and man-made nature;
    - Internal design basis initial events that occurred during the operation of the facility under consideration and have a lower frequency of occurrence than events classified as events of I, II and III categories.

The list of initial events of ISF-2 normal operation violations, design basis and beyond design basis accidents was made on the basis of analysis of equipment possible failures during the performance of operations on SNF preparation for storage and storage at ISF-2 using HOLTEC technology.

Failures resulting in exceeding the operating limits and safe operation limits and/or conditions of the following equipment/elements, systems important to ISF-2 safety were considered:

- equipment of the main systems of technological process:
    - TK-8 rail car handling systems;
    - SFA handling systems;
    - Fuel tube (FT) handling systems;
    - DWC handling systems;
    - Hot chamber solid RAW handling systems;
- process support systems important for safety:
    - Liquid Radioactive Waste Handling Systems (LRWHS);
    - Forced Gas Dehydration System (FGD);
    - Hot Chamber Ventilation Systems (HCVS);
    - Radiation Monitoring Systems (RMS);
- structures and elements that perform safety functions – biological shielding and localisation of nuclear materials (NM) and radioactive materials (RM): protective windows, doors, penetrations, on-site transport container (OSTC), building structures SFPF and CSM.

The list of the main design basis initial events (DBE), which were taken into account during the safety analysis, is presented in Table 11. The DBEs are grouped depending on the frequency of their occurrence in accordance with the approach of ISF-2 TS described above. Classification and analysis of possible consequences of design basis events were performed taking into account the following factors:

- Frequency of DBE (DBE group);
- Potential possibility of violation of operational limits, limits and/or conditions of safe operation of ISF-2 as a result of occurrence of the design basis event;
- Implemented in the project solutions and measures to ensure the safe operation of systems/equipment/elements in the event of design basis events - external and internal effects of natural and man-made nature (for example, design of systems/equipment/elements important to safety taking into account the principle of single failure);
- Characteristics of reliability and durability of systems and equipment important to safety;
- System locks of exceeding operational limits and safe operation limits by technological parameters of systems/equipment important to safety;

- Compensatory measures and means provided in the project and technological regulations for elimination of consequences of violations of normal operation, emergency situations and accidents.

The list of the main design basis initial events (DBE) of design basis accidents (Table 25) is made taking into account the principle of single failure. Design Basis Accidents Initial Events (DBIE) accompanied by more than one independent failure are classified as Beyond Design Basis Accidents Initial Events (BDBIE).

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
Internal man-made IEs related to the technological process				
Errors of personnel with the subsequent application of corresponding corrective actions when operating process systems of TK-8, SFA, FT, DWC, HC SRW handling	Incompatible movement (mutual blocking) of equipment of TK-8, SFA, FT, DWC, HC SRW handling systems. Hanging of SFA/TTB/FT/OSTC/basket/ drum with SRW Errors of personnel performing DWC welding operations (AWS operator, manual welding operator), which were detected during the quality inspection of welded joints	Group II DBE	TK-8/SFA/FT/DWC structures integrity damage. Overheating of fuel, possible excess of temperature limits of FE cladding, packages materials, which can lead to their damage Additional exposure of personnel above the established limits during the consequences elimination SFA/TTB/FT/DWC structure damage Poor-quality welded joints, possible overheating of fuel, elimination of defects in welds associated with additional exposure of personnel	ANO (abnormal operation)
	Error of SFA cutting device (CD) operator during the pointing of gripper and the process of gripping Error of operator when handling SFAs on the DFPT		Destruction of fuel during acceptance and preparation for storage Complete destruction of one fuel element of the lower fuel bundle is	ANO

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
	Errors of operator when driving the OSTC trolley		taken as the maximum damage Release of the gas-aerosol fraction into the space of HC	
	Errors of crane operators (going beyond the "working area" of the crane) during lifting operations of TK-8, SFA, FT, DWC, HC SRW handling systems Erroneous opening of gripper by crane operator	Group III DBE	Collision with surrounding structures, walls during lifting operations of TK-8, SFA, FT, DWC, HC SRW handling systems Damage to TK-8/SFA/FT/DWC structure integrity, which can lead to FE damage Fall of SFA/TTB/FT/OSTC with DWC/basket, drums with HC SRW, which can lead to a damage to their structure integrity, loss of localizing barriers, damage to FEs, release of radioactive materials and ionizing radiation into the environment above the established limits	DBA
Failures of TK-8, SFA, FT, DWC, HC SRW handling systems equipment	Shutdown/failure of cranes of the main technological process as a result of mechanical damage, malfunction of drives, etc.	Group II DBE	Hanging of TTB/SFA/FT/OSTC with loaded DWC/basket with HC SRW Exceedance of temperature limits of fuel element cladding, packages materials, which can lead to their damage	ANO

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
			Additional exposure of personnel above established limits	
	Uncontrolled movement, spontaneous actuation of equipment, including cranes, other lifting mechanisms, lids of wells No. 1, 3, OSTC trolley			ANO
	Destruction of fuel during acceptance and preparation for storage	Group II DBE	Fuel damage (complete destruction of one fuel element of lower fuel bundle is taken as maximum damage.	ANO
	Failure of lifting system of cranes of the main technological process - deformation or rupture of ropes due to overload Failure of SFA/TTB/FT/OSTC grippers	Group III DBE	Fall of SFA/TTB/FT/OSTC with loaded DWC/basket with HC SRW May lead to damage to structure integrity, loss of localizing barriers, damage to FE, release of radioactive materials and ionizing radiation into the environment above the established limits	DBA[6]
	SFA cladding failure, which led to SFA damage and FE depressurization	Group III DBE	FE damage (see DBE “destruction of fuel in the process of acceptance and preparation for storage”)	DBA
	DWC fault in leak tightness during long-term storage	Group IV DBE	DWC fault in leak tightness - the leakage of helium from DWC containment higher	DBA

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[6] Design Basis Accident

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
			than the ANSI N14.5 leak tightness criterion, is detected during long-term storage in CSM Loss of helium leads to violation of heat removal and possible excess of FE cladding temperature Exceedance of radiation parameters limits in CSM, release of radioactive materials outside the CSM	
Internal man-made IEs not related to the technological process				
Malfunction of automatic welding machine/station (AWS)	AWS failure during welding operations	Group II DBE	Violation of thermal conditions, possible excess of temperature limits of FE cladding, equipment materials	ANO
Failure of hot chamber ventilation system (HCVS). HC filters failure	Failure of supply and exhaust systems equipment Failure of HCVS fine and coarse filters Failure of HC pre-filters	Group III DBE	Release of radioactive substances into premises where personnel stay Gases and aerosol release of radioactive substances higher than those established for ISF-2 permissible release	DBA
Malfunction of radiation monitoring system		Group II DBE	Failure to fulfil the safety function “continuous radiation monitoring”	DBA
Fall of objects that can lead to a change in SFA location and/or a damage to	Fall of SFA on TTB Fall of FT on loaded DWC Fall of DWC inner lid on loaded DWC	Group III DBE	Fall of SFA/TTB/FT/OSTC with loaded DWC/basket with HC SRW May lead to damage to structure integrity, loss	DBA

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
SFA structure integrity			of localising barriers, damage to FE, release of radioactive materials and ionizing radiation into the environment above the established limits	
Flying objects (a consequence of internal explosions)	It is excluded because there are no internal sources of explosion	Group IV DBE		
Fire associated with sources of fire and explosion hazard in SFPF building and at the ISF-2 site (diesel-generator unit)	There are no fire hazard sources in SFPF building A fire event caused by spillage and ignition of 880 liters of flammable vehicle fuel is postulated. This estimated value is related to the volume of diesel-generator tank.	Group IV DBE	Exceedance of temperature limits of fuel element cladding, packages materials, which can lead to their damage Destruction of DWC structures can lead to criticality Loss of HI-TRAC-H biological shielding and personnel exposure above established limits	DBA
Flooding of storage areas (if possible)	Excluded by technological process	Group IV DBE		
Partial blockage of CSM air duct openings	Partial blockage of CSM air vents is defined as an event in which, during normal storage, half of ventilation inlets are blocked by debris.	Group III DBE	Violation of thermal conditions, exceedance of temperature limits of FE cladding, DWC materials	DBA
Complete blockage of CSM air duct openings		Group IV DBE	Violation of thermal conditions, exceedance of temperature limits of	DBA

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
			FE cladding, DWC materials Possible destruction of DWC structures	
Loss of power supply		Group III DBE	Similar to DBE “complete loss of power supply”	DBA
Formation of explosive, flammable, corrosive, toxic or radioactive clouds	see DBE “fires”, “explosions”			
Safety barriers damage (destruction)	see DBE “tornado, flying objects generated by tornado”			
Natural external IEs				
Earthquake (Design Basis Earthquake)	Design Basis Earthquake with a spectrum of seismic responses of ChNPP site in accordance with TS Seismic loads on structures and equipment of ISF-2, including building structures of SFPF, CSM, HI-TRAC-H with a loaded DWC at the HTS and free-standing	Group IV DBE	Safety barriers damage (destruction) Dropping, overturning storage containers, transport packages TK-8, SFA, FT, DWC handling systems equipment failures	DBA
Flood	The maximum rise of water is postulated to a level of 112.60 m above the see level, due to a rise in the water level in local rivers or the level of groundwater	Group IV DBE	SFPS, CSM flooding	DBA
Tornado, flying objects generated by tornado	Design characteristics of tornado and flying objects in accordance with TS	Group IV DBE	Safety barriers damage (destruction)	

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
			Dropping, overturning storage containers, transport packages	
Landslides (landfalls), land subsidence and other natural collapses		Group IV DBE	Safety barriers damage (destruction) Damage to SFPF building structures, fall of loads, partial blockage of CSM ventilation openings Dropping, overturning storage containers, transport packages	DBA
Lightning strike		Group IV DBE	Fire, explosion, destruction of structures	DBA
River banks erosion	similar to DBE “flood”	Group IV DBE	SFPS, CSM flooding	DBA
Extreme weather conditions (extreme wind, extreme temperature, snowfall, rainstorm)	parameters according to initial design data	Group IV DBE	Load on building structures and equipment	DBA
External man-made IEs				
Plane crash	It is excluded from consideration due to the low probability of the event, since there is no air corridor above the ChNPP site	Group IV DBE		
Complete loss of power supply	SFPF power supply is made with redundancy; however, it is assumed that a complete loss of normal power supply is possible	Group IV DBE	Loss of power supply to systems and elements performing technological operations can potentially lead to failures associated with	DBA

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
			FE damage (maximum “damage to one fuel element with spillage during storage”)	
Explosions (air blast)	Possible explosions at ChNPP or Yanov station. The source of explosion can also be a flammable object transported near the ISF-2 facility (from the TS)	Group IV DBE	Safety barriers destruction, release of nuclear and radioactive materials beyond localising barriers	DBA
Formation of explosive, flammable, corrosive, toxic, or radioactive clouds	Similar to DBE “fires”, “explosions”	Group IV DBE		
Fires	Parameters in accordance with TC	Group IV DBE	Safety barriers destruction, release of nuclear and radioactive materials beyond localizing barriers	DBA
Beyond design basis accidents initial events				
Emergence of self-sustaining nuclear chain reaction	Filling the DWC with SNF with water of different density Changing the structural dimensions of SNF, FT and fuel basket inside the DWC; reducing the concentration of B_4C in the Metamic alloy by 25%.		Complete destruction of all SNF in the DWC with the formation of a homogeneous mixture of fuel matrix with water in the lower part of FT	BDBA
Collapse of building structures leading to damage to the SFA storage area	Collapse of SFPF building structures can cause disturbances in the operation of lifting crane equipment, while the shielding structures of HC retain their integrity		Possibility of critical mass formation as a result of SNF spillage Release of radioactive substances into the environment	DBA

Design basis event	**DBE parameters/dependent failures**	**DBE classification**	**Potential consequences of DBE (operational events, emergencies and accidents)**	**DBE consequences classification**
	Collapse, full coverage of CSM with debris		see DBE “complete blockage of CSM air duct openings”	DBA

Table 11 – List of design basis initial events (DBE) and potential consequences of such events

6.2. Design measures to prevent accidents and eliminate the consequences of accidents

When analysing accidents for any SNF management technology, including for SNF storage facilities, it is first expedient to determine the acceptance criteria for accident development scenarios and their consequences for each DBIE (Design Basis Initial Event).

For ISF-2 DBIE listed in Table 11, such criteria were established on the basis of safety standards and requirements (technological, nuclear and radiation) established in regulatory documents of Ukraine and contract documentation that defines the design basis of ISF-2.

Further, during the analysis of accidents, the fulfilment of such acceptance criteria is checked and an assessment of compliance with the basic safety principles implemented in the design and operation of the ISF-2 facility is made.

The ISF-2 design establish the following basic requirements and safety criteria for ensuring the operability and durability of ISF-2 equipment, systems, elements and structures under conditions of external effects of natural and man-made nature, internal events of man-made nature:

- the equipment for storage should be designed in such a way that the effective neutron multiplication factor (K_{eff}) does not exceed 0.95 even when the storage facility is filled with water, as well as in case of such an amount, distribution and density of water as a result of initial events, which leads to a maximum K_{eff};
- the design of baskets, racks in storage facilities, vehicles for SNF transportation should ensure their stability under normal operating conditions, during MDE[7] and other natural phenomena specific to this region;
- SNF packages that are transported must be secured in such a way as to prevent their overturning under normal operating conditions, violations of normal operation and design basis accidents, as well as under conditions of any natural phenomena specific to this region;
- SNF handling equipment should prevent the possibility of packages or SFAs fall during normal operation, as well as such damage to packages and SFAs that can lead to an accident in initial events causing fall of packages or SFAs;
- technical means must be provided to exclude uncontrolled, spontaneous movements of equipment for SNF handling;
- when designing a system for storing and handling nuclear fuel, measures and devices must be provided to exclude the possibility of increasing the temperature of fuel element cladding above the design values for normal operation and design basis accidents;

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[7] Maximum Design Basis Event

- the transport and process equipment for nuclear fuel displacement, along with the main transport speed, must have a finishing speed. Displacement speeds should exclude damage to fuel assemblies and equipment;
- the design of cranes and other lifting mechanisms for SNF transportation should exclude the possibility of SNF fall and uncontrolled movement of mechanisms;
- the grippers of lifting mechanisms must be designed in such a way as to reliably lift and move nuclear fuel, which must be ensured by the following measures:
    - before the start of nuclear fuel lifting, the gripper of lifting mechanism must be positioned over the gripping device of package, basket, fuel assembly with the required accuracy;
    - the gripper must remain in closed position in the event of a power outage;
    - using the blockage, it is necessary to ensure that the gripper with the suspended fuel assembly cannot be disengaged spontaneously or as a result of personnel error;
- when designing equipment for nuclear fuel storage and handling, it is necessary to take into account all mechanical loads arising during normal operation and as a result of initial events, including asymmetric loads and loads during acceleration. It is necessary that the stresses resulting from the action of the loads do not exceed the permissible limits for various fasteners (bolts, nuts, etc.);
- electric motors mechanisms for transport and process equipment for SNF transportation, failures of which can lead to an accident, must have a redundant power supply. Manual drives must be provided to ensure that the systems can be brought into a safe state in case of power outage, as well as blockage of lifting and transport mechanisms;
- during transport and process operations with SNF under conditions of normal operation, violations of normal operation and design basis accidents, the possibility of damage to fuel elements leaktightness due to residual energy release should be excluded and radiation protection of personnel should be ensured;
- the design of SNF handling equipment should exclude, during normal operation, shocks and other loads that can cause damage or change in the size of SFAs and FEs;
- it is necessary that, during initial events, the fall of fuel assemblies out of baskets, racks and packages should be excluded;
- the complex of technological systems for nuclear fuel storage and handling must be able to perform its functions under specific effects (DBE, MDBE) considered in the design;
- the design of dry-type ISF provides and justifies the sufficiency of measures to prevent failures or protect the ISF systems and elements against failures of systems or components important to safety that arise as a result of a single failure, personnel error, internal or external effect;
- during SNF storage, it is necessary to provide for SNF cooling, taking into account that the temperature of protective barriers should not exceed the design values for normal operation conditions, violations of normal operation and design basis accidents;
- the design should provide for equipping the systems and elements of dry-type ISF with automatic devices and measuring instruments that allow for process and radiation monitoring of SNF storage, transport and process operations with SNF under normal operating conditions, violations of normal operation and design basis accidents;
- the design should provide for safe and reliable handling of all types of RAW that will be generated during normal operation of dry type ISF and during design basis accidents.

The ISF-2 design should, where necessary, provide for the availability of ventilation systems and gas removal systems to ensure the non-proliferation of radioactive aerosols under normal operating conditions and violation of normal operating conditions.

At the storage stage, the ISF-2 design must ensure the integrity of protective safety barriers and monitoring of their condition, including the ability to detect and eliminate gas leaks through the barriers on the way of spread of radioactive substances.

The design of infrastructure systems important to safety should provide for the possibility of redundancy of these systems to the extent necessary to perform safety functions by these systems in case of a single failure.

The design of systems used to eliminate the consequences of accidents should ensure the possibility of performing operational tests, including tests with the transition from main to emergency power supply, as well as ensure the operation of associated safety systems.

ISF-2 design should provide for a timely transition to a reliable emergency power supply system for instrumentation and controls, infrastructure, central signalling device of physical protection system and process systems in case of loss of main power supply. Emergency power supply must be sufficient to maintain conditions for safe storage of spent nuclear fuel and for operation of all systems that ensure safe storage, monitoring, physical protection and accounting of spent nuclear fuel.

When designing equipment for SFA and HLW handling and storage, it is necessary to ensure that it can be easily dismantled or removed for replacement, repair and maintenance.

A separate chapter was devoted to the analysis of accidents in the ISF-2 safety analysis report (ISF-2 SAR) prepared for obtaining a license for commission of the facility.

On the basis of ISF-2 SAR, State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) in September 2020 issued a license for commission of interim SNF storage facility No. 2 at ChNPP.

The approach to the analysis of accidents, similar to that described for ISF-2, was also implemented during the safety analysis of other SNF storage facilities existing in Ukraine. The license for operation of spent fuel storage facilities of various designs is issued by the SNRIU only on the basis of the agreed SAR for each storage facility.

7. Handling the radioactive wastes packages contained SNF, FCM or HLW/LLW generated due to ChNPP accident

7.1. General information

During Chornobyl accident in 1986 some nuclear fuel and fissile materials was released into the environment. Estimates of the amount of nuclear fuel released into the environment during the accident give a value of about 3.5% of the total fuel in the reactor (the total mass of fuel in the reactor is ~ 190 tons), and part of the fuel was released in the form of particles of finely dispersed fuel.

At the time of the accident, according to the expeditions of the Kurchatov Institute, in the 4th power unit there were 196 tons of nuclear fuel in the active zone of the reactor and about 10 tons in the immediate vicinity of the power unit.

In the course of initial work on localisation and liquidation of the consequences of the accident, a large amount of radioactive waste were generated, including those containing fissile materials. Subsequently, these RAW were sent to temporary RAW storage/disposal sites in the Chornobyl Exclusion Zone (ChEZ).

Near the 4th power unit, several repositories were build. The repository with the most radioactive substances occupied 5.4 hectares and was called “North” and in the future, it could not remain there. It was decided to build the Podlesnoye repository (surface type) and the Buryakovka (a trench-type of repository).

During the implementation of priority measures to mitigate the Chornobyl accident, during 1986-1987, facilities for the disposal and localisation of large volumes of emergency radioactive waste were created on the territory of the exclusion zone. These are radioactive waste disposal sites: Buryakivka storage facility (PZRO), Podlesny storage facility (PZRO), Chornobyl stage III storage facility and temporary radioactive waste storage facilities (PVLRO).

The Buryakivka PZRO has been in operation since 1987. The disposal site consists of 30 near-surface storage facilities (trenches) for the disposal of radioactive waste. Since the beginning of facility operation, about 687 thousand m^3 of radioactive waste of Chornobyl origin have been placed in the storage facilities of the Buryakivka PZRO. Today, due to the exhaustion of the design capacity of the RWDF, the possibility of reconstructing the facility is being considered.

The Podlesny PZRO and the III stage of the Chornobyl NPP were created in the first years of the liquidation of the Chornobyl accident. These facilities housed the most dangerous high-level and long-lived emergency radioactive waste. In the future, radioactive waste must be removed from these facilities and reburied in a geological repository.

As a result, in summing up the above, on the territory of the exclusion zone there are nine temporary local places for radioactive waste (PVLRO): “Yanov Station”, “Neftebaza”, “Sandy Plateau”, “Red Forest”, “Old Stroybaza”, “New Stroybaza”, “Pripyat”, “Kopachi” ", "Chistogalivka", with a total area of about 10 hectares. Trenches and piles with radioactive waste are located in the territories of the PVLRO. Work is constantly underway to inspect the territories of the PVLRO, maintain and support the condition of trenches and piles.

The main volume of post-accident (generated during the accident at the 4th power unit in 1986) high-level waste (HLW) is located at the Chornobyl NPP site. Most of them are concentrated inside the Shelter object, and some, including fragments of nuclear fuel, are localised in temporary sites for radioactive waste (PVLRO). In addition, the solid waste storage facility (SWSF) of the Chornobyl Nuclear Power Plant contains HLW generated during the operation of the Chornobyl NPP, as well as HLW generated during the remediation activities after the accident (also fragments of nuclear fuel).

In 2019-2021, the inspection of temporary radioactive waste disposal sites continued in order to substantiate/control their safety and remove radioactive waste from the most dangerous places.

Accurate information about the amount, physical form and composition of such RAW at temporary disposal sites is either fragmentary or not available at all. It is assumed that RAW from such temporary storage facilities will be gradually removed and processed at specialised enterprises/installations (see sub-chapter 7.2).

However, when planning work on the extraction of nuclear fuel fragments of fuel-containing materials from places/objects of temporary storage/disposal of radioactive waste, it is necessary to have some, at least an estimated, idea of the possible characteristics of radioactive waste at such objects.

In order to obtain such information, extensive studies are carried out at RAW temporary storage/disposal facilities using various geophysical equipment and radiochemical techniques. Some details about such studies are presented in the section 1.3 – “Damaged nuclear fuel, fuel fragments and fissile materials in radioactive waste disposal facilities in the Chornobyl exclusion zone”.

What is stated in the section 7.1 applies only to temporary storage/disposal of radioactive waste in the Chornobyl exclusion zone (ChEZ).

Possible ways to solve the problem of handling thousands of tons of Solid Radioactive Waste (SRW) and Fuel Containing Materials (FCM) containing nuclear fuel fragments and fissile materials located in the Shelter are still being discussed and, apparently, will begin to be implemented in full only in a next decades.

7.2. Special installations at ChNPP for radioactive waste processing

7.2.1. Industrial Complex for Solid Radwaste Management

A specialised complex for processing solid radioactive waste (SRW) was built at the Chornobyl NPP (ICSRM - Industrial Complex for Solid Radwaste Management). It consists of three facilities: an installation for the extraction of solid radioactive waste at the Chornobyl nuclear power plant industrial site with a capacity of 525 cubic meters of solid radioactive waste per year, a solid radioactive waste processing plant at the Chornobyl nuclear power plant industrial site with a capacity of 3,500 cubic meters per year, and a near-surface solid radioactive waste storage facility at the site of the Vector complex in the exclusion zone.

The ICSRM project is one component of an integrated radioactive waste management programme for the entire Chornobyl Nuclear Power Plant. The Project includes radioactive waste retrieval, processing and packaging for interim storage or final disposal. Waste management operations performed as part of the ICSRM Project include the following:

- Waste volume reduction through compaction and incineration.

- Waste solidification through immobilisation in concrete, also known as grouting. The immobilisation material provides good resistance to external factors, such as water and weather. Also, grouting creates a monolith with few voids, thus ensuring the integrity of the waste form.

The ICSRM complex consists of four lots:

Lot 0 – Is a temporary storage for low- and intermediate-level long-lived waste as well as high-level waste. This is within the Liquid and Solid Waste Storage Facility and was commissioned in 2010.

Lot 1 – A retrieval facility for low, intermediate and high level long-lived waste on existing solid waste storage facility. It will handle 3 cubic metres of waste per day over an operational life of 30 years.

Lot 2 – A waste treatment facility for solid and liquid radioactive waste allowing for remote sorting, incineration, compaction, evaporation and cementation.

Lot 3 – Is a near-surface storage facility for low- and intermediate-level short-lived waste with a capacity of 55,000 cubic metres. It will accept waste for 30 years and store it for 300 years.

The ICSRM was handed over to the State specialised enterprise «Central Radioactive Waste Management Enterprise» in 2009. The hot commissioning was completed in 2015.

7.2.2. Liquid RW processing facility

Also, a plant for processing liquid radioactive waste was built at the Chornobyl nuclear power plant site.

The Chornobyl NPP Liquid Radioactive Waste Processing Plant (LRWPF) is necessary for processing the liquid radioactive waste (LRW) and LRW accumulated at the Chornobyl NPP, which will be generated during the process of decommissioning the Chornobyl NPP units. The LRWPF will process waste only from Chornobyl nuclear power plant facilities and is not intended for the management of liquid radioactive waste from other nuclear facilities. In the LRWPF facility, as the main technology for processing low- and intermediate-level liquid waste (bottom residue, ion-exchange resins and perlite pulp[8]), cementing technology has been implemented, which makes it possible to transform liquid radioactive waste into a state allowing for disposal. This technology provides the most optimal solution for the disposal of radioactive waste, taking into account the economic factor.

The design capacity of the plant for processing liquid radioactive waste is 42 packages per day (cemented liquid radioactive waste in a 200-liter barrel), 2500 m^3/year based on the original LRW. Design service life of the LRWPF is 20 years. The plant was put into operation and tests began in December 2012.

7.2.3. HLW temporary storage facilities at ChNPP

Based on different origins, characteristics and handling technologies, HLW on ChNPP is divided into three characteristic groups:

- Operational HLW, which is accumulated in an existing storage facility;
- HLW that will be generated during the decommissioning of the 1st – 3rd power units of the Chornobyl NPP;
- HLW generated during the transformation of the Shelter object (fuel-containing materials (FCM) and heavily contaminated materials).
- The third group is divided into three subgroups in accordance with the volume of HLW and the degree of development of technological solutions:
    - HLW during the stabilization of the Shelter object and the construction of a new safe confinement (NSC);
    - HLW during dismantling of unstable structures of the Shelter object; HLW at the stage of extracting FCM from the Shelter object.
    - HLW at the stage of extracting FCM from the Shelter object. This sub-group also includes HLW that will be discovered during the conversion of existing temporary radioactive waste containment facilities (PVLRO, PZRO).

Most of HLW were stored in the existing HLW storage facilities at the Chornobyl NPP - solid waste storage (HTO-SWS) and temporary solid HLW storage (TSHLWS). The main part of them (507 m^3) is located in KhTO. Filling of waste in storages began in 1978 and continued during the operation of the power units, but it was used most intensively during the liquidation of the accident at the 4th power unit.

The HTO compartments for low- and intermediate-level waste were taken out of service after they were filled with operational waste and waste generated during the liquidation of the consequences of the accident at the 4th power unit in 1986, and were mothballed. Heavy compartments for high-level solid radioactive waste were in operation until 2003. Radioactive waste was stored in bulk.

During the process of filling the HTO facility, an analysis of the radionuclide composition of the waste was not carried out due to the lack of appropriate instrumental, methodological and metrological capabilities. Since the main filling of the chemical storage facility occurred during the liquidation of the consequences of the accident at the 4th power unit, the radionuclide composition of the waste can be

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[8] Perlite pulp is perlite used mainly for treatment of process media and removal of mechanical admixtures and corrosion products

equated to the average radionuclide composition of emissions during the accident. Thus, in terms of radionuclide composition, HLW is represented by a mixture of radionuclides of cesium, strontium, cobalt and transuranium elements (isotopes of plutonium, americium). The HTO facility has been closed for waste collection since May 2003 due to the start of construction of the ICSRM facility. As part of the creation of this complex, it was planned to reconstruct the existing storage facility for liquid and solid radioactive waste (HGTO), which was built, but not put into operation.

Currently, HGTO storage facility has been completed, which will make it possible to use it as a temporary storage facility for low- and medium level long lived waste and for high-level waste.

At the stage of decommissioning of the Chornobyl Nuclear Power Plant, all SRW will be processed at the ICSRM to such a state in which they can be long-term stored (HLW and low and medium level waste) or put in disposal facilities (low and medium level waste and short lived waste).

With the commissioning of ICSRM, solid radioactive waste contained in the HTO facility will be removed and, after sorting, placed for storage in the temporary storage facility for LLW-MLW and HLW in the HGTO building.

HLW located in VHTVAO must also be sent to HGTO after repackaging. A temporary storage facility for HLW and LLW-MLW in the HGTO building is being created as part of the ICSRM project at the Chornobyl NPP industrial site. The design service life of the storage facility is 30 years.

7.3. Damaged nuclear fuel, fuel fragments and fissile materials in radioactive waste disposal facilities in the Chornobyl exclusion zone

During ChNPP accident April 26, 1986 the explosions and the resulting fire were accompanied by the release of a huge amount of radioactive materials, including fragments of nuclear fuel (NF). All these materials were radioactive waste (RAW) with different characteristics and different activities.

Accurate information on the amount, physical form and composition of RW at temporary disposal sites is either fragmentary or not available at all. It is assumed that RW from such temporary storage facilities will be gradually removed and processed at specialised enterprises/installations (see above Sub-chapter 7.2).

Information stated in this section applies only to temporary RAW storage/disposal facilities in ChEZ.

Possible ways to solve the problem of managing thousands of tons of SRW and FCM containing nuclear fuel fragments and fissile materials located in the Shelter are still being discussed and, apparently, will begin to be implemented in full only in a few decades.

However, when planning work on retrieval of nuclear fuel fragments/fuel-containing materials from places/facilities of RAW temporary storage/disposal, it is necessary to have some, at least an estimated, idea of the possible characteristics of the radioactive waste at such facilities.

In order to obtain such information, extensive studies are carried out at temporary RAW storage/disposal facilities using various geophysical equipment and radiochemical techniques.

As an example, we can cite the work [5], carried out by the State Research Institution "Chornobyl Center for Nuclear Safety, Radioactive Waste and Radioecology" at several RAW disposal sites - a total of 4 facilities.

A complex of field geophysical and laboratory-analytical methods was used for the studies [6]. The study of each facility was carried out in two stages. At the first stage, studies were carried out without violating the protective insulating properties of the facility: geodetic survey, surface gamma survey, magnetometry, ground-penetrating radar measurements, and electrometry. At this stage, the configuration and geodetic parameters of the facility were determined, and the primary radiological characterisation was performed. At the second stage, work was carried out with an invasion of the main disposal body to characterise the types and distribution of disposed RAW, and to take samples for laboratory studies. Drilling of superficial and deep wells and development of pits was performed. In wells and pits, neutron and gamma-ray logging, photo and video filming, and sampling for laboratory research were carried out. Sample analysis included gamma- and alpha spectrometry, radiochemical analysis, and mass spectrometry.

The work was carried out in the following order:

- Surface gamma spectrometry survey of the facility to identify significant sources of radiation.
- Magnetometric study of disposal site to detect positive magnetic anomalies indicating the presence of metal objects.
- In points with the highest values of equivalent dose rate, exploration wells were drilled.

As a result of surveys of temporary RAW storage/disposal facilities, the following results were achieved [7]:

1. The main part of the activity is contained in the surface layer of the soil. No fissile material was found. Such disposals should be examined and can be classified as very low level waste (VLLW) or low level waste (LLW) disposal sites according to the classification proposed to be introduced in Ukraine, which will make it possible to exclude their reburial.

2. The estimate of the content of radioactive materials in the ChNPP Stage III PZRO, according to the results of experimental studies, is $3.89 \cdot {}^{10}$Bq ^{90}Sr. In some containers, fuel materials were found containing long-lived radionuclides of uranium, plutonium, americium in concentrations corresponding to the SNF of the 4th power unit. Such waste should be classified as high-level waste (HLW).

3. The preliminary studies of the content of fissile materials in the Pidlisnyi PZRO confirmed the presence of post-accident SNF in the facility. Such waste (HLW) is located directly on the surface of the preservative layer of concrete in module B1 (Б-1). The content of uranium in the selected sample is 3.9%, which is comparable to the LFCM of the shelter and, in terms of the specific activity of radionuclides, classifies this material as HLW containing fragments of nuclear fuel.

4. The set of methodological recommendations, developed in the course of the work, for conducting a survey of radioactive waste disposal facilities in the ChEZ allows obtaining the necessary information (data) regarding the detection of nuclear fuel fragments and fissile materials in them and can be used in the future.

On February 24, 2022 Russian armed forces took control of all Chornobyl nuclear power plant facilities and the Chornobyl exclusion zone.

On March 31 2022, the occupiers left the Chornobyl nuclear power plant.

On August 21 2022, the Chornobyl NPP transferred the first batch of radioactive waste for disposal after the de-occupation of the industrial site.

8. Conclusions

April 26, 1986 at 1 hour 23 minutes. At the 4th power unit of the Chornobyl nuclear power plant in northern Ukraine, an accident (explosion) occurred with the destruction of the core of a high-power reactor of the RBMK-1000 type with the release of a huge amount of radioactive substances. The radioactive fission products released from the destroyed reactor zone into the atmosphere were carried by air currents over hundreds and thousands of kilometers, leading to radioactive contamination of the territories, having a negative impact on the environment and the health of the population living there.

The accident at the Chornobyl nuclear power plant in terms of the totality of its consequences is the largest man-made disaster in the history of mankind. It affected the fate of millions of people living in vast territories not only of the former Soviet Union, but also of Europe. The total release of radioactive substances into the atmosphere was about $1.5 \cdot 10^{19}$ Bq, as a result of which the total area of radioactively contaminated territories reached 200 thousand km^2.

The emergence of large-scale problems of overcoming the consequences of the accident at the Chornobyl nuclear power plant required the solution of many extremely complex problems affecting almost all spheres of public life, many aspects of science, technology, morality and law.

There was no experience in eliminating this type of beyond design basis accidents, this scale and nature of radioactive contamination. Therefore, much had to be done in conditions of complete uncertainty, relying on one's own experience and common sense. Many mistakes and miscalculations were made, which were covered in detail in many critical publications.

It was the Chornobyl accident that served as a powerful impetus for the development of work on radioactive waste management throughout the world and the development of a number of technologies used in the management of emergency radioactive waste.

The lessons learned during the liquidation of the Chornobyl accident served as important incentives for improving technologies for handling spent nuclear fuel, in particular damaged nuclear fuel, and for developing and improving engineering solutions for managing radioactive waste.

It is very important to take into account and use the experience gained at the Chornobyl Nuclear Power Plant and in the Chornobyl zone in recent years in handling post-accident high-level radioactive waste containing fragments of in-reactor structures and nuclear fuel fragments.

Radioactive waste management is one of the main aspects of the task of eliminating the consequences of an accident. Unfortunately, accidents in the field of nuclear energy are no exception to technological progress. That is why the experience gained in eliminating such accidents needs to be carefully studied and the necessary lessons learned.

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