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THE SHELTER OBJECT IN CONDITIONS OF THE NEW SAFE CONFINEMENT

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In the monograph, based on the results of many years of scientific researches on the occasion of the 35th anniversary of the Chornobyl disaster, the New Safe Confinement (NSC), enclosing perimeter, technological and auxiliary buildings and communications, main crane system, life support, safety and control systems are described. The issues of nuclear and radiation safety in the NSC conditions are considered, the dynamics of neutron activity and fuel-containing materials temperature in the process of humidity and temperature changes, which occurred after the Arch covered the Shelter object, are given. The directions of improvement of efficiency of nuclear safety maintenance are shown. The change of gamma radiation fields after the NSC installation in the design position, activity of radioactive aerosols and water accumulations in the premises of the object was estimated. The impact of the Shelter object in the conditions of Confinement on the environment is analyzed, the programs of scientific and technical support of the activity on the object transformation into an ecologically safe system are considered. Further works on dismantling of unstable structures of the Shelter object, reconstruction of the building parts extending beyond the enclosing perimeter, as well as potential scenarios of the Shelter object transformation are described.

The book is intended for specialists of nuclear power plants, scientific and engineering employees of the services of nuclear safety and radiation protection, emergency response as well as higher education students. It can be useful for wide range of readers who want to acquire and systemize their knowledge on considered issues.

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LIST OF ABBREVIATIONS

AGFD	— access gate of fire departments
AMAD	— activity median aerodynamic diameter
ARMS	— automated radiation monitoring system
BSCS	— building structures control system
CCBMC	— central control board of monitoring and control
CF	— core fragment
CP	— cooling pond
CH	— central hall
DR	— dose rate
DS	— deaerator stack
DSS	— dust suppression system
EP	— enclosing perimeter
ER	— exposure rate
FA	— fuel assembly
FE	— fuel element
FCHP	— fuel and construction hot particles
FCM	— fuel containing materials
FVU	— filter ventilation unit
GSFS	— gadolinium solution feed system
HLW	— high level waste
HP	— hot particles
HVAC	— heating, ventilating and air conditioning
IACS	— integrated automated control system
IAE	— Institute of Atomic Energy
IAEA	— International Atomic Energy Agency
ICS	— integrated control system
ICRP	— International Commission on Radiological Protection
ILW	— intermediate level waste
IRS	— ionizing radiation source
ISP	— Institute for Safety Problems
ISTC	— Interdisciplinary Scientific and Technical Centre
LFCM	— lava-like fuel containing materials
LLW	— low level waste
LRW	— liquid radioactive waste

MCS	— main cranes system
MDSS	— modernized dust suppression system
MIP	— mobile instrumental platform
NAM	— neutron absorbing materials
NAS	— National Academy of Sciences
NFD	— neutron flux density
NPP	— nuclear power plant
NSC	— New Safe Confinement
NSMS	— nuclear safety monitoring system
NVS	— new ventilation stack
PED	— potential exposure dose
PPE	— personal protective equipment
PS	— protruding sections
PSP	— pressure suppression pool
RA	— radioactive aerosols
RAW	— radioactive waste
RCU	— remotely controlled unit
RMS	— radiation monitoring system
RW	— radioactive water
SCP	— south cooling pond
SDC	— steam distribution corridor
SFM	— special fissile materials
SIP	— Shelter Implementation Plan
SMS	— seismic monitoring system
SNRIU	— State Nuclear Regulatory Inspectorate of Ukraine
SRV	— steam relief valve
SRW	— solid radioactive waste
SSCR	— self-sustaining chain reaction
SSE	— State Specialized Enterprise
SSLRW	— storage of solid and liquid radioactive waste
VLLW	— very low level waste
WA	— work area

PREFACE

The Shelter object (a preserved destroyed fourth power unit of the Chornobyl NPP) was accepted for maintenance on November 30, 1986 [1]. Built in extremely severe radiation conditions, this complex of building protection structures as well as control, management and safety systems after commissioning required constant supervision, control and application of corrective measures in case of deviation of safety parameters from the established standards. Direct human participation was impossible under the installation of the Shelter object, and the used remote construction methods resulted in several shortcomings. In particular, a large amount of concrete has got into the rooms, which significantly complicated the passage to them and significantly increased the amount of radioactive waste (RAW), a redistribution of loads on building structures took place, and there was an uncertainty in the strength of some supports, where the old structures affected by the accident were used [2].

During the elimination of the consequences of the Chornobyl accident, one of the most important and the hardest tasks was the transformation of nuclear fuel remaining in the Shelter object to a controlled state. It was necessary to determine the location of the main accumulations of fuel containing materials (FCM) and their physical and chemical properties, to assess the degree of nuclear and radiation safety, to create control systems and prepare countermeasures in case of possible accidents, and in the future — to remove nuclear fuel from the Shelter object and to isolate it in waste disposal [3]. The implementation of this task began in the first days after the accident and continued throughout the last 35 years. Despite the success of many of its components, a comprehensive solution to the problem has not been achieved yet. FCM remaining inside the Shelter object are not fully controlled [4]. This forces excessive safety measures based on deliberately conservative assumptions.

The Shelter object contains a large amount of finely dispersed fuel, which was formed during and after the accident due to different physical and chemical effects in the FCM. Fuel dust is dangerous because of internal human exposure formation and the spread of radioactive substances beyond the location. In the post-accident period, due to the destruction of lava-like FCM a secondary fuel dust is formed. The rate of destruction and, consequently, the rate of dust formation increase over time. In lava-like FCM, there are visible changes

in the strength properties, which are manifested in the cracking of FCM, the destruction of large fragments, and increasing dust formation rate [5]. Besides fuel dust, there is also a significant amount of dust in the object, which is formed due to the degradation of building structures and the destruction of dry dust suppression coatings under the influence of aging and climatic factors. Because these structures and dust suppression coatings are contaminated with radionuclides, such dust is often radioactive.

During the active stage of the accident, most of the graphite layer burned out and dispersed with the radioactive release, and a smaller part was released into the reactor hall, on the power unit site territory, and its roof. The part of the graphite was dispersed due to the explosion and distributed in the dust form in the rooms of the reactor compartment.

One of the main hazards of the Shelter object is the presence of water, which alters reproduction systems and, when interacting with FCM, dissolves and carries radionuclides that may enter the environment. Precipitation penetrates through the cracks in the roof and walls of the Shelter object. The size of the cracks is small, but all the water flowing from the sloping sections of the light roof on the horizontal ledges, almost free move into the building space. Precipitation, technogenic solutions and water condensate moving from the upper marks to the lower ones leach the most soluble components of concrete. Heavy metals pass into the solution due to corrosion of metal structures. As a result of these processes, the radionuclide composition of water is formed, which, according to the content of radionuclides, belongs to liquid radioactive waste (LRW) [6]. Part of the activity is concentrated in silty sediments and is hazardous as an additional source of radioactive aerosols when it dries in the summer-autumn period. Another source of water in the Shelter object is the water of condensation and technogenic solutions.

The water accumulated in several rooms of the Shelter object contains soluble compounds of uranium, plutonium, and americium radionuclides. Their formation is explained by the destruction of various modifications of the fuel under the action of a set of factors, the main of which is the water that enters the Shelter object. The concentration of radionuclides in this water is most affected by air temperature and precipitation intensity. During the period of positive temperatures, heavy precipitation slightly reduces the concentration of radionuclides in aquatic environments. In cold and dry periods, on the contrary, the amount of water at the lower marks decreases, the time of contact of water with structures and accumulations of FCM increases, and, as a result, the concentration of radionuclides and salts increases.

In such circumstances, the long-term safe operation of the Shelter object was not possible. Therefore, as early as 1991, the main approaches to the transformation of the object into a long-term ecologically safe system were formed. In 1992, the Government of Ukraine decided to hold an international competition for projects and technical solutions to transform the Shelter object into an ecologically safe system. In 1993, following the decision of

the jury of the international competition, a technical requirement was issued to develop a feasibility study for the transformation of the Shelter object. At the same time, a list of priority measures to improve the safe operation of the object was being developed.

The transformation of the Shelter object into an ecologically safe system should have consisted of several stages. The first stage is the stabilization of the building structures of the object, i. e. the implementation of a set of measures aimed at long-term maintenance of its safety. The second stage is the construction of a new localizing shell or a New Safe Confinement (NSC), which would meet the established norms and rules of safety during the processing and removal of radioactive materials from the Shelter object. The third one is removing and the disposal of fuel containing and radioactive materials, and the ultimate goal is the decommissioning of the fourth unit of the Chornobyl NPP.

To implement the first two stages, in 1997, American, European and Ukrainian experts developed an action plan for the Shelter object — Shelter Implementation Plan (SIP), which identified measures and scope of work to transform the object into an ecologically safe system [7].

The main conclusion of the international experts was to significantly reduce the danger to the environment due to the construction of a new protective structure over the Shelter object — the NSC. The Law of Ukraine “On General Principles of Further Operation and Decommissioning of the Chornobyl NPP and Transformation of the Destroyed Fourth Power Unit of this NPP into an Environmentally Safe System” formulates the basic requirements for the NSC. It is a multifunctional complex for transforming the Shelter object into an ecologically safe system. Thus, the NSC should create safe conditions for the environment and make it possible to dismantle the structures of the Shelter object and remove the FCM from the fourth power unit.

At the first stage of the project, a set of stabilization measures was implemented to increase the durability, reliability and efficiency of existing and newly installed structures and systems (construction, control, dust suppression, emergency ones) for maintaining or improving the safety of the facility. The main result of the measures taken is the installation of the NSC in the design position at the Chornobyl NPP at the end of 2016. With the NSC, the level of radiation safety increases due to the limitation of radiation exposure to personnel, the population and the environment for the entire period of its operation; and the probability of accidental collapse after dismantling of unstable structures under the NSC decreases. The implementation of the strategy of transformation of the Shelter object into an ecologically safe system is ensured due to the durability of structures, and the possibility of dismantling unstable structures and removal of FCM.

Installation of the NSC is only the initial stage in the transformation of the Shelter object into an ecologically safe system. There is still a lot of research to be done, organizational and technical measures need to be taken to achieve the ultimate goal: removing nuclear materials from the facility, packing them in containers, and placing the containers in a specially

designed repository [8]. Here are the main scientific problems associated with the Shelter object, that require solutions and constant attention:

- monitoring of the level of nuclear and radiation safety;
- control and forecast of the state of nuclear materials;
- nuclear materials and RAW management;
- development of technologies for dismantling building structures and removing nuclear materials.

Each of these scientific problems entails a huge amount of research, experimentation, analytical modeling, and calculations.

Scientific and technical support of works at the Shelter object began in 1986 (simultaneously with its design and construction) by a group of researchers from the Kurchatov Institute of Atomic Energy (IAE). They, with the assistance of other departmental and academic research institutions, carried out pre-design and ongoing research of the destroyed unit. In 1987, a Complex Expedition of the Kurchatov Institute was created on the basis of this group. In 1992, after Ukraine became independent, the Interdisciplinary Scientific and Technical Centre (ISTC) “Shelter” of the National Academy of Sciences (NAS) of Ukraine became the successor of the Complex Expedition, and in 2004 it was transformed into the Institute for Safety Problems of Nuclear Power Plants (ISP NPP) [9]. The staff of the Institute provided scientific and technical support on all major radiation-hazardous projects related to the stabilization of building structures, the creation of safety systems, the transformation into an ecologically safe system. The researchers studied the radionuclide and chemical composition of FCM and predicted their behavior [10]. A huge amount of work has been done to study the ways of water distribution inside the Shelter object, the dynamics of its radionuclide contamination in the facility and on the industrial site. The object was constantly monitored, hazard factors were identified and studied, nuclear and radiation safety analysis was performed, and scientifically substantiated recommendations were issued to increase its level.

After the installation of the NSC, the conditions of temperature and humidity of the Shelter object have been changed significantly. How exactly? This question is answered by this monograph prepared on the basis of long-term research conducted by scientists of the ISP NPP of the NAS of Ukraine in cooperation with the Research Institute of Building Structures, Kyiv Research and Design Institute “Energoprojekt”, specialists of the State Specialized Enterprise (SSE) “Chornobyl NPP” and the international consortium Novarka with the participation of Ukrainian and foreign companies.

The monograph consists of six chapters. The first one describes the NSC, the enclosing perimeter, technological and auxiliary buildings and communications, the system of main cranes, systems of life support, safety and control.

The second and third chapters consider the issues of nuclear and radiation safety in the conditions of the NSC, the dynamics of the neutron activity and the temperature of FCM

in the process of temperature and humidity changes that occurred after the Shelter object was covered with an arch. The directions of increasing the maintenance efficiency of nuclear safety are shown. The change of gamma radiation fields was estimated after the NSC was set to the design position, the activity of radioactive aerosols and water accumulations in the premises of the facility was assessed.

The impact of the Shelter object on the environment under the confinement is discussed in chapter four.

In the fifth chapter, the programs of scientific and technical support of activities to transform the object into an ecologically safe system are analyzed.

The sixth chapter is devoted to the description of further works on dismantling of unstable constructions of the Shelter object, reconstruction of the building sections protruding outside the enclosing perimeter, and also the analysis of potential scenarios of transformation of the Shelter object.

The publication is recommended for specialists of nuclear power plants, scientific and engineering workers of the services for nuclear safety, radiation protection, and emergency response, as well as students of higher educational institutions. It can be useful for a wide range of readers who want to obtain and systematize their knowledge of the issues considered.

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Chapter 1. INSTALLATION OF THE NEW SAFE CONFINEMENT

In a set of tasks that arose in connection with the Chornobyl accident, among many others, the most important task was to create a protective shell over the destroyed nuclear reactor. The work for creating the Shelter object was entrusted to the Ministry of Medium Machine-Building Industry of the Soviet Union, which included the Department of Construction no. 605, consisted of several construction and erection divisions, concrete mixing plants, departments of mechanization, motor transport, power supply, etc. The Shelter object was designed in three months, from May 20 to August 20, 1986. The project documentation was handed over to the builders upon its readiness and, if necessary, was clarified or supplemented by the author's supervision team. From the moment of the decision on construction of the object to the end of construction only six months have passed. The Shelter object was approved for maintenance by the State Commission on November 30, 1986.

Construction of the Shelter object on the destroyed structures of the fourth power unit in extremely severe radiation conditions did not allow compliance with the rules and regulations for the design of not only nuclear installations or facilities for radioactive waste management but also compliance with the rules and design standards for ordinary industrial facilities. Building structures do not meet the requirements for structural integrity and reliability and have an indefinite working life. Given the above, constant monitoring of the condition of such structures and intervention in the event of a threat of dangerous deviation from their stable condition are required.

Therefore, the condition of the Shelter object did not allow expecting its long-term safe operation. So, in 1991, the main approaches to transforming the facility into a long-term, ecologically safe system were formulated. In 1992, the Government of Ukraine decided to hold the International Competition of projects and technical solutions for the transformation of the Shelter object into an ecologically safe system. In 1993, following the decision of the jury of the International Competition, a technical task was developed and issued for the development of a feasibility study on the transformation of the Shelter object. At the same time, a list of priority measures to improve the safe operation of the facility has been developed.

Thus, since 1993, Ukraine has been taking measures on the transformation of the Shelter object into an ecologically safe system together with the international community. In 1997, Ukrainian, American and European experts have developed an action plan for the Shelter

object named SIP, which defined measures and scope of work to transform the facility into an ecologically safe system, and construction of a new protective shell, which should guarantee the safety of the object for at least 100 years. The Chornobyl Shelter Fund was established to finance SIP. At the end of 2016, the NSC was installed into the design position.

1.1 The purpose of creation, the main functions and realization stages of the design of the New Safe Confinement

The Law of Ukraine “On General Principles of Further Operation and Decommissioning of the Chornobyl NPP and Transformation of the Destroyed Fourth Power Unit of this NPP to an Environmentally Safe System” [11] determined that “confinement is a protective structure that includes a set of technological equipment for removing materials that contain nuclear fuel from the destroyed fourth unit of the Chornobyl NPP, RAW management and other systems. It is designed to carry out activities to transform this unit into an ecologically safe system and ensure the safety of personnel, population, and the environment”.

The NSC makes it possible: 1) to protect personnel, the population and the environment from the impact of nuclear and radiation hazard sources associated with the presence of the Shelter object; 2) to create conditions for practical activities to transform the Shelter object into an ecologically safe system, in particular for the removal of nuclear fuel residues and FCM, dismantling and strengthening of unstable structures, and RAW management.

One of the main functions of the NSC is *to prevent the spread of RAW outside the NSC* under conditions of normal operation, violations of normal operation, emergencies and accidents. This function is provided by:

- the integrity of the protective structures of the NSC for a long period of operation (not less than 100 years);

- preventing the threat of collapse of unstable structures due to their dismantling or strengthening for a period determined by the conditions of the NSC safe operation;

- limitation of precipitation entry inside the building;

- protection of the hydrogeological environment from RAW contamination in the NSC;

- limiting the spread of RAW within the NSC.

Based on the existing radiation situation outside the Shelter object and taking into account the expediency of reducing the radioactive impact only in the personnel working areas, additional requirements for the performance of shielding functions by NSC building structures have not been formulated. Shielding is provided only in the service areas of structures and systems, as well as in the areas of other radiation-hazardous work.

The function of technological support is realized through the placement and operation of systems and elements, as well as enabling the normal operation of the NSC, the implementation of measures for control and maintenance of the Shelter object; dismantling/strengthening of

unstable structures of the Shelter object; RAW management; further transferring of FCM to a controlled state.

The function of physical protection is protecting the nuclear and radioactive materials contained in the Shelter object to ensure the functioning of the International Atomic Energy Agency (IAEA) safeguards system.

These functions indicate that the NSC is a multifunctional facility, the operation of which requires consideration of the many relationships between the newly created systems and elements and the existing components of the Shelter object.

According to the NSC project implementation strategy [12], three stages were envisaged.

The first stage is the preparatory work: dismantling the berm of the pioneer wall; preparation of the NSC construction site; construction of a new ventilation stack (NVS); dismantling of the existing ventilation stack VT-2.

The pioneer wall berm was built in 1986 and was used as a site for the Demag erecting crane at the final stage of construction of the Shelter object. In 1987—1988, it was completed in connection with the installation of a new coating over the turbine island. Later, the berm surfaces were additionally concreted to organize the drainage of water from the walls of the turbine island. The need to dismantle the berm of the pioneer wall was due to the location of the NSC foundations in this area.

According to the construction of the berm, for its dismantling there were used various technologies and technical means of destruction of concrete and reinforced concrete monolithic structures, dismantling of prefabricated structures, as well as disassembly of backfill materials of complex structure (gravel, sand, soil, concrete and metal fragments). Works were performed in radiation-hazardous conditions, directly near the Shelter object (Fig. 1.1), and ended in April 2008.

Preparation of the NSC construction site included the performance of a large amount of work on cleaning and planning of the territory, arrangement of ditches for the construction of foundations, as well as mounting the site for large-scale erecting of arch structures (Fig. 1.2). Initially, the existing buildings, structures and roads within the construction site were dismantled, and the areas were cleared of various objects (fences, landfills of structures and materials, vegetation, etc.) and performed vertical planning.

Further earthworks on the arrangement of ditches under the foundations were held. Since the anthropogenic soils were radioactively contaminated significantly in the designated areas [13], a technological scheme of safe soil management was introduced. This scheme covered postoperative radiation control and sorting of soils by categories depending on the specific activity. In technogenic soils, various large-sized elements were found, in particular mechanisms (two cranes, the tractor, earth-moving machine), buried during the elimination of the accident in 1986 (Fig. 1.3). During the preparatory work, approximately 55,000 m³ of technological materials were removed, and about 90 thousand m² of the territory of the NSC construction site was concreted.



Fig. 1.1 — Disassembly of the pioneer wall berm with a hydrohammer



Fig. 1.2 — Preparation of the construction site for the New Safe Confinement

The ventilation stack VT-2 of the Chornobyl NPP, located on the unit B roof, prevented from the installation of the eastern end of the NSC. So it was necessary to dismantle it and construct a NVS with commissioning before dismantling VT-2. After the construction of the NVS was completed in 2012, there were two ventilation stacks on the roof of the third power unit at the same time: the NVS and VT-2 (Fig. 1.4). VT-2 weighing about 330 t was dismantled by the end of 2013.

Due to the large VT-2 dimensions and mass, and difficult radiation conditions in the work areas at service sites (dose rate reached 3 mSv/h), dismantling of this structure turned out to be an extremely complex technological operation consisted of seven separate blocks (the number of blocks was determined by the characteristics of a unique cargo lifting crane, Fig. 1.5), with the involvement of highly qualified personnel and the implementation of effective measures for radiation protection. Dismantling of a VT-2 unit is shown in Fig. 1.6.

The removed blocks were placed on the storage site near the third power unit (Fig. 1.7). Additional radiation examination of dismantled blocks and their fragmentation was performed here. After that, the fragments of the blocks were transported by special vehicles to the turbine island of the third power unit for temporary storage.



Fig. 1.3 — The mechanism removed from the ditch



Fig. 1.4 — VT-2 (in the foreground) and new ventilation stack

After dismantling VT-2, the hole in the coating was closed, providing thermal insulation and protection against precipitation.

The second stage involved the design and construction of a protective structure (NSC) with technological life support systems and the necessary infrastructure, as well as: a) preparation of a working project for the dismantling of unstable structures of the Shelter object; b) purchase, installation and commissioning of technological equipment and systems for dismantling of unstable structures [2]. It should be noted that the design of the dismantling infrastructure was supposed to start in parallel with the design of the NSC, but, unfortunately, such a design scheme was not implemented.

The third stage of the project implementation after the commissioning of the NSC is the early dismantling of unstable structures of the Shelter object in the volumes determined at the stage of dismantling working design.

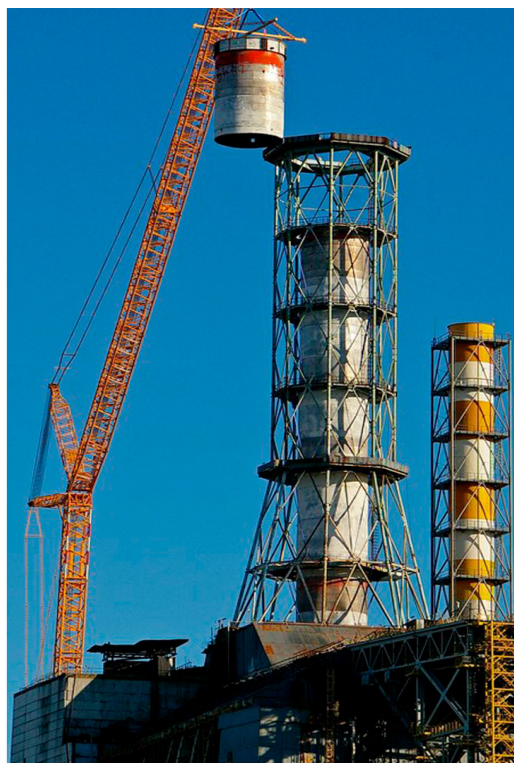
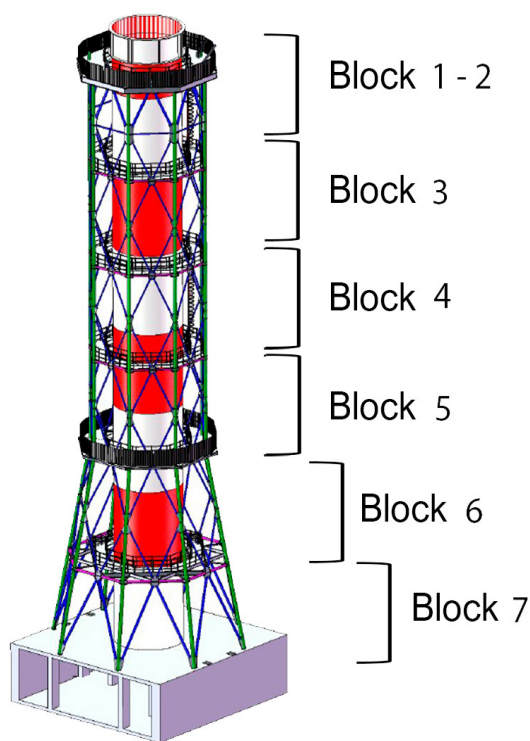


Fig. 1.5 — Division of the VT-2 into dismantling blocks



Fig. 1.6 — Dismantling of the intermediate part of the stack trunk with a support platform



Fig. 1.7 — Dismantled blocks on the storage site

1.2 Basic constructive and technological decisions

The NSC building structure has three main components [14]: a steel arch, which was erected at a distance from the Shelter object with its subsequent placing into the design position; existing and newly erected building structures of the Chornobyl NPP, which perform the functions of the NSC enclosure perimeter; technological building and other auxiliary buildings and structures.

The location and list of the main structures and buildings of the NSC are shown in Fig. 1.8. The general view of the NSC after construction is shown in Fig. 1.9.

1.2.1 Arch

The arch is divided into two parts — western and eastern ones, its height is 108.935 m, the length is 162.000 m, the width is 257.115 m (Fig. 1.10). The main load-bearing structure consists of 16 arched trusses, located in increments of 12.5 m. In the design position, the arched trusses rest on the foundations through special supports.

Beams of an external covering lean against the top boom of arched trusses, and elements of an internal covering fasten to the lower boom. A sealed annular space is formed between the outer and inner cladding, which protects the arch structures from external climatic influences and condensate that may form inside the NSC.

Lattice beams are attached to the arched trusses on the upper marks, creating a crane platform. Crane girders, in turn, are attached to the crane platform (Fig. 1.11) and assembled on an erecting site during the construction of an arch (Fig. 1.12).

The structural scheme of the western and eastern walls of the arch consists of a system of vertical lattice columns and horizontal lattice trusses, as well as a system of connections. Before placing the arch, the western wall was completely suspended from the arch, and in the design position it rests with one lattice column, located in the central part of the wall, on the reinforced concrete column of the technological building. The east wall is suspended from the arch and does not transmit any effort to the structure.

The total mass of the fully erected arch together with technological systems reaches more than 36 thousand tonnes.

The technology of erecting the eastern and western parts of the arch (Fig. 1.13) consisted of a serial connection of the segments mounted from factory-made elements on the erecting site, and its three liftings. The arch was erected on a mounting platform at a distance from the Shelter object and then placed into the design position [5]. To do this, tower, crawler and pneumatic wheel cranes of various capacities were used, as well as special auxiliary installation equipment (temporary supports; rotating beams; movable stands; locking devices; lifting beams and towers; temporary extensions; connecting joints; jacks, carts, winches, etc.).

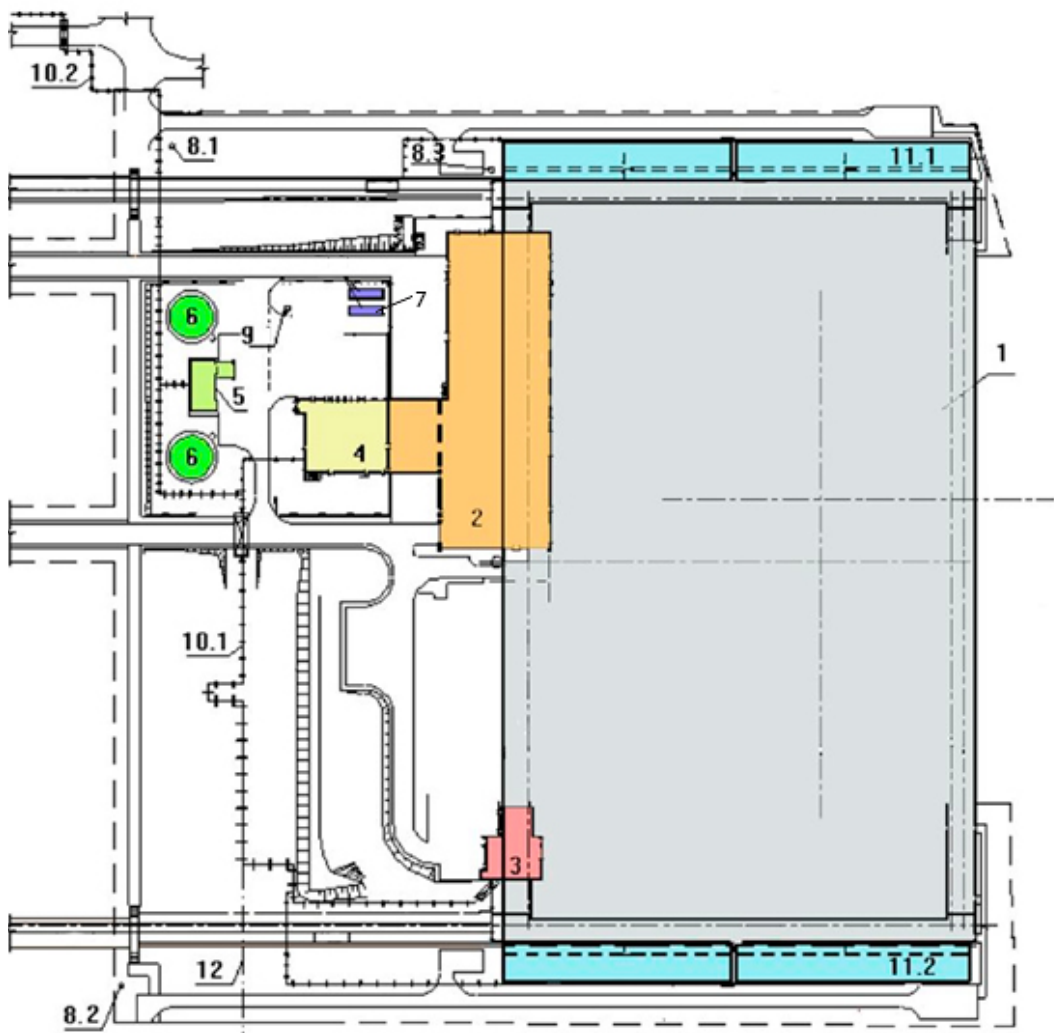


Fig. 1.8 — Layout of buildings and structures of the NSC:

1 — NSC protective structure (steel arch + NSC enclosing perimeter); 2 — technological building;
 3 — access gate for fire departments; 4 — the building of electrical devices; 5 — pumping station
 for firefighting; 6 — fire extinguishing tanks with a capacity of 1,500 m³ each one (2 pcs.); 7 — site of diesel
 generators of reserve power supply; 8.1 — station for stormwater pumping no. 1; 8.2 — station for stormwater
 pumping no. 4; 8.3 — station for stormwater pumping that does not require treatment, no. 5;
 9 — point for refueling the forklift; 10.1 — overpass of technological pipelines important for safety;
 10.2 — overpass of technological pipelines not important for safety; 11.1 — northern basin of stormwater
 collection from the arch; 11.2 — southern basin of stormwater collection from the arch; 12 — cable route



Fig. 1.9 — General view of the NSC after completion of construction

The first batch of metal structures of the arch was delivered to the erecting site in February 2012, and on November 24 of the same year, the first lifting of the eastern part of the arch weighing 5,300 t took place. After the second and third liftings (Fig. 1.14), the eastern part weighing 12,600 t was moved 112 m in the west-east direction to the waiting area.

The technology of construction of the western part of the arch coincided with the technology of construction of the eastern one as a whole. The differences were only in the installation of the eastern and western walls, the designs of which differ significantly. After the completion of the main works on the construction of the western part of the arch, the eastern part was moved to the western one and connected into one unit.

In parallel with the erecting of the arch, the end walls of the arch, crane girders, main cranes system (MCS), garages, closed shielded galleries and passages inside the space under the arch, stairwell and elevator inside the west wall, the ventilation stack with stairwell and ventilation system outside the western wall, ventilation systems, power supply, lighting, etc. were installed.

The general view of the arch on the erecting site before it is placed into the design position above the Shelter object is shown in Fig. 1.15. The placing process began on

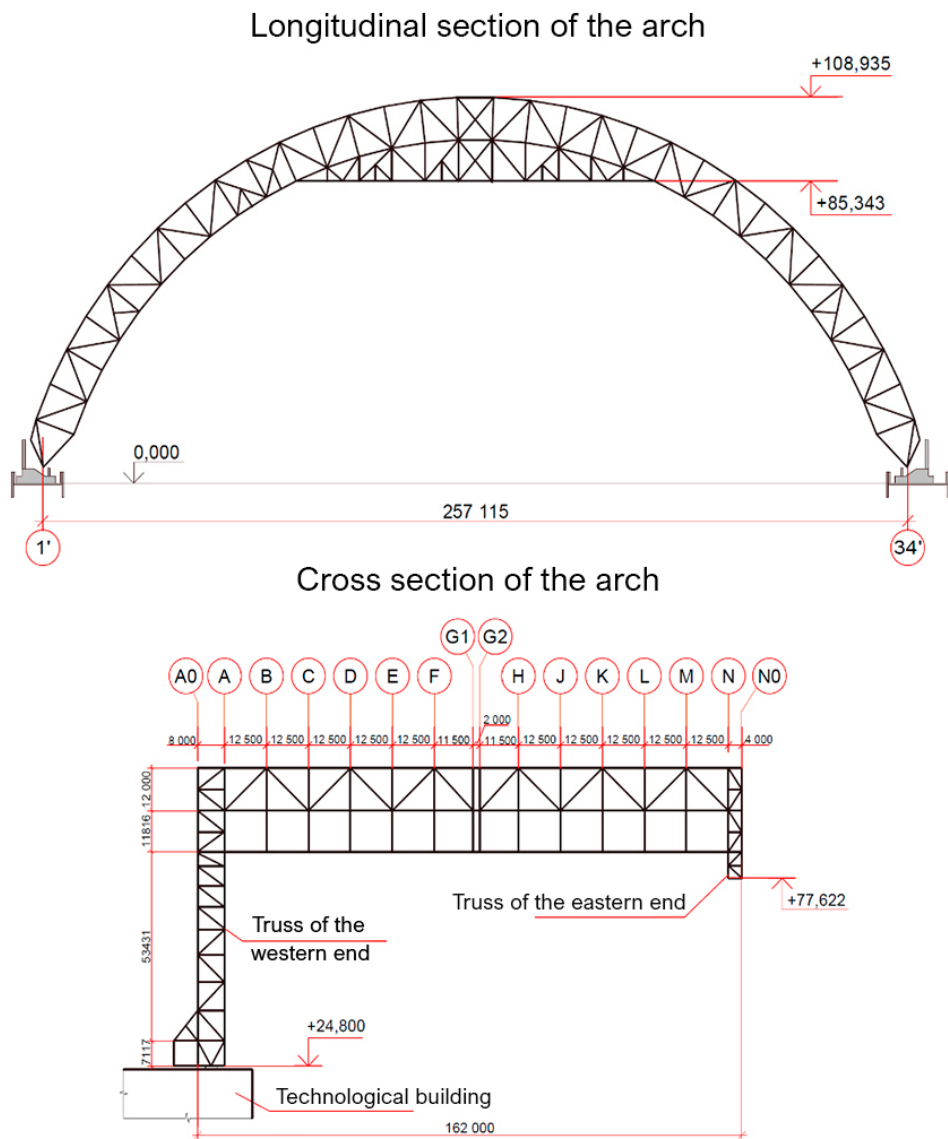


Fig. 1.10 — Constructive scheme of the arch

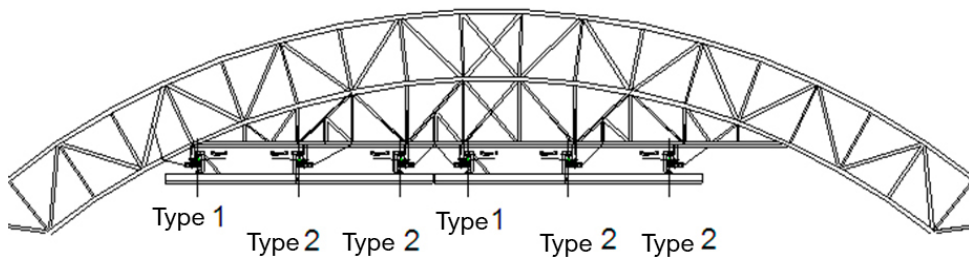


Fig. 1.11 — Layout of crane girders

November 14, 2016, and ended successfully on November 27 of the same year. A huge structure weighing 36.2 thousand tonnes with the help of a unique placing system (Fig. 1.16) was moved 327 m from the erecting site and installed on the foundations. To pass the eastern end wall of the arch over the Shelter object its design provided folding panels (Fig. 1.17). During the placing, they were raised, and before the final installation of the arch in the design position they were turned.

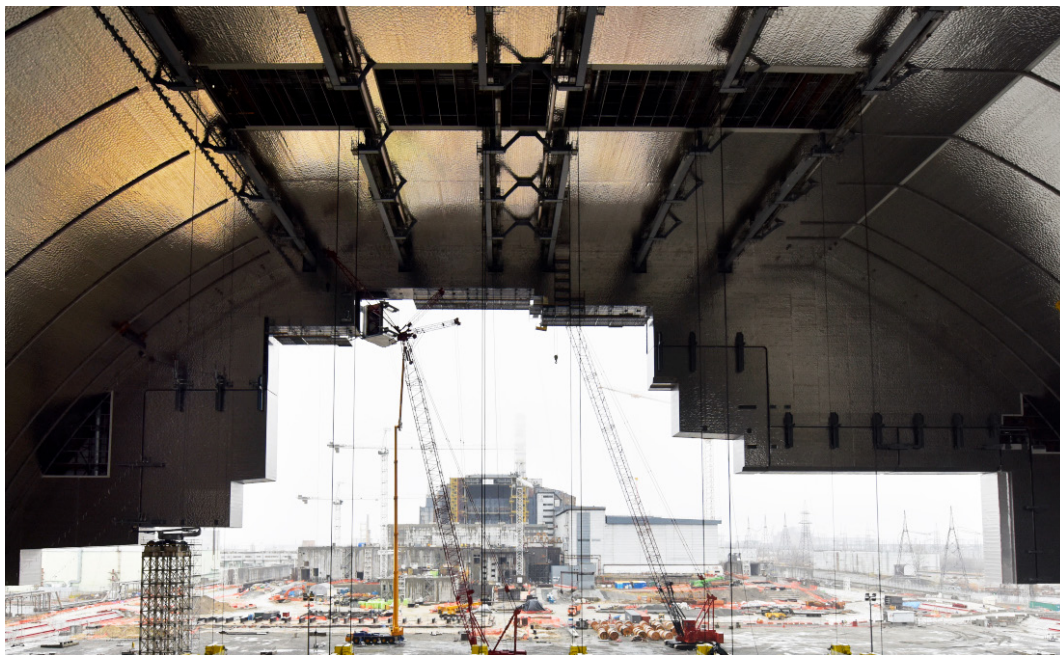


Fig. 1.12 — Crane beams installed on the arch



Fig. 1.13 — Erecting the segment of the arch



a) after the first lifting



b) after the second lifting



c) after the third lifting



d) the eastern part of the arch in the waiting area

Fig. 1.14 — The eastern part of the arch at different stages of its construction



Fig. 1.15 — Arch on the erecting site before it is placed into the design position

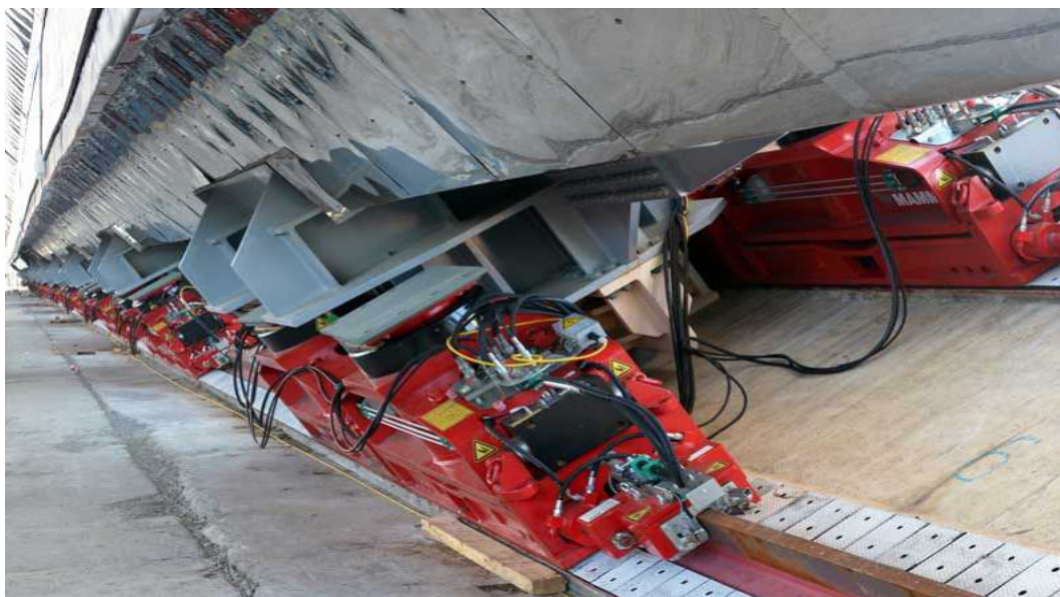


Fig. 1.16 — Arch placing system

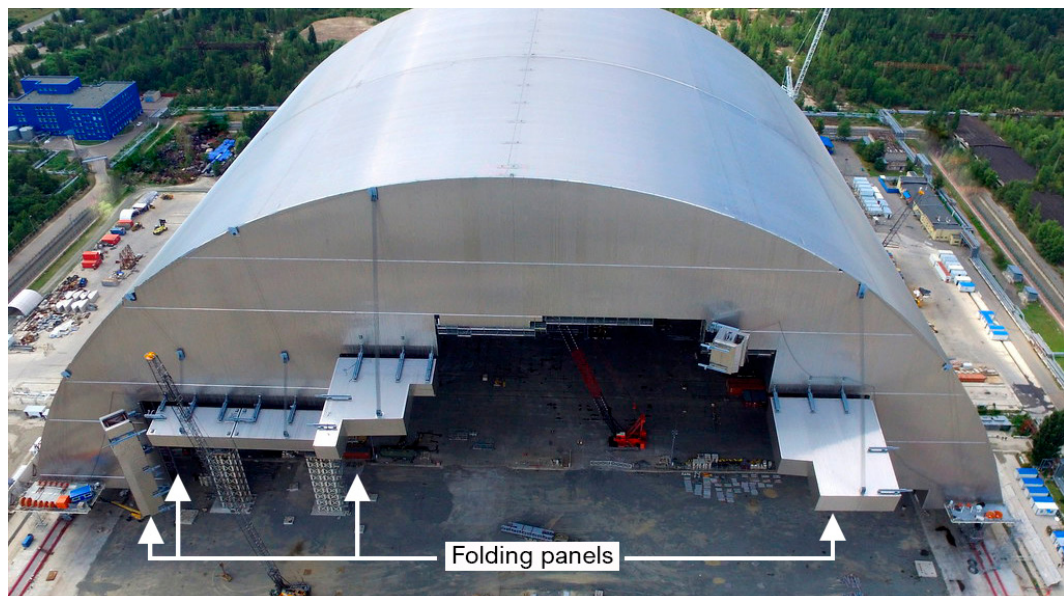


Fig. 1.17 — Folding panels on the east end wall

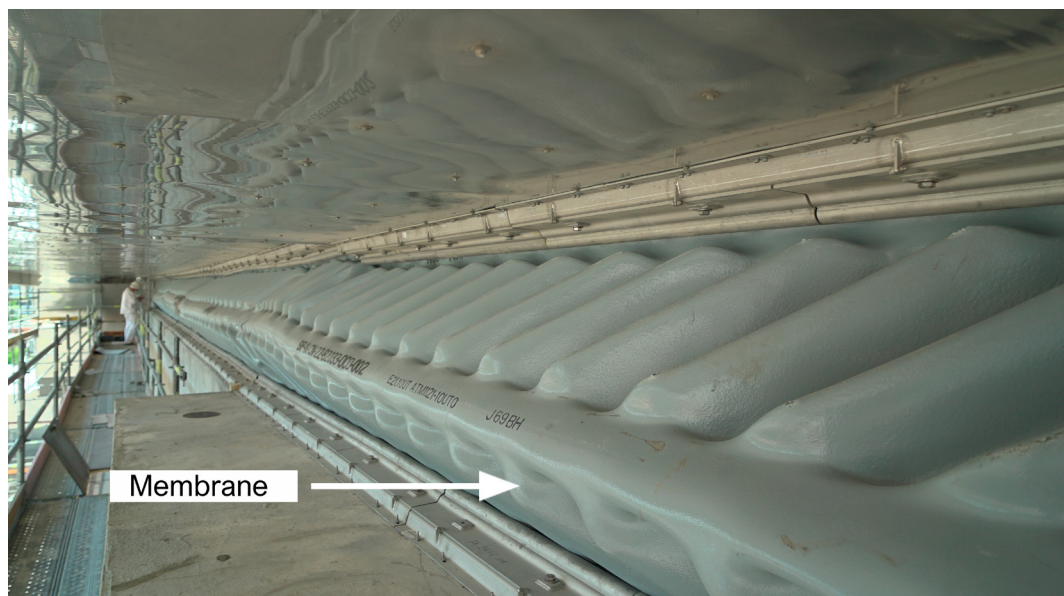


Fig. 1.18 — Sealing the inner space of the arch

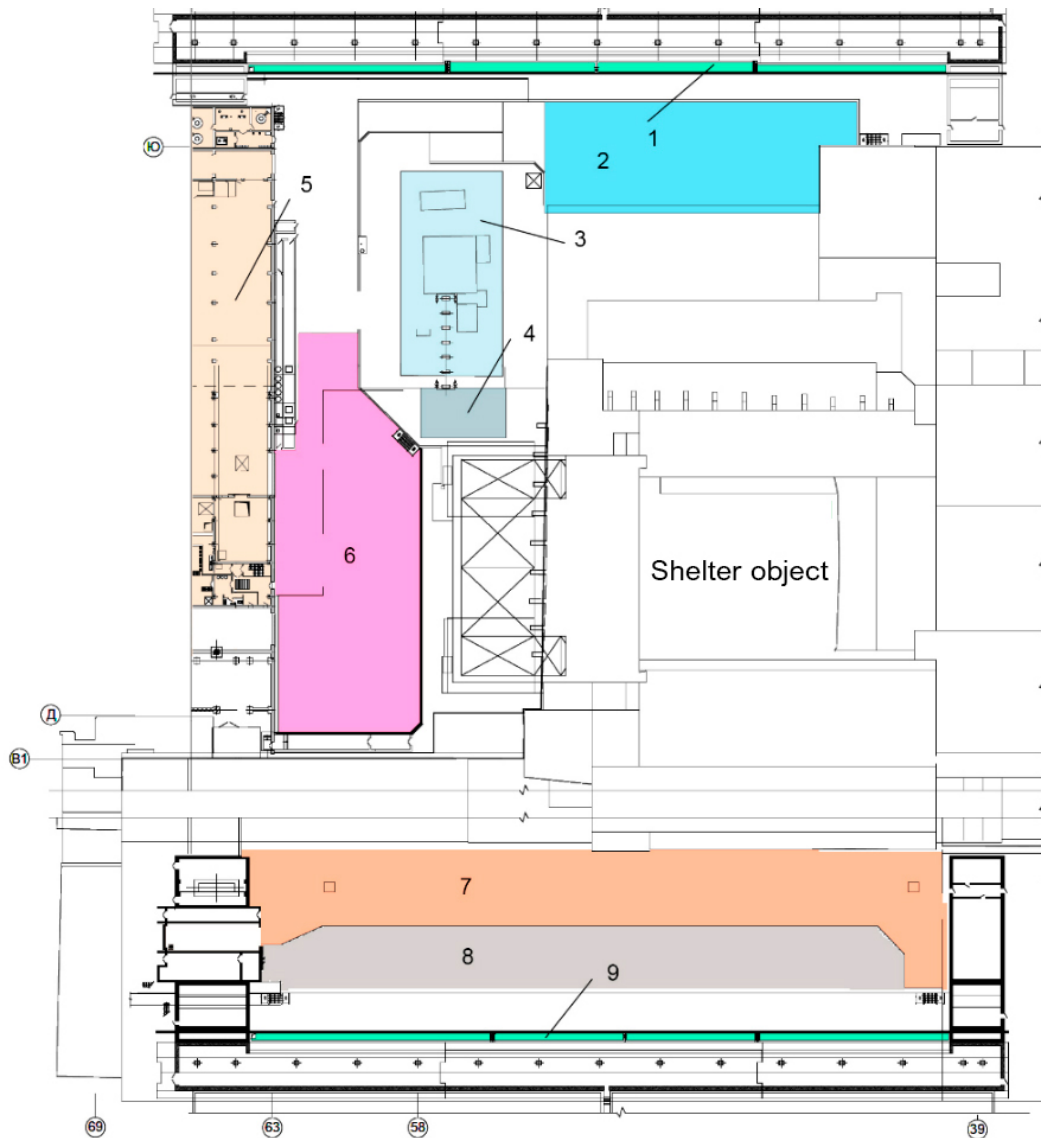


Fig. 1.19 — Location of buildings (sites) inside the arch:

- 1 — the northern basin of fire water collection; 2 — the platform on a cascading wall;
 3 — the site of the existing dust suppression system; 4 — the site of a new mobile dust suppression system;
 5 — the part of the technological building; 6 — the temporary storage area; 7 — the area for access of fire engines; 8 — the temporary storage area; 9 — the southern basin of firewater collection



Fig. 1.20 — Gallery of hinged supports

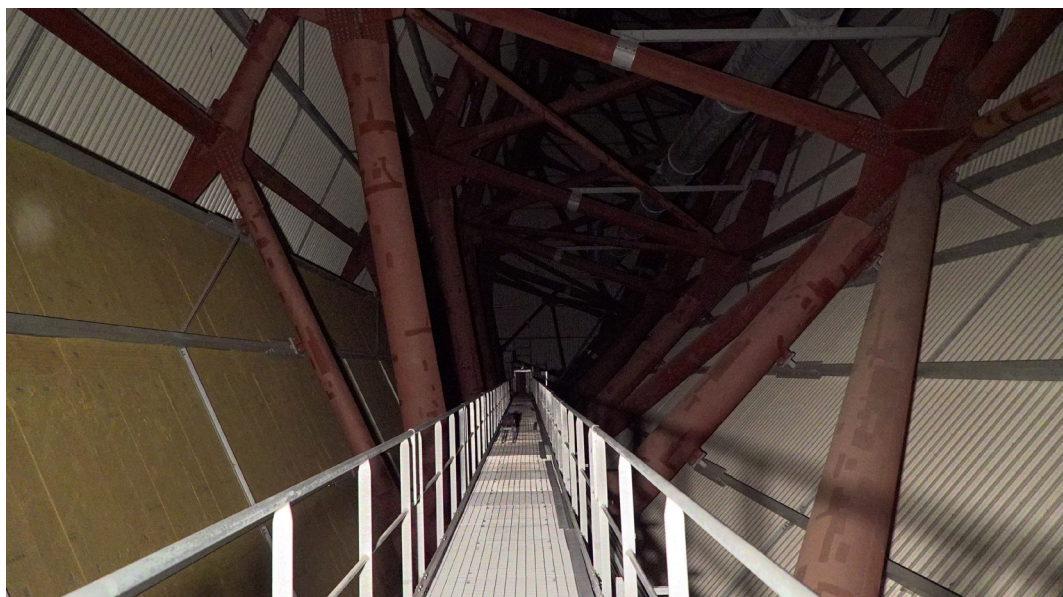


Fig. 1.21 — Gallery of the ring space



Fig. 1.22 — Structures suspended on the western wall of the arch

The lower vertical parts of the western and eastern end walls of the arch in a stationary position adjoin the structures of the outer fence of the NSC (the NSC enclosing perimeter, technological buildings, access gate of fire departments (AGFD) and reinforced concrete walls) with a gap of about 1.5 m along the entire abutment length.

The structures of the arch are connected with the structures of the outer fence of the NSC by corrugated membranes of the herringbone type (Fig. 1.18). Such membranes of a special form provide sealing of internal space of an arch and also compensate mutual movements between an arch and constructions of an outer fence of the NSC. Special tests have shown that the material of corrugated membranes can be exposed to radiation for 100 years at a dose of 300 kGy, which is three times higher than the expected dose for this period.

Inside the NSC there are buildings (sites) for the dismantling of unstable structures of the Shelter object and other current activities (Fig. 1.19).

To ensure control and maintenance of the foundations and hinged supports of the arch, a gallery of hinged supports was arranged (Fig. 1.20), and a gallery of annular space was set up for control and maintenance of load-bearing structures (Fig. 1.21).

Inside the space of the arch, the maintenance garage and the MCS storage garage are fixed on its load-bearing structures, and outside a ventilation stack, external stairs and ventilation centers are suspended on the west wall of the arch (Fig. 1.22).

The maintenance garage is designed for technical service and repair of MCS carts, a mobile tool platform and maintenance carts. Also in this garage, it is possible to carry out a replacement of tools on the mobile instrumental platform (MIP), and decontamination of freight carts of MIP.

The storage garage serves as a parking space for MCS trucks or for moving trucks from one bridge to another.

The ventilation stack is designed for controlled release into the atmosphere of the air, which is removed by exhaust ventilation systems from the main volume of the arch and the technological building. The inner diameter of the ventilation stack is 3.5 m, and the length is 91.654 m.

1.2.2 Enclosing perimeter

Enclosing perimeter (EP), as well as the arch, is an important component of the NSC. The EP is organized within the existing building structures of the Chornobyl NPP. Its main function is to prevent the spread of radioactive materials outside the NSC in the conditions of normal operation, disturbances of normal operation, emergencies and accidents. This function should be ensured by the integrity of the NSC EP structures for 100 years, taking into account all types of impacts to be considered, including extreme ones.

The NSC EP includes existing and newly constructed building structures of the Chornobyl NPP.

The eastern end within the turbine island consists of a reinforced concrete foundation and a reinforced concrete wall with buttresses (Fig. 1.23). The lower slab of the foundation is 12.0 m in width and 2.7 m in height and located in the basement of the turbine island. The upper slab is 6.0 m in width and 1.0 m in height and located at the mark of +12.000. The plates are connected by a system of pylons.

Above the +13.000 mark, a monolithic reinforced concrete wall 400 mm thick with buttresses was designed. The buttresses are located on both sides of the wall (in the same plane with the pylons) and have a variable cross-section.

The eastern end of the NSC EP within the deaerator stack (DS), units B and auxiliary systems of the reactor compartment (ASRC) includes the existing load-bearing structures of the prefabricated reinforced concrete frame and reinforced concrete floors, as well as new walls and diaphragms made of monolithic reinforced concrete 400 mm thick. Thus, the eastern end is a combination of existing structures and newly built monolithic reinforced concrete walls.

The western end within the turbine island is designed in the form of a reinforced concrete wall with buttresses, which rests on a reinforced concrete foundation (Fig. 1.24). The monolithic reinforced concrete foundation is made in the form of a slab 4.5 m high and 11.2 m wide, which rests on the existing foundation slab of the turbine island.

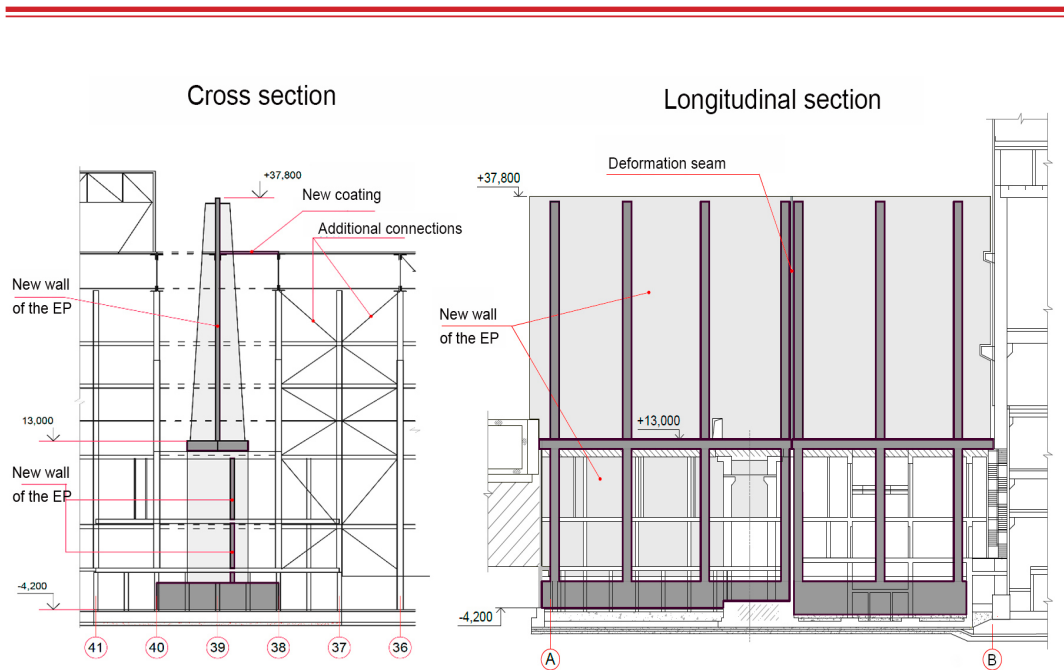


Fig. 1.23 — Construction of the eastern end of the NSC EP within the turbine island

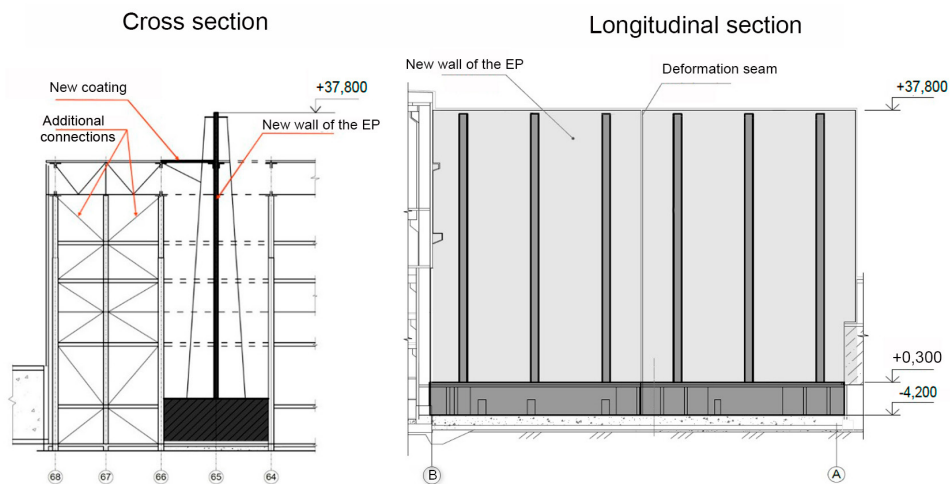


Fig. 1.24 — Construction of the western end of the NSC EP within the turbine island

The western end of the NSC EP within the DS is the existing load-bearing structures of the prefabricated reinforced concrete frame and reinforced concrete floors, as well as new walls and diaphragms made of monolithic reinforced concrete 400 mm thick.

Much of the work was performed in extremely difficult conditions inside the Shelter object (high radiation fields, availability of technological equipment, clutter, etc.) [15]. The condition of the work area before the construction of the western wall of the NSC EP in the turbine island is shown in Fig. 1.25, the work area in the process of construction is shown in Fig. 1.26.

The construction of the NSC EP covered a set of works, namely:

- preparatory work related to the organization of the construction site, installation of lifting mechanisms and temporary buildings, arrangement of access routes for personnel, etc.;

- dismantling of existing technological equipment, pipelines and cable ducts that fall into the construction zone of the NSC EP, and further — installation at a new location;

- dismantling of decommissioned equipment and communications, as well as building structures that fall into the construction zone of the NSC EP;

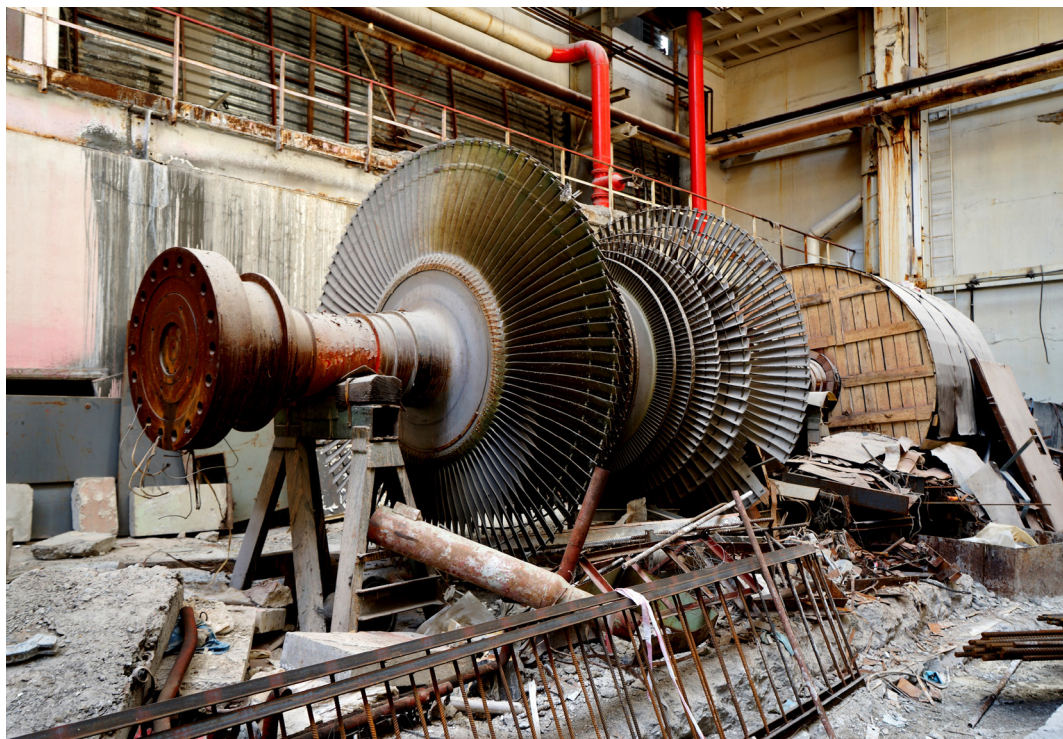


Fig. 1.25 — Construction zone of the western wall of the NSC EP in the turbine island

removal of combustible materials on the roof of existing structures at the junctions of the eastern and western ends of the NSC;

installation and concrete works during the construction of new walls and reinforcement of existing walls of NSC EP.

Construction of the NSC EP lasted 35 months. About 14,000 m³ of concrete and 1,450 t of reinforcement were laid in the walls of the western and eastern ends of the NSC EP within the turbine island. The general view of the eastern end of the NSC EP in the turbine island at the final stage of construction is shown in Fig. 1.27.

On November 8, 2017, an act on the completion of construction and readiness for operation of the facility “Strengthening and sealing of building structures of the Chornobyl NPP, which perform the functions of the NSC enclosure” was signed. On January 22, 2019, the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU) issued a special permit to the Chornobyl NPP for the right to operate existing NPP building structures, which perform the functions of the NSC, after their reinforcement and sealing.



Fig. 1.26 — Construction of the western wall of the NSC EP in the turbine island



Fig. 1.27 — Eastern end of the NSC enclosing perimeter

1.3 Technological building and other auxiliary buildings and structures

The technological building is located in the area of the western wall of the arch and partly inside the arched space. It contains several structural units and structures (Fig. 1.28): technological unit; additional unit; central control panel unit; extension for the system of LRW management; unit of the HEPA filters; a building for the entrance to the Shelter object.

The technological unit, equipped with an electric bridge crane with a capacity of 20 t, is a one-storey building 103.20 m long and 14.80 m high. The thickness of the outer walls

is 600 mm, the thickness of the coating plate is 400 mm, which meets the requirements of radiation protection (shielding). The technological unit includes a northern gateway, a southern gateway and built-in rooms.

The northern gateway is designed to transport RAW containers from the NSC to the RAW management facilities of the Chornobyl NPP, for access to firefighting equipment, as well as the departure of a forklift working inside the arch to the point for refueling with diesel fuel. The northern gateway includes a container transshipment facility, a vehicle decontamination facility and an air gateway. These rooms are separated by an airtight gate.

The southern gateway is intended for transportation of equipment to the NSC, transportation of large fragments of dismantled structures of the Shelter object, as well as for access to firefighting equipment. The southern gateway includes a sliding gate and an air gateway. Radiation control and decontamination of vehicles are performed in the air gateway.

For solid radioactive waste (SRW) management in the technological unit, there are rooms (sites) with a radiometric laboratory and equipment maintenance shop, where the RAW primary treatment and preparation, decontamination of the equipment, vehicles and containers are.

In the additional unit, there are storages for inventory, reagents, personal protective equipment (PPE), PPE decontamination room, wardrobes, medical center, bathrooms and other auxiliary premises.

The unit of the central control panel contains the central control board of monitoring and control (CCBMC), the control panel of the MCS, the room of devices for communication with the object, server room and others (Fig. 1.29).

The one-storey annex for the LRW management system is located on the north side of the technological unit on a common foundation slab. There is a room for receiving gutters, a room of tanks of gutters and LRW, a room of pumps of gutters and LRW, and other rooms. Reinforced concrete walls and coverings have a thickness of 600 mm.

The building for the entrance to the Shelter object is located on the south side of the technological unit.

Auxiliary buildings and structures are divided into two types depending on whether their construction belongs to the systems important for safety or not.

Buildings and structures whose construction belong to the systems important for safety (see Fig. 1.28) are building of electrical devices; AGFD; pumping station for fire water supply that contains two water supply tanks with a capacity of 1,500 m³ each; site of diesel generators of reserve power supply, on which two diesel generators are installed (one with a capacity of 1,350 kV · A and the other with 730 kV · A); section of the overpass of technological pipelines; section of the cable route.

Buildings and structures whose construction do not belong to the systems important for safety are pump stations for pumping (transferring) stormwater no. 1, 3, 4, and 5; storm sewer



Fig. 1.28 — Buildings near the western end of the arch:

1 — technological unit; 2 — additional unit; 3 — central control panel unit; 4 — the building of electrical devices; 5 — extension for the LRW management system; 6 — southern gateway; 7 — northern gateway; 8 — building for the entrance to the Shelter object; 9 — access gate for fire departments



Fig. 1.29 — The unit of the central control panel

treatment facilities; a site for refueling a forklift (with a fueling station and an underground tank for diesel fuel with a capacity of 3.0 m^3); foundation for an underground tank of diesel fuel with a capacity of 5.0 m^3 for diesel generators; northern and southern basins of storm-water collection from the arch; section of the overpass of technological pipelines; section of cable route; retaining walls at the NSC industrial site; masts and lighting poles of the NSC industrial site.

In the building of electrical devices, there are NSC life support systems, premises of distribution devices for own needs, premises for transformers, accumulator rooms, workshops. In part of the premises, there is an equipment for water supply systems, ventilation, domestic sewage pumping.

The AGFD building contains a foam fire-extinguishing station and a 0.4 kV self-contained switchgear, a transport airlock, a supply ventilation center and a corridor.

The pumping station for fire extinguishing serves for water supply. The building is equipped with a suspended crane beam and a monorail with a capacity of 3.2 t and 10.0 t, respectively.

The northern and southern pools for the collection of stormwater from the arch are located along the foundations of the service area and have the following dimensions: length 163.30 m, width 13.00 m, depth 1.50 m. The bottom (600 mm thick) and walls (400 mm thick) of the pools are made of monolithic reinforced concrete.

1.4 Main cranes system

The MCS functionally provides dismantling of unstable building structures of the Shelter object, and in the future — activity on the transformation of the Shelter object into an ecologically safe system (removal of FCM and other RAW), as well as decommissioning.

The system includes the following basic equipment: two bridges 96.0 m long each and three carts: standard cargo truck with a capacity of 50 t; special safe truck with a capacity of 50 t; cargo truck equipped with the MIP.

The crane bridge consists of two crane beams. Crane beams are welded, box-section, each of them has one of the rails on which trucks move (Fig. 1.30).

Crane bridges move on rails of tracks under the crane and have a suspended design. As the length of the bridge is large (96 m), each of the bridges moves on six crane tracks. The length of each crane track is 150 m. The crane bridges move in the east-west direction, and the trucks move in the north-south direction (Fig. 1.31).

To increase the length of the trucks, the bridges are equipped with cantilevers in the northern and southern directions and capture the northern buttress wall on the north side and the “Octopus” beam on the south side.

A standard truck with a capacity of 50 t is equipped with a lifting device with one electric motor.



Fig. 1.30 — Construction of a crane bridge prepared for installation on crane girders at the erecting site

The special safe truck is equipped with one main lifting mechanism and one emergency lifting mechanism. Loading capacity of each mechanism is 50 t. The main barrel is used in the mode of normal work of the crane. The emergency barrel in this mode remains in the initial position and is used only for raising and lowering of cargo to a safe condition in case of failure of the main barrel at the loaded cart.

The truck with the MIP is equipped with a special sling system. The MIP consists of upper and lower platforms (Fig. 1.32). The bottom is suspended on six ropes, which create a three-dimensional triangular truss structure. The MIP is adapted for the installation of equipment and is equipped with a power supply system.

To organize the MCS maintenance and repair work, there are two garages in the arch at the level of the truck movement zone: the main one is for maintenance and decontamination (located in the northern part of the building); the south one is for changing or storing of the cart (located on the south side above the turbine island). Trucks can move from one



Fig. 1.31 — General view of the main crane system

bridge to another by racing them in the garage from either end of the bridge and then racing to the next bridge. The maintenance garage with a cargo truck, equipped with a MIP is shown in Fig. 1.33.

In case of failure of one of the bridges, the MCS is equipped with aids of emergency removal of it through another bridge.

The MCS is controlled remotely from the CCBMC premise.

1.5 Management and control systems

An integrated control system (ICS) is provided for control of the main technological equipment, monitoring of operational parameters and main characteristics of the NSC. Together with other systems and subsystems, the ICS provides nuclear, radiation and industrial safety to the NSC by maintaining the equipment in working order and using a minimum of personnel. The system is built based on modern, high-performance digital software and hardware. According to the impact on safety, it is referred to the system of normal operation conditions, important for safety. It is a system distributed on the technological, functional and territorial principle, in which control and management systems of various purposes and functions are integrated. It is designed to be compatible with the integrated automated



Fig. 1.32 — Cargo truck equipped with a mobile instrumental platform

control system (IASC) of the Shelter object and should provide ongoing monitoring and control of the various NSC systems throughout its lifetime.

The ICS interacts with the following main systems: the MCS; the system of building structures control and the seismic control system; the radiation monitoring system; the IASC for the Shelter object; the power supply and electrical equipment system; the fire protection system; the access control system; the communication system; the industrial television system; and the water supply system.

Interaction with the MCS. An industrial Ethernet network and a wireless radio network are provided for communication between the technical means of the MCS control and management system. In the mode of normal operation, the MCS is controlled from the premises of the MSC control panel, where the command automated workstation, the workstation of the standard trolley, the workstation of the special safe trolley, the MIP workstation and the backup workstation are located. A portable MCS control panel is provided to perform some specific MCS maintenance operations and procedures inside the arch. In the event of loss of communication between the operators' workstations and the MCS components, trolleys and bridges can be controlled locally using controls on these components or by using



Fig. 1.33 — Maintenance garage with a truck, equipped with a mobile instrumental platform

a wireless portable emergency control panel. The portable emergency control panel enables to control any MCS component and uses an alternative method of communication by the radio. All MCS control commands and feedback information from MCS components are processed by the control programmable MCS logic controller.

System of building constructions control and seismic control. This system performs seismic and meteorological control; monitoring of corrosion of structures, as well as deformations of structures and foundations of the arch; three-dimensional survey of NSC objects. It provides comprehensive data processing; display of information; archiving and documentation; assessment of the arch condition; diagnostics of hardware and software; providing information to the ICS.

Radiation monitoring system (RMS) in the NCS. It is a set of technical means and organizational measures aimed at ensuring radiation safety standards in order not to exceed the established dose limits (principle of non-exceeding); reduction to a reasonably achievable minimum of individual dose levels and the number of irradiated personnel (optimization principle, ALARA); non-spread of radioactive contamination between work areas (with different radiation parameters) and into the environment. It provides a measurement of

parameters used to assess the impact of the facility on personnel and the environment, as well as parameters used to determine the operation of technological systems and the condition of technological equipment.

Technical means of the RMS provide the following types of radiation control: radiation technological control; radiation dosimetric control; personal dose monitoring; radiation control of the environment; radiation control of non-spread of radioactive contamination.

The structure of the RMS provides continuous remote monitoring using stationary means; control using portable devices; control by a method of environmental sampling with the subsequent processing and measurement in the laboratory.

The RMS of the NSC consists of two parts: 1) equipment and means of individual dosimetry (including remote dosimetry), which are an extension of the PDM system of the Chornobyl NPP; 2) RMS devices and means designed for continuous measurement of parameters of radiation condition in the NSC premises and radiation monitoring of personnel. The RMS is connected to the ICS of the NSC. Each of these two parts has a two-level architecture with a lower level for measuring, processing and collecting data and an upper level for recording, transmitting, displaying, and forecasting the data.

The basis of technical equipment of the RMS for continuous and periodic control is automated RMS (ARMS), which includes devices for detecting the dose rate of gamma radiation with light and sound signals; devices for detecting the volumetric activity of alpha- and beta-active aerosols with light and sound signals; devices for measuring radioactive air contamination in the ventilation stack; devices for individual control of radioactive contamination of hands, feet and clothes; laboratory equipment; equipment calibration sources; portable radiation monitoring devices; remote control terminals (data collection and processing stations); programmable logic controller and ARMS application server; duplicated auxiliary systems of the reactor compartment data collection network; equipment of the automated ICS system.

Access control system. The system is intended for control and management of access of the personnel into an arch, a technological building and a building of electrotechnical devices. It is an autonomous system of the NSC, it is not integrated into the general access control system to the Shelter object and other facilities of the Chornobyl NPP. The access control system is controlled from the automated workstation of the access control system operator located in the premise of the CCBMC. All access control points are equipped with video cameras.

1.6 Life support systems

The NSC life support is performed by the ventilation, heating and air conditioning systems; the power supply system; the fire protection system; the RAW management system; the decontamination system; the dust suppression system; the water supply and sewerage system; the compressed air system; the lighting system; the lightning protection system; the industrial television system; the communication and notification system.

Heating, ventilation, and air conditioning (HVAC) systems. These systems are made separately for the arch, technological building, the building of electrical devices, access gate of fire departments.

Functions of the HVAC of the arch (annular space and main volume) are: ensuring the direction of airflow from potentially low contamination zones to potentially high contamination zones; maintaining the level of radioactive emissions into the atmosphere within the established [14] limits; ensuring the minimum allowable speed of the supply air to prevent the resuspension and transport of dust, preventing the formation of flammable and explosive vapors, gases and dust mixtures within the limits set above [14]; preventing the spread of smoke and combustion products in the event of a fire; maintaining in the annular space of the arch relative humidity below 40% to prevent the formation of condensate and, accordingly, atmospheric corrosion of the steel structures of the arch; preventing of condensation on the inner skin of the arch (preventing of LRW formation).

Maintenance of temperature and humidity in the annular space of the arch is achieved by supplying dried air.

Functions of the HVAC of the technological building are: ensuring the direction of airflow from potentially low contamination zones to potentially high contamination zones; maintaining the level of radioactive emissions into the atmosphere within the established [14] limits; protection of escape routes for personnel from the effects of dangerous factors of fire (smoke); maintaining optimal environmental parameters for the safety and comfort of personnel.

The main purpose of the ventilation system of the northern and southern air gateways is to prevent environmental contamination through a direction of airflow from outside to inside the NSC.

Organized discharge from the arch and the technological building was carried out through a ventilation stack suspended from the western end of the arch.

Functions of the HVAC of the electrotechnical devices building are: support of optimum parameters of environment for safety and comfort of the personnel; providing an independent supply ventilation system with aerosol filters for the CCBMC; protection of escape routes for personnel from the effects of dangerous factors of fire (smoke).

In the access gate for fire departments, the air heating combined with supply ventilation is accepted.

Power supply system. It was designed to power all consumers of the NSC in the conditions of normal operation, disturbances of normal operation and design basis accidents. The power supply system includes equipment to support the operation of all systems that provide technological operations for RAW management, as well as the operation of systems that ensure the operation of the NSC, process control, operation of monitoring, lighting, communication, radiation control, ventilation.

The NSC power supply is provided from the existing 6 kV switchgear located on the territory of the Chornobyl NPP industrial site.

The reserve sources of the NSC power supply, which provide power supply to consumers of a special reliability group, are diesel generator sets: a diesel generator with a capacity of 1,350 kV · A and a diesel generator with a capacity of 730 kV · A.

In case of power supply loss for consumers who allow a power outage of 15 s or more and require a power supply in any initial events, in particular in case of loss of external power supply, such consumers will receive power from a diesel generator with a capacity of 1,350 kV · A.

In case of loss of power supply for consumers who do not allow a power outage for more than 20 ms and require power supply at any initial events, in particular in the event of loss of external power supply, such consumers will receive power from uninterruptible power supplies that provide continuous operation for 90 min.

Fire protection system. It consists of a fire alarm system; fire warning and evacuation control system; fire extinguishing system; fire water supply system.

The fire alarm system provides early detection of fire and signaling the occurrence of fire to the receiving and control fire device installed on the CCP of the fire protection system.

The fire warning and evacuation control system, installed in the buildings and structures of the NSC, has audible warning devices and light indicators “Exit”. It works in the mode of remote control from the CCP of the system of fire protection. Information received from the fire alarm system is used for notification.

The NSC provides *foam, gas and powder fire extinguishing systems*. The roof of the turbine island is subject to protection by a foam fire extinguishing system. Foam generators are installed on the towers located along the turbine island (Fig. 1.34).

Electrical premises and premises with electronic equipment available in the technological building, buildings of electrical devices and AGFD, as well as diesel generators are equipped with automatic gas fire extinguishing systems (Fig. 1.35). CCBMC premises are equipped with a gas fire extinguishing system with a manual start, and a diesel pump premise in the pump fire water supply station has an automatic powder fire extinguishing system.

To ensure fire safety during the operation of the MCS in the area of technological sites and garages, as well as in the premises of the technological building, the presence of powder fire extinguishers is provided.

Firewater supply system. It consists of an external fire water supply system and an internal fire water supply system. There is a high-pressure fire water supply system for firefighting of buildings and structures of the NSC.

The fire water supply system provides storage of water for firefighting in fire tanks (two tanks with a capacity of 1,500 m³ each); water intake for firefighting by fire pumps; water supply for firefighting purposes.



Fig. 1.34 — Foam fire extinguishing system



Fig. 1.35 — Automated gas fire extinguishing system

The RAW management system consists of LRW and SRW management systems.

The LRW management system is designed to collect radioactively contaminated water effluents from work sites/areas inside the arch and the process building. It provides collection, control of LRW and their transfer to the system of LRW management of the Chornobyl NPP.

All sources of LRW generation have a system of special sewerage for collection, accumulation and transfer for preliminary treatment of LRW, which are formed during the operation of facilities, the NSC infrastructure facilities, sites and RAW management facilities.

The LRW management system of the NSC includes a pressureless special sewerage system; pressure special sewerage system; sanitary sluice wastewater collection and dispatch system.

The SRW management system performs a collection of SRW; sorting of it by physical, chemical and radiation characteristics; fragmentation of SRW to a size convenient for transportation or loading into a container; filling of SRW container with a capacity of 1.3 m³; characterization of the package content; control of radiation characteristics of the container with SRW (surface contamination and dose rate); preparation of documents for transportation to the treatment facilities of the Chornobyl NPP; buffer storage of RAW for the organization of transportation.

The system is provided with equipment for collection, fragmentation, characterization, containerization and transportation of SRW within the NSC.

The decontamination system envisaged by the NSC project includes the decontamination of PPE; walls and floors of the technological building; areas of space under the arch, where the contamination with radioactive substances is possible; the inner shell of the arched structure; MCS; cranes of the technological building; containers and vehicles; equipment and pipelines of the LRW management system.

There are special premises for decontamination: decontamination rooms in the technological building, garages of the MCS, PPE decontamination rooms.

The dust suppression system (DSS) covers the site for mobile DSS; the area of preparation of solutions for dust suppression; pipeline for supplying solutions for dust suppression to the site of mobile DSS. In the future, it is planned to create a mobile DSS, which will be moved by the MCS.

Water supply and sewerage system. The sources of the cold and hot water supply of the NSC are the systems of domestic and drinking water supply and heat supply of the Chornobyl NPP. The backup source of the hot water supply is electric water heaters.

The NSC project provides for industrial, storm and domestic sewage.

The system of the industrial sewerage provides assignment and treatment of industrial effluents. Discharge of industrial sewage after treatment and radiation control is provided to the external storm sewer network.

The storm sewer system is assigned to collect precipitation on the surface of the arch, the roofs of the technological building and the building of electrical devices, as well as on the roof protruding beyond the arch. The northern and southern basins are arranged for collecting stormwater, snow/ice from the roof of the arch. Precipitation is collected into the collector of the NSC effluents and discharged into the inlet channel of the system of hydraulic structures of the Chornobyl NPP. In addition, the storm sewer system collects precipitation from the area adjacent to the arch. Precipitation is provided into the NSC stormwater collection reservoir.

The domestic sewerage system ensures the diversion of household sewage of the NSC into the domestic sewerage network of the Chornobyl NPP.

Compressed air system. It consists of a compressed air supply network for technological and repair needs and a compressed air supply network for the pneumatic actuators of the ventilation system. Four compressors with built-in receivers and dehumidification units are installed to supply compressed air.

NSC lighting system provides working and emergency lighting. The space under the arch is illuminated by three searchlight towers 30 m high, the temporary storage area is equipped with searchlights additionally installed on the roof of the technological building. The constructions of the main cranes are equipped with lighting devices that are switched on during the operation of the cranes. Luminaires mounted on reinforced concrete supports 10 m high and on three steel masts 30 m high are used to illuminate the NSC territory.

Barrier lights are used for warning lighting of the NSC.

Lightning protection system. It consists of lightning rods, taps and a ground circuit. The system protects personnel, equipment, buildings and structures of the NSC from lightning.

The system of industrial television allows remote control of mechanisms and visual control of the main technological processes. It is also used to monitor personnel involved in operations directly related to the process.

1.7 Commissioning of the New Safe Confinement

The Cabinet of Ministers of Ukraine by Resolution dated April 26, 2017 no. 305 approved the Procedure for commissioning a New Safe Confinement, defining the features of the procedure for the commissioning of this facility, taking into account all individual construction projects that are part of the entire property complex.

According to the resolution, the commissioning of the facility is carried out by obtaining a certificate for the entire construction site. The date of commissioning of the integral property complex of the object is the date of issuance of the certificate for it.

After the arch was installed in the design position at the end of November 2016, in parallel with the completion of the NSC construction, individual tests of some NSC systems and equipment began (Figs. 1.36—1.39).

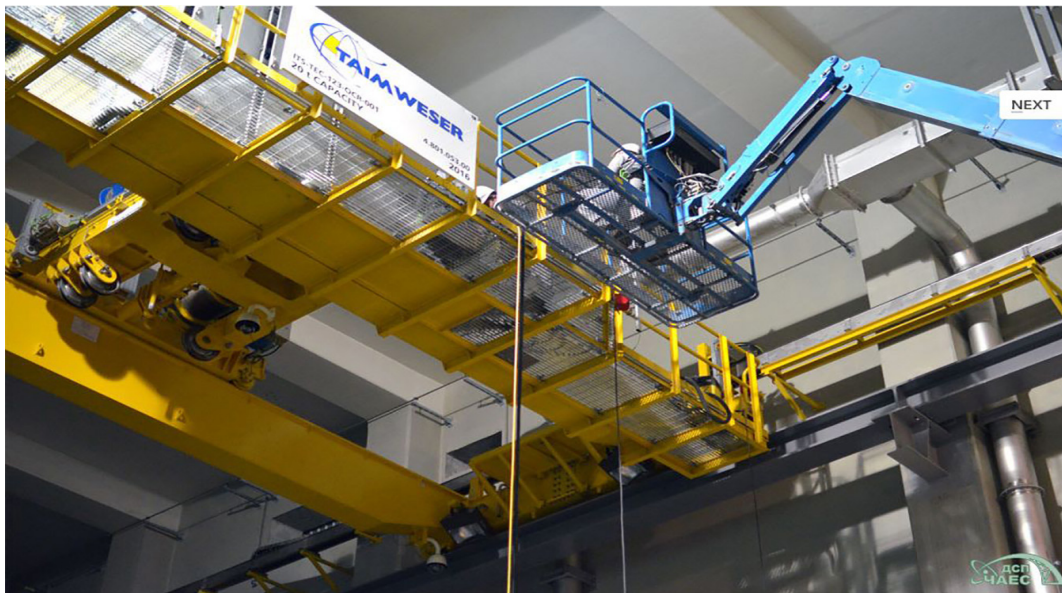


Fig. 1.36 — Testing of a bridge crane in a technological building



Fig. 1.37 — Testing of the radiation monitoring system



Fig. 1.38 — Testing of the foam fire extinguishing system

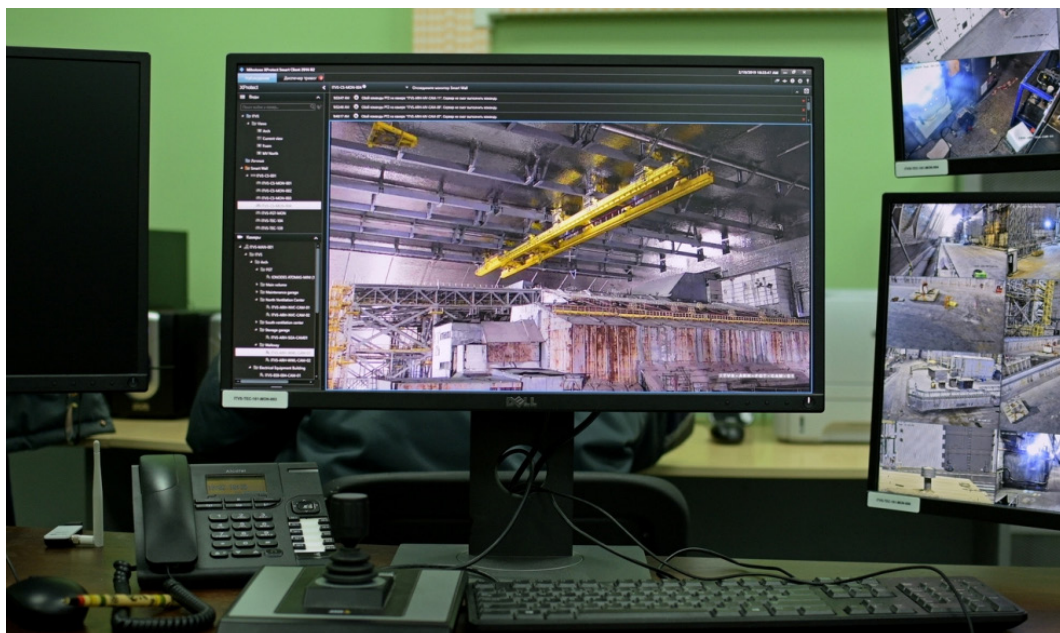


Fig. 1.39 — Testing of the main cranes system after modification

In August 2018, the Chornobyl NPP received a certificate from the State Architectural and Construction Inspectorate of Ukraine, which certifies the compliance of the completed NSC facility [16]. The certificate confirmed the fact of performance of works in full accordance to the project documentation and cleared the way to the final stage — commissioning of the NSC as an integral property complex together with internal systems.

At the beginning of 2019, comprehensive tests of the NSC RMS (Fig. 1.37), the NSC power supply system under the scenario of complete power outage and fire protection system (Fig. 1.38) took place [16]. During the tests, emergencies were simulated and the response of individual systems to them was checked.

To complete other tests, some technological systems, including power supply, lighting, communication and notification systems, fire protection, HVAC, RMS, ICS, remained in an operation mode.

Tests of the MCS after its modification were conducted on February 18—22, 2019 (Fig. 1.39) [16]. Earlier inspections revealed the problem of exceeding the torque of electric motors on the drives of the MCS axes. After eliminating the reasons for this problem, the crane manufacturer implemented several measures related to both the mechanical part of the MCS and its control system.

During the tests, there were checked the operation of the MCS at maximum load (100 t per bridge), the movement of each of the bridges with one engine off, and the operation of the bridge positioning system. Also, the bridges were moved along the entire length of crane tracks (from the western wall to space above the Shelter object).

The tests showed a positive effect of the MCS modification and the need to refine some functions in the control and management system of the MCS, and complete the tests of the bridge positioning system and customize individual mechanical components.

On April 22, 2019, the NSC was put into trial operation [16]. Its task was to make sure that all equipment and facilities perform their functions. During the trial operation, almost all NSC equipment and systems operated in the design mode for 72 hours.

In addition, working in this mode made it possible to check the level of qualification obtained by the personnel of the Chornobyl NPP during training. At the first stage of trial operation, training with MCS was carried out: moving carts from overhead cranes into the maintenance garages. In the second stage, the sub-crane beams of the MCS were inspected and two cranes (western and eastern) were trained to move over the roof of the Shelter object. This was followed by a simulation of the dismantling, lifting and moving to a temporary storage site of a metal truss installed during the stabilization of the Shelter object.

After the completion of construction and installation works on the establishment of the NSC and successful testing, on July 10, 2019, at the meeting of the Assembly of donor countries at the Chornobyl NPP an act of acceptance of the NSC from the Contractor (consortium Novarka) to the Customer (SSE “Chornobyl NPP”) was signed [16].

In September 2019, the Chornobyl NPP received a certificate from the State Architectural and Construction Inspectorate of Ukraine, which certified that the completed NSC facility with its technological life support systems and infrastructure meets the design documentation and is ready for operation [5], all works are performed following state building specifications, standards and rules, the equipment is installed following the acts of its adoption after testing following the approved procedure.

On September 27, 2019, the Act of readiness for the operation was signed. Units of the Chornobyl NPP were fully staffed with the NSC maintenance and repair personnel, who passed theoretical and practical training and were allowed to work independently.

On July 24, 2020, the State Inspectorate for Nuclear Regulation of Ukraine issued special permission for the experimental and industrial operation of the NSC launch complex [16]. The validity of the special permission is from July 24, 2020, until the commissioning of the NSC complex and the Shelter object (issuance of licenses for processing, storage of RAW that exist and are formed during the transformation of the Shelter facility into an ecologically safe system), as a part of the NSC operation together with the Shelter object.

Chapter 2. NUCLEAR SAFETY

As a result of the accident at the fourth power unit of the Chornobyl NPP (Fig. 2.1, *a*), the reactor core and all safety barriers, which performed the function of localizing the radioactivity leak, were completely destroyed. About 190 t of irradiated nuclear fuel in various modifications were distributed in the destroyed premises [1]. These include core fragments (CF) in the form of fuel elements (FE), graphite stack, radioactive aerosols (RA), dust and, most dangerously, formed accumulations of lava-like fuel containing materials (LFCM), in particular those that under certain conditions can become potentially nuclear hazardous.

Due to the leakage of the protective structure built over the destroyed fourth power unit (Fig. 2.1, *b*) — the Shelter object — precipitation began to enter inside. As a result of the interaction of water with radioactively contaminated structures, especially with LFCM, a significant (up to 4,000 m³) amount of highly active radioactive water (RW) was formed and accumulated on different levels of the destroyed power unit.

For 30 years, the Shelter object has largely localized the environmental impact of the radioactive materials that were contained in it [5]. An analysis of the processes that took place at the Shelter object during these years revealed the main factors that affect nuclear and radiation safety:

- lava-like fuel containing materials formed during the destruction of the reactor core;
- radioactive aerosols (dust), in particular highly dispersed, containing transuranic α -emitters due to the destruction of LFCM and other radioactive materials;
- radioactive water as a consequence of the interaction of moisture with LFCM and radioactive materials.

After the construction and commissioning of the NSC (Fig. 2.1, *c*), a new integrated system appeared, in which, due to changes in humidity and temperature, the processes that previously took place in the Shelter object also were changed, both in positive and in negative aspects:

- if before the construction of the NSC potentially nuclear hazardous accumulations of lava-like fuel containing materials were in a waterlogged and subcritical state, now they can become nuclear hazardous due to moisture loss and the beginning of the process of reverse criticality;



Fig. 2.1 — Transformation of the fourth power unit of the Chornobyl NPP from the accident to the creation of the NSC:

- a* — destroyed fourth power unit of the Chornobyl NPP (1986);
- b* — protective structure — Shelter object (2006); *c* — NSC (2017)

before the construction of the NSC, due to the ingress of moisture into the Shelter object, a significant amount of RW was formed, which worsened the state of radiation safety due to the need for constant removal and processing of RW in liquid RAW management systems of the Chornobyl NPP. After the construction of the NSC, these risks disappeared, but instead, after drying of RW accumulations and the exposure of highly active bottom sediments, a threat of the formation of additional sources of radioactive dust arose;

before the construction of the NSC, RA generated inside the Shelter object were released into the environment due to leaks and a ventilation stack, significantly deteriorating the radiation condition. After the construction of the NSC, this risk disappeared, and the NSC became a reliable protective barrier to RA leakage. However, the loss of moisture and temperature rise inside the Shelter object can accelerate the RA formation process due to the destruction of radioactively contaminated concrete structures, which will lead to an increase in RA inside the NSC.

2.1 Fuel containing materials of the Shelter object

The main source of the radionuclides release in the environment and the most important source of radiological danger is LFCM containing irradiated fuel. LFCM are continuously exposed to fluctuations in temperature and humidity, as well as significant radiation exposure, because they contain the developed products of fission and activation — transuranic isotopes, in particular plutonium and americium. Over time, their degradation occurs, which is a change in mechanical properties in the form of a significant reduction in strength characteristics. The decrease in the strength of LFCM is due to the presence of macrocracks in the material and occurs by the reason of the accumulation of micro defects in the structure — radiation damage in the volume of LFCM as a result of α -decay of the irradiated fuel components.

Analyzing the research data for the past 35 years, we can state that even today there is no consensus on the exact description of the processes of origin and formation of LFCM [17—23]. At the same time, it should be acknowledged that the main process of lava formation was the process of high-temperature interaction of silicates with fuel rods and oxidized fuel [24].

Before the accident in the reactor compartment of the fourth power unit, nuclear fuel was in the core of the reactor RBMK-1000, in the cooling pond (CP) of spent fuel assemblies (FA), at the FA preparation unit in the central hall (CH), in the fresh fuel preparation room. At the time of the accident, the reactor core contained 1,659 FA, one additional absorber and one unloaded channel. Most of the FA were ones that had a burnout of 11—13 MW per day/kg (U) from the beginning of the campaign. The total amount of nuclear fuel at the fourth power unit (together with nuclear fuel in the reactor shaft) before the 1986 accident was 214.6 t [25].

The composition and amount of materials contained in the reactor shaft (room 504/2) and the sub-reactor room 305/2 and participated in the formation of LFCM, are given in Table 2.1, and the ratio of materials included in the LFCM — in Fig. 2.2 [26].

Table 2.1 — The composition and amount of materials that participated in the formation of the LFCM

Material	Contained in rooms 504/2 and 305/2, t	Became a part of LFCM, t
Fuel (U)	120	90
Steel	1,300	< 20
Serpentine mixture	580	160
Concrete of a reactor plate	130	130
Concrete of the building structures from the upper marks	950	480
Shaft filling materials	300	280
Zirconium	70	45
Graphite	750	Practically absent

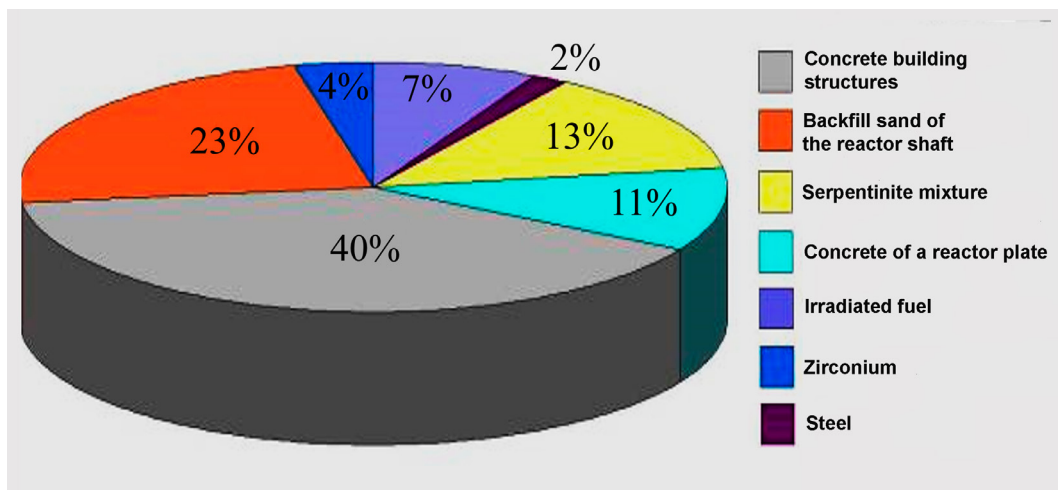


Fig. 2.2 — The ratio of materials included in the LFCM

Lava-like fuel containing materials were formed in room 305/2 due to residual heat release and exothermic processes (graphite combustion, vapor zirconium reaction) in a wide temperature range — from 1,100 °C and possibly to the melting temperature of UO₂ grains (about 2,800 °C) [24]. It can be considered as established that most of the LFCM were formed as a result of the blast-furnace process in room 305/2. The newly formed lava spread to adjacent rooms, corridors, cable penetrations and other free channels, forming local accumulations of LFCM (Fig. 2.3). The melt reached the lower premises: the steam distribution corridor (SDC) and two levels of the pressure suppression pool (PSP-1 and PSP-2) [17].

Summarizing the data for the past 35 years, we can estimate the amount of fuel in the premises of the Shelter object and its activity as of 2020. At the time of the accident, the mass of fuel loaded into the core was 190.2 t. The mass of fuel remaining in the Shelter object, according to studies of the release of radioactivity from the facility, is not less than 95% of the initial load of the reactor (about 180 t) [27].

Content of uranium in lavas:

Room	304/3	217/2	210/7	210/6
Number of samples	34	27	17	10
Average U content, %	4.1	4.9	8.8	6.2
Maximum U content, %	8.1	8.8	10.6	7.2

The LFCM density [28, 29] is largely determined by gas cavities [17]:

Room	LFCM density, g/cm ³
SDC and 217/2 (black LFCM)	2.69 ± 0.17
SDC (brown LFCM)	3.00 ± 0.13
PSP (pumice)	0.14...0.18
304/3:	
the least porous layer (at the bottom of the accumulation adjacent to the floor)	1.8...2.4
the central layer of the accumulation	0.9...1.8
the top layer of accumulation (the most porous layer)	0.7...0.9

Clarifying data on the number and location of the LFCM in the premises of the Shelter object are given in Table 2.2 [30]. The data on their activity today is presented in Table 2.3.

The total specific activity as of 31.12.2020 is $1.89 \cdot 10^9$ Bq/g (U).

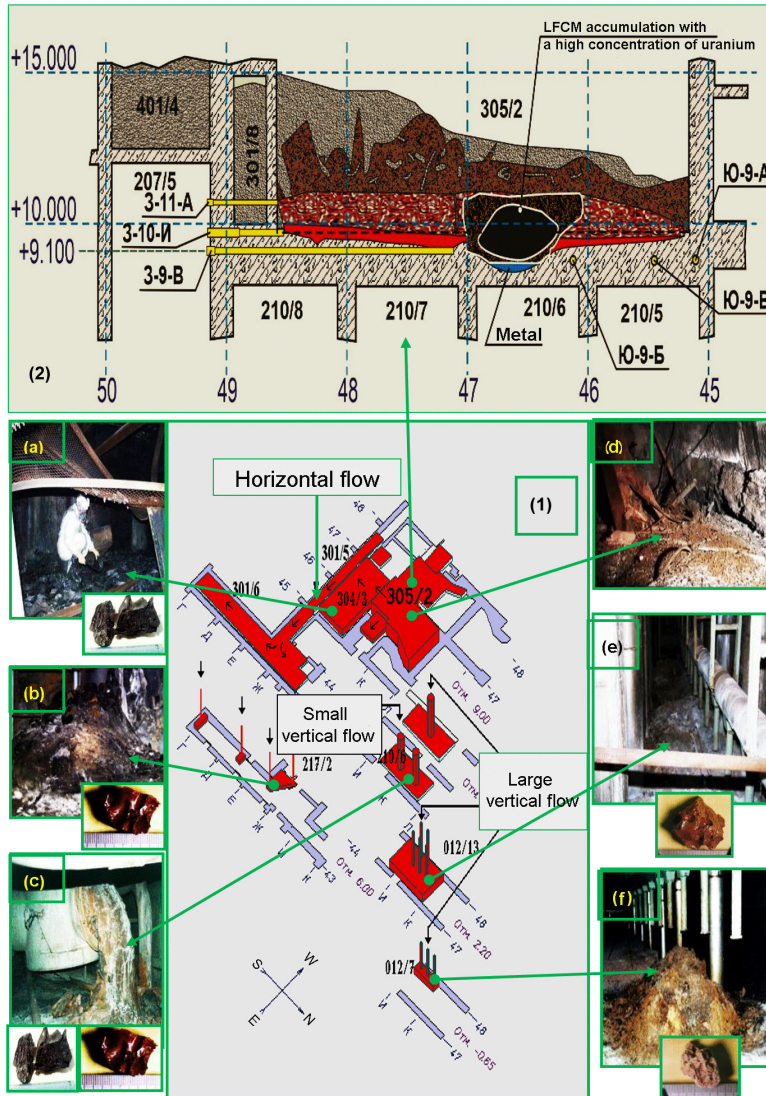


Fig. 2.3 — Scheme of distribution of local accumulations of LFCM in the Shelter object:
 a — room 304/3 (black LFCM); b — room 217/2 (“elephant’s foot”); c — steam distribution corridor, room 210/6 (brown and black LFCM); d — room 305/2 (LFCM with high uranium content); e — PSP-2, room 012/13 (brown LFCM); f — PSP-1, room 012/7 (brown LFCM);
 g — accumulation of LFCM in room 305/2 with a high concentration of uranium (fragment of the cross-section of the fourth power unit of the Chornobyl NPP on row I_{+1650})

Table 2.2 — Clarifying data on the number and location of LFCM in the premises of the Shelter object

Room	FCM modifications	Fuel, t (U)
Central hall (914/2)	CE, LFCM	< 22
South CP (505/3)	129 spent FA	14.8
Upper rooms, central hall (mark +24.000)	Fuel dust	≈10
304/3	LFCM	6 ± 2
301/5+301/6+303/3	LFCM	5 ± 2.5
217/2	LFCM	0.4 ± 0.2
Sub-reactor rooms 305/2 and 504/2 up to the mark +24.000	CE, LFCM, fuel dust	80 ± 30
SDC (210/5+210/6+210/7)	LFCM	12 ± 6
PSP-2 (012/14+012/15+012/16)	LFCM	3—12
PSP-1 (012/5+012/6+012/7)	LFCM	1.0 ± 0.5
Fuel under the cascade wall	CE, fuel dust	(0.9 ± 0.3)
RW in all rooms	Soluble uranium salts	≈4 · 10 ⁻³
Fuel at the Shelter object site	CE, fuel dust	0.75 ± 0.25

Table 2.3 — Specific activity of radionuclides, Bq/g (U), the base composition of the fuel as of 31.12.2020

α-emitters		β-emitters		β-γ-emitters	
²³⁸ Pu	5.91E+06	⁹⁰ Sr	5.16E+08	¹²⁵ Sb	1.32E+04
²³⁹ Pu	5.00E+06	⁹⁰ Y	5.16E+08	¹³⁴ Cs	7.61E+03
²⁴⁰ Pu	8.17E+06	¹⁰⁶ Ru	2.62E-01	¹³⁷ Cs	6.30E+08
²⁴¹ Pu	4.33E+03	¹⁴⁷ Pm	3.94E+05	¹⁴⁴ Ce	8.66E-04
²⁴² Pu	1.30E+04	²⁴¹ Pu	1.81E+08	¹⁵⁴ Eu	4.69E+06
²⁴¹ Am	2.59E+07			¹⁵⁵ Eu	4.90E+05
²⁴³ Am	1.95E+03				
²⁴⁴ Cm	5.83E+05				

Before the NSC construction, the classification of FCM accumulations in the Shelter object premises was changed from the point of view of nuclear safety depending on changes in the conditions in which the accumulations were located and the completeness

of knowledge about their physicochemical properties and physical state. The CH and the south cooling pond (SCP) in rooms 505/3 and 305/2 were considered as potentially nuclear hazardous [27].

After the NSC construction and the change of humidity and temperature inside it and according to new computational and experimental studies, there was a need to reassess the level of nuclear safety of all FCM accumulations and creating a new classification of materials (special fissile materials — SFM) in the Shelter object.

All accumulations of fissile materials located inside the Shelter object are divided into three main groups.

The first group consists of accumulations of FCM, the properties of which are sufficiently studied and any changes to their storage conditions will be nuclear safe [17, 21, 27, 30, 31]. In general, these are open accumulations of LFCM in rooms 304/3, 217/2 of the Shelter object (“elephant’s foot”), in the steam distribution corridors, covering rooms 210/6 and 210/7, in room 012/13 on the second floor of the PSP, room 012/7 on the first floor of the PSP.

The second group includes hidden accumulations of FCM, which are insufficiently studied (due to inaccessibility to them) and under certain conditions can be potentially nuclear hazardous. The issue of their nuclear danger must be resolved shortly. This requires additional research.

The third group includes accumulations, which with a high probability can be attributed to nuclear hazardous (we will pay special attention to them in subsection 2.2).

The first group includes room 304/3, which has a large amount of radioactive dust and traces of destruction. LFCM occupy its entire area as a whole accumulation of 0.6—1 m layer on the floor of the room (Fig. 2.4). The surface of LFCM is inhomogeneous, black, with cracks and consists of separate pieces. Visually, the structure of LFCM is porous. There are many large cavities in the solidified lava, the volume of some of which reaches 1—2 dm³. LFCM are very heterogeneous in porosity. The least porous layer is at the bottom of the accumulation, which is adjacent to the floor and has a density of about 1.8—2.4 g/cm³. The central layer has a higher porosity and lower density — about 0.9...1.8 g/cm³. The upper, porous layer has a density of about 0.7—0.9 g/cm³. The volume of LFCM is 50—70 m³, fuel mass is 6 ± 2 t (U).

Lava-like fuel containing materials flowed into one of the sub-reactor room 217/2 from room 301/6 through penetrations in the covering. Back in the fall of 1986 in room 217/2 there was found a giant solidified mass, resembling a glass drop in shape that was called “elephant’s foot” (Fig. 2.5). The exposure rate (ER) near its surface reached 8,000 R/h. The surface of the “elephant’s foot” in 1986—1988 could be described as a black molten mass with a smooth shiny surface. The length of the lava path from room 305/2 to the upper part of the “elephant’s foot” is 25 m. Lustreous (according to the results of inspections of 1986—1988) glassy surface of LFCM over time became matte.

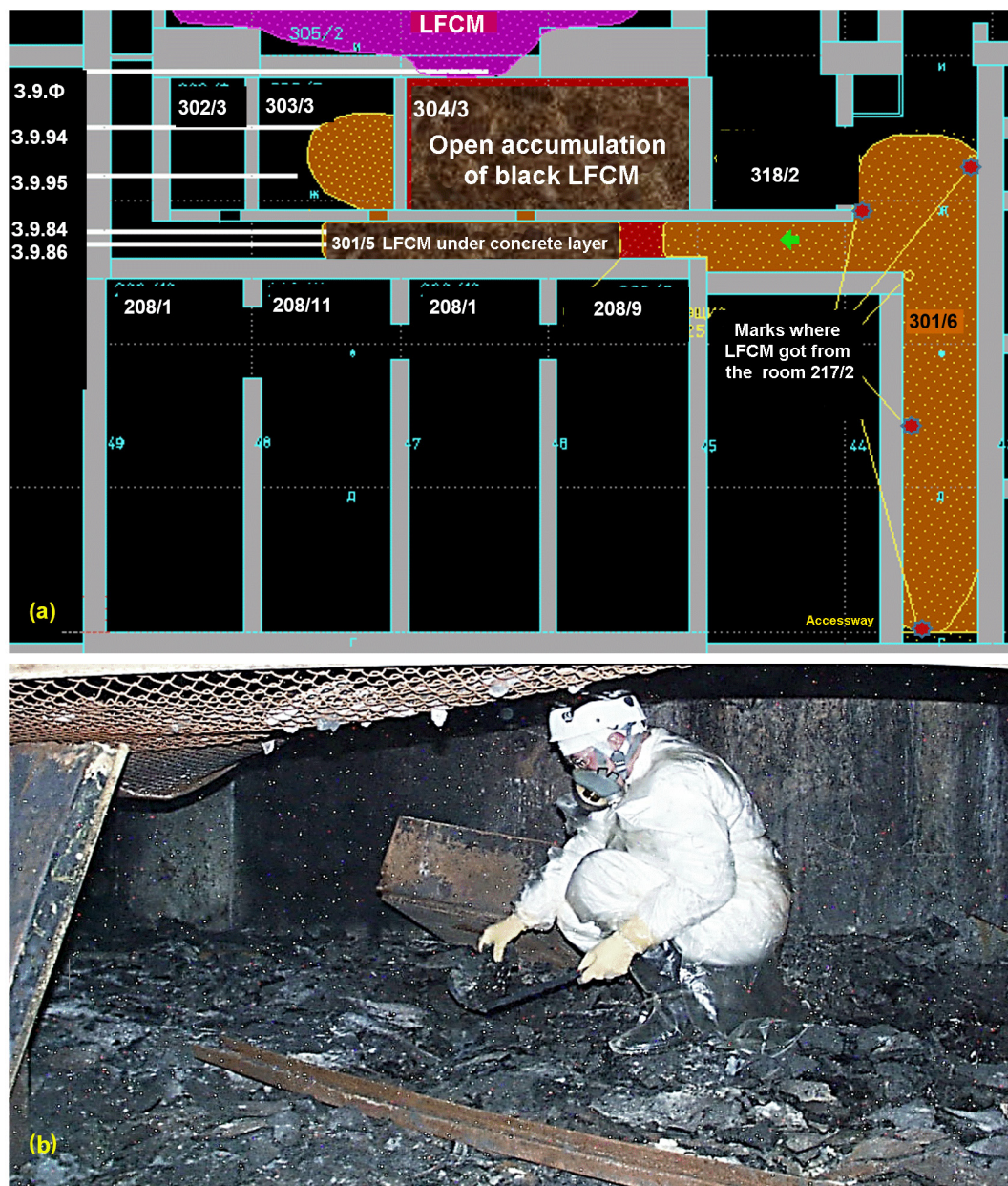


Fig. 2.4 — Room 304/3 of the Shelter object:
 a — location of accumulations of black LFCM [30, 31]; b — sampling of LFCM

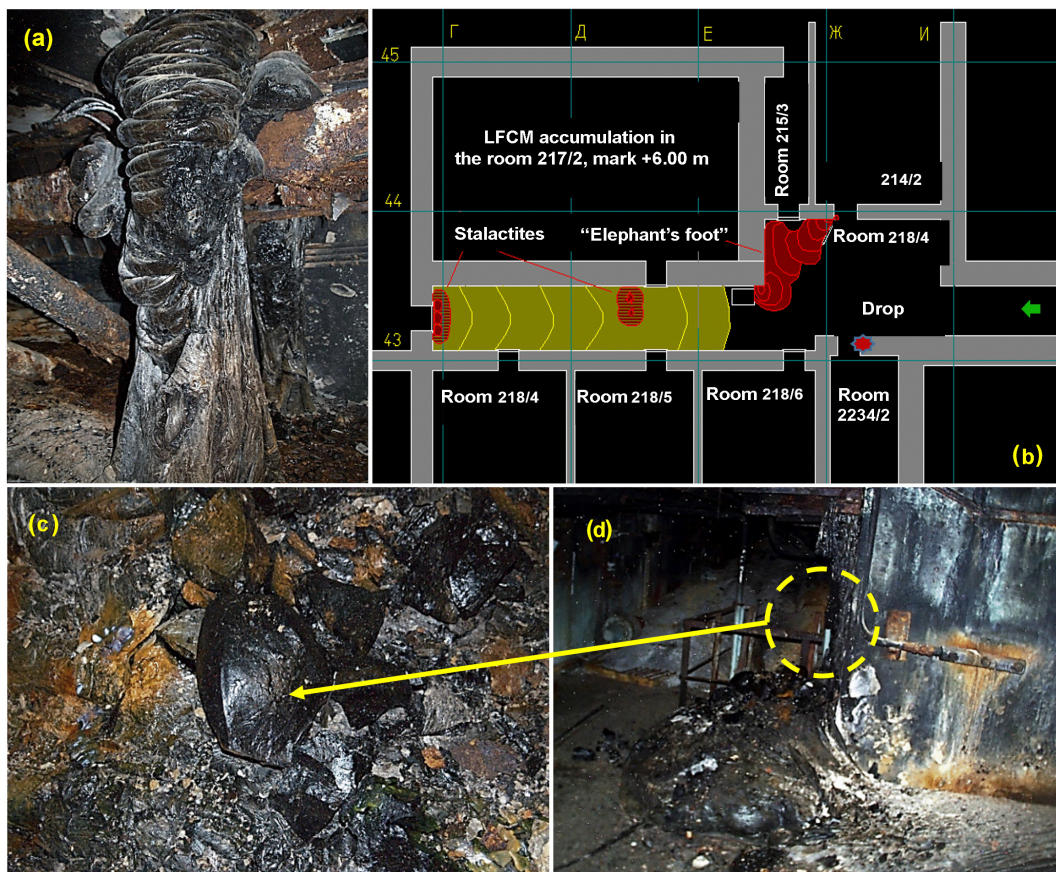


Fig. 2.5 — Room 217/2:

a — “stalactites”; *b* — location of the LFCM accumulation; *c* — fragments of the “elephant’s foot” destruction; *d* — a modern look of the LFCM “elephant’s foot”
(photo by O. V. Kupnyi)

The surface of the accumulations was constantly exposed to the external environment. Numerous cracks and massive destructions appeared on it later. The area of the “elephant’s foot” base is 6...7 m². The bases of “stalactites” are hidden under concrete [32, 33]. The corridor is filled with concrete on both sides. The surface of the concrete near the southern end reaches the room ceiling. The total volume of accumulations is approximately 2—4 m³, fuel mass is 0.4 ± 0.2 t (U).

Into room 210/7 (Fig. 2.6) LFCM got through the fourth steam relief valve (SRV) from the south-western part of room 305/2. During the accident in 1986 fresh concrete flowed

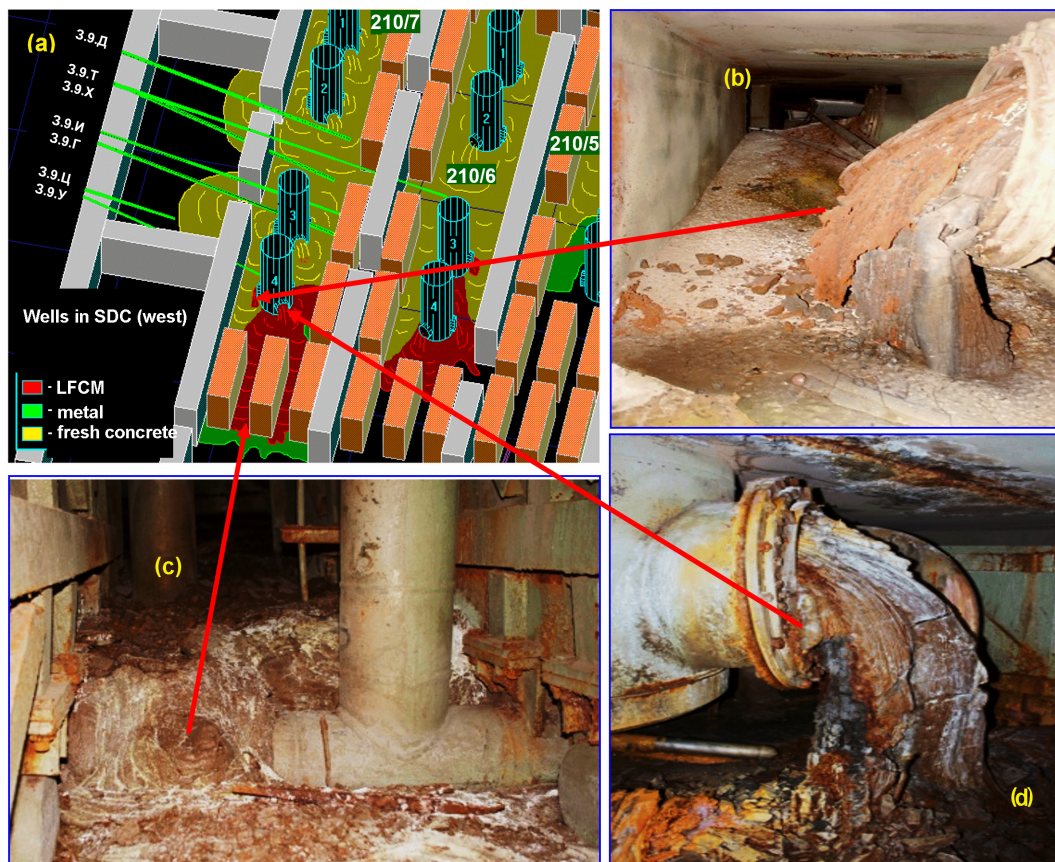


Fig. 2.6 — Premises in the steam distribution corridor:

- a* — layout of the premises in the steam distribution corridor and the spatial location of LFCM accumulation in rooms 210/5, 210/6 and 210/7 [30, 31];
- b* — LFCM accumulation in the fourth SRV, the first branch pipe;
- c* — LFCM between condenser batteries;
- d* — LFCM accumulation in the fourth SRV, the third branch pipe

through the other three valves. In the first branch pipe of the fourth SRV in room 210/7, there is a kind of solidified spillway of brown LFCM with large drops and streams of metal (Fig. 2.6, *b*). The second pipe is a solidified stream of coal-black LFCM. The third pipe is a chocolate-brown solidified mass (Fig. 2.6, *d*). Next to the solidified stream of LFCM, opposite the fourth branch pipe and close to the condenser battery, the solidified metal exposes from the layer of LFCM.

The thickness of the LFCM layer near the western wall reaches 0.5 m. Further, in the northern direction the LFCM are covered with fresh concrete. Directly under the break in the wall between rooms 304/3 and 305/2 the lava penetrated room 210/6 and lies in the gap of the steel seam of the metal ceiling cladding. The LFCM volume in room 210/7 is approximately 13—28 m³. Fuel mass is about 3.7...10.4 t (U).

Into room 210/6 of the SDC (Fig. 2.7) LFCM got through the third and fourth SRV from the south-eastern part of room 305/2 [28]. Valve branch pipes are filled with black LFCM (Fig. 2.7, *a, c*). There are many small fragments of metal structures in the pipes among the LFCM. On the surface of the LFCM leaked from the valves, there are bright yellow spots of

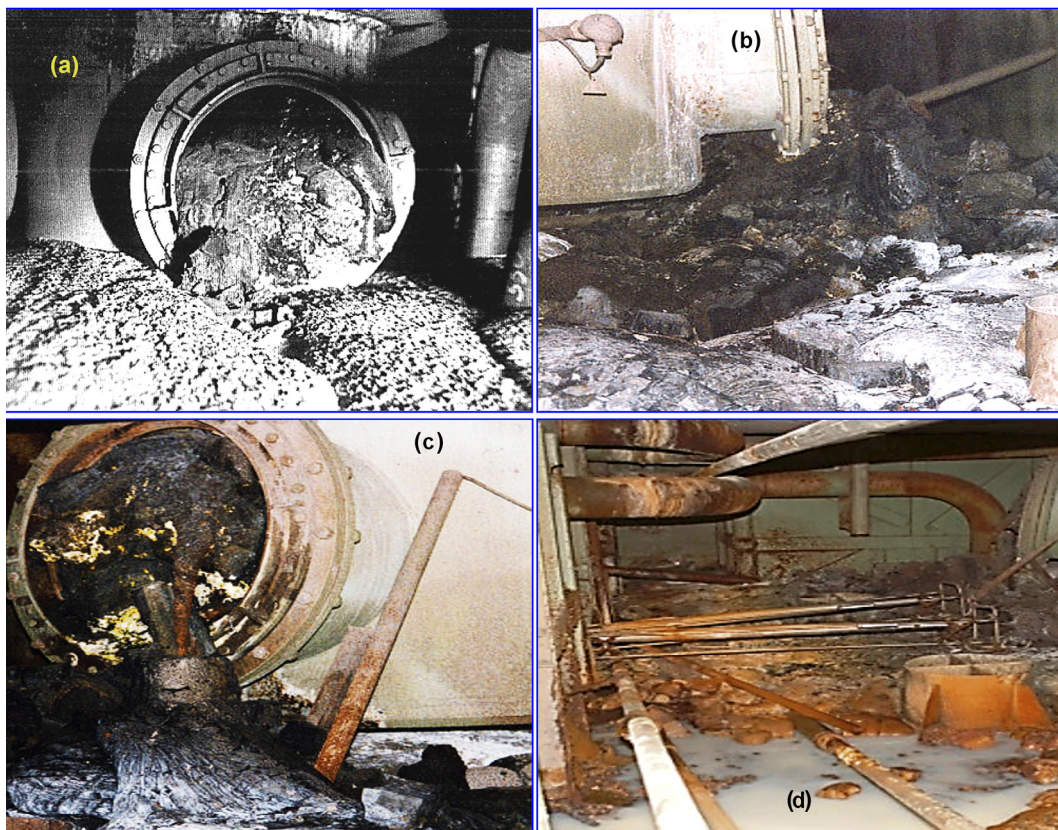


Fig. 2.7 — LFCM in room 210 of the SDC:

- a* — the third SRV, the first branch pipe; *b* — the fourth SRV, the second branch pipe;
- c* — the fourth SRV, the third branch pipe (yellow spots are new formations of uranium oxides);
- d* — molten metal in the water

new formations of uranium salts (Fig. 2.7, *b*). The thickness of the layer of open LFCM accumulations in room 210/6 is from 0.1 to 0.6 m [30, 31]. Melted and solidified metal (Fig. 2.7, *d*) was found in the area of the fourth SRV, and matte LFCM were permeated with large gas cavities. The LFCM along the condenser batteries are filled with fresh concrete, which got here during the elimination of the accident in 1986.

Under room 210/6 four steam pipes are filled with LFCM, the layer thickness of which is not less than 0.35 m. The solidified metal masses are observed visually, their thickness does not exceed 0.2 m. The LFCM on the floor and steam distribution valves are mostly black. The LFCM volume in room 210/6 is approximately $17 \dots 30 \text{ m}^3$, fuel mass is about $2.4 \dots 6.2 \text{ t (U)}$.

An open accumulation of the LFCM on the second floor of the PSP-2 (Fig. 2.8) is located in room 012/15. The structure of the accumulation is a system of interconnected ridges with dips 0.1—0.3 m deep, and this system is covered at the edges with a layer of concrete, which was poured in 1986. On the northern side, the level of concrete reaches about 0.8 m. The open surface is covered in places with a vitreous crust, occasionally pumice-like. Inside the LFCM there are granules of brown LFCM [29, 30, 31]. LFCM rise above the floor level up to 1.2—1.3 m. The width of the accumulation base is almost 4 m, the length is 8 m, the volume is $23 \pm 6 \text{ m}^3$. Probably, under concrete inflows up to 0.9 m there are LFCM accumulations or molten metal (it is indicated by the ER high values over concrete) [32, 33].

In room 012/13 a molten metal pipe is located (see Fig. 2.8, *d*). The metal cladding of part of the wall (the passage from room 012/14 to room 012/13) in front of this pipe is also partially melted. The area of open LFCM in room 012/15 is approximately 15 m^2 . The total volume of LFCM in PSP-2 is approximately 50 m^3 . The mass of fuel in the PSP-2 can reach 12 t (U) .

LFCM on the ground floor of the PSP-1 (Fig. 2.9) got from a steam pipe (see Fig. 2.9, *b*) [28]. The accumulation, the top of which reaches almost 0.8 m from the floor level, was covered with 0.2—0.4 m of concrete in 1986, occasionally with a vitreous crust, and sometimes with a pumice-like one. Inside it contains a granular glassy substance of dark brown color (brown LFCM) [32, 33]. In March 2000, the part of the accumulation was covered with a layer of radiation-resistant organosilicon material EKOR to isolate and preserve LFCM and prevent the uncontrolled spread of radionuclides (see Fig. 2.9, *c*).

LFCM in the form of separate fragments are located in different places of the PSP-1, some of them are on horizontal sections of steam pipes and metal structures at a height of more than 1 m. In five steam pipes (diameter 280 mm) from 0.06 to 0.3 t (U) of the LFCM can be contained [29]. Under the concrete inflows (up to 1 m) there is a fragment of the LFCM accumulation with a high ER value.

In room 012/5 a molten pipe with a metal teardrop is located. There are traces of temperature influence on the ceiling near the melted pipe. The area of open LFCM in the room 012/7 is approximately $3\text{—}4 \text{ m}^2$. The LFCM amount in the premises of the PSP-1 can be estimated as $0.5\text{—}1.5 \text{ t (U)}$.

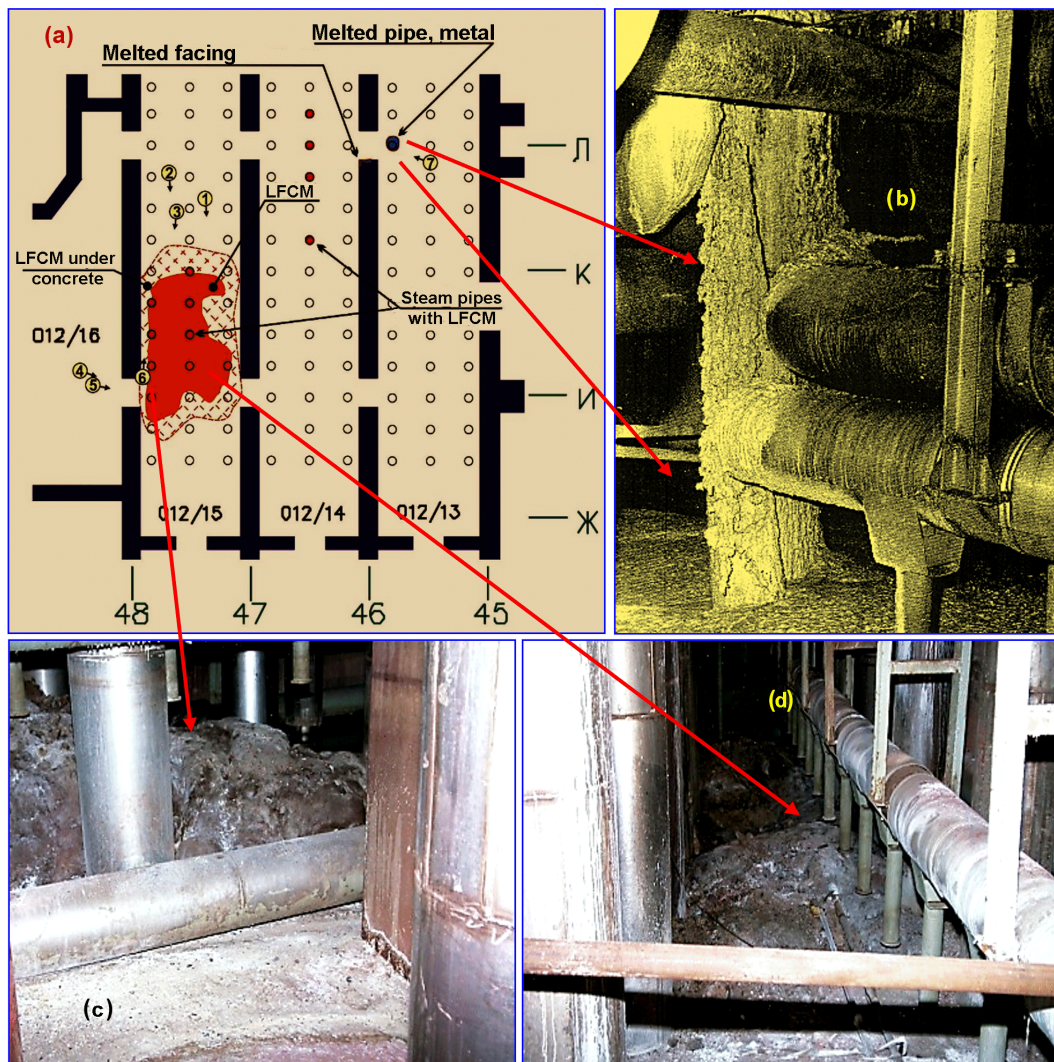


Fig. 2.8 — Layout of the premises in the PSP-2:

- a* — the spatial location of the LFCM accumulation in room 012/15;
- b, c* — photo of the LFCM accumulation in room 012/15; *d* — melted pipe

The second group includes clusters of LFCM accumulations, the guarantees of nuclear safety of which can be said only after clarification (based on additional research) of their parameters [17, 21, 30, 31] and the implementation of some organizational and technical

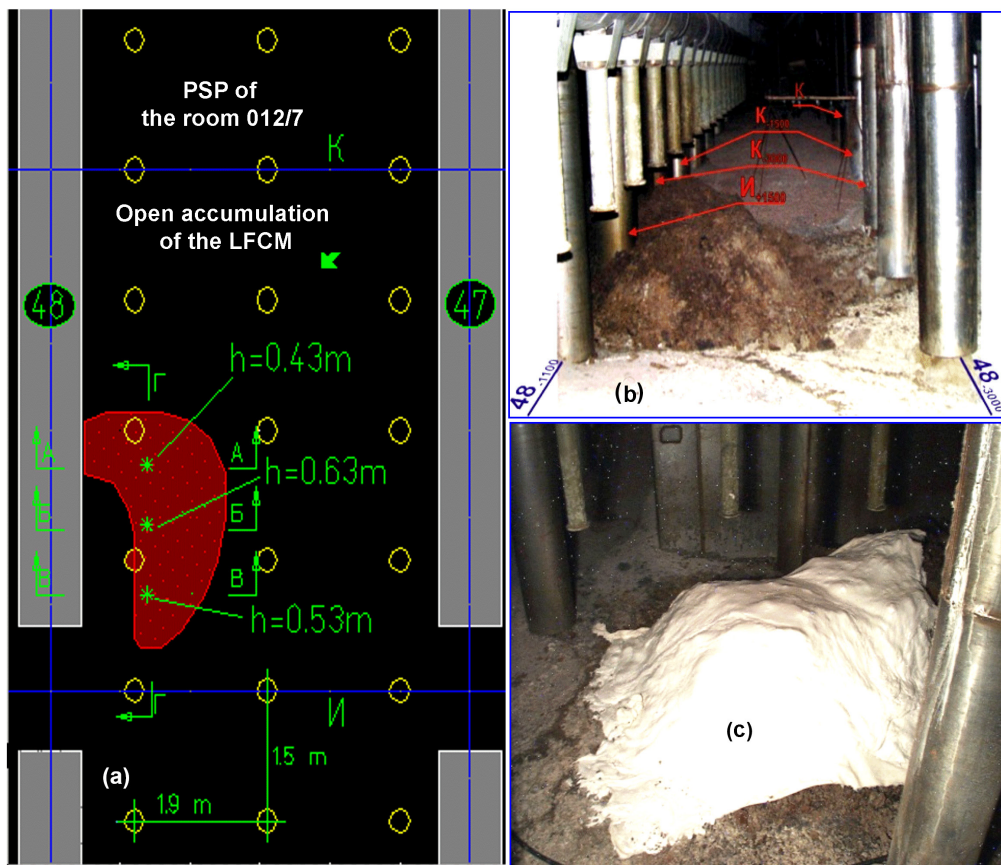


Fig. 2.9 — The scheme of room 012/7:

a — the spatial location of the LFCM accumulation [30, 31]; *b* — the LFCM accumulation (1999);
c — LFCM after covering with EKOR (2000)

solutions. Such compositions include spent nuclear fuel in the SCP(room 505/3) and fuel containing materials in the CH (room 914/2).

In normal mode, the SCP was filled with water. At the time of the accident, it contained 129 FA of 14.8 t (U) weight with an average burnout of more than 12.5 MW [25]. In the early 1990s in the SCP five wells were drilled from room 515/3: B-19-103, B-22-80, B-22-90, B-21-96, B-20-100 (Fig. 2.10). After inspecting the condition of FA, suspensions and floors, as well as measuring ER, it was found that the cover above the well was destroyed, CF did not get to the SCP from the CR, pencil cases were in normal mode, and there was no water.

According to the calculations [34], in a cooling pond filled with water, the FA remain deeply subcritical. In the case of the destruction of the suspensions, the fall of the assemblies to the bottom, their compact location and flooding with water, the system still remains subcritical ($K_{\text{ef}} < 0.9$) [35]. Based on the performed research and development work [36], it was established that a hypothetical nuclear hazardous composition could be formed only in the case of falling and destruction of assemblies with subsequent integration of their end parts into a compact structure.

At present, monitoring in the SCP is carried out by only two detection units of the nuclear safety control system installed in the wells. Analysis of the γ -radiation ER and the neutron flux density (NFD) in the wells showed that the ER in the upper part of this room decreased from 3,500 R/h in 1990 to 370 R/h in 2013, and the NFD in the lower part increased, respectively, from 140 n/(cm² · s) to 400 n/(cm² · s). This indicates that a significant part of the FA, most likely, collapsed and fell to the bottom of the room.

The fact that there is no water in the SCP, stable (almost unchanged) dynamics of neutron activity, as well as the high probability of assemblies falling gives reason to believe that the configuration of FCM in this room is nuclear safe. However, as part of a conservative approach to nuclear safety, a visual inspection of the premises should be conducted to obtain information on the current state of the FA. Only then acceptable guarantees of nuclear safety can be obtained.

At the time of the accident, there were 48 fresh FA at the suspension unit located in the northeastern part of the CH. To date, only seven deformed assemblies have been visually detected. The rest are probably located under the rubble. According to the latest data,

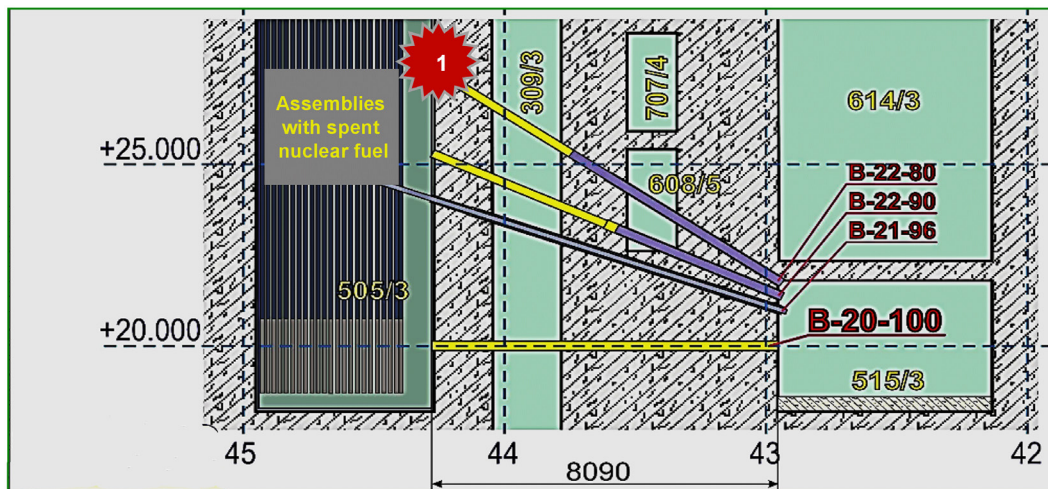


Fig. 2.10 — Southern cooling pond of spent nuclear fuel;
1 — possible location of the camcorder

under the rubble in the area of the scheme “E” more than 1 t of FCM still can be located [30]. Most of the CH is hidden under a multimeter layer of materials of the backfill, which were dropped in 1986 from helicopters (Fig. 2.11). There is no access to the FCM under the rubble of backfill materials.

According to calculations [36, 37], only hypothetical critical compositions (nuclear uranium-graphite cluster in the regular structure of the core with a diameter of 5 m and a height of 3.5 m or compact formation of a composition of FA with fresh fuel) could pose a nuclear hazard in the CH. So far, according to the results of visual observations, the existence of such compositions has not been confirmed. Most likely, the bulk of the fuel in the CH (except for FA in the scheme “E”) lies on the floor of room 914/2, under a layer of the embankment of sand, lead and dolomite. Most of the FCM can be (Fig. 2.12) in the areas closest to the reactor shaft, as well as under the main embankment. We should also note that almost all information about the state of the FCM contained in the CH (visual information, radiation fields, NFD data) are obtained only from “above”. At the same time, areas, where large accumulations of FCM are expected, have not been studied.

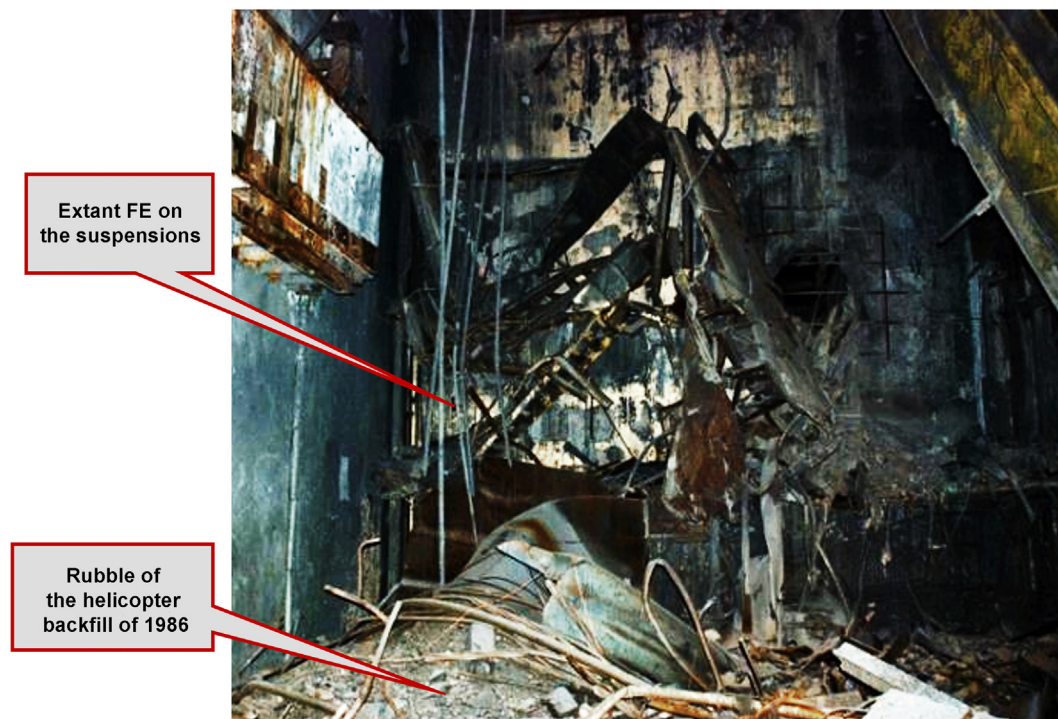


Fig. 2.11 — Rubble and fresh fuel in the CH of the Shelter object

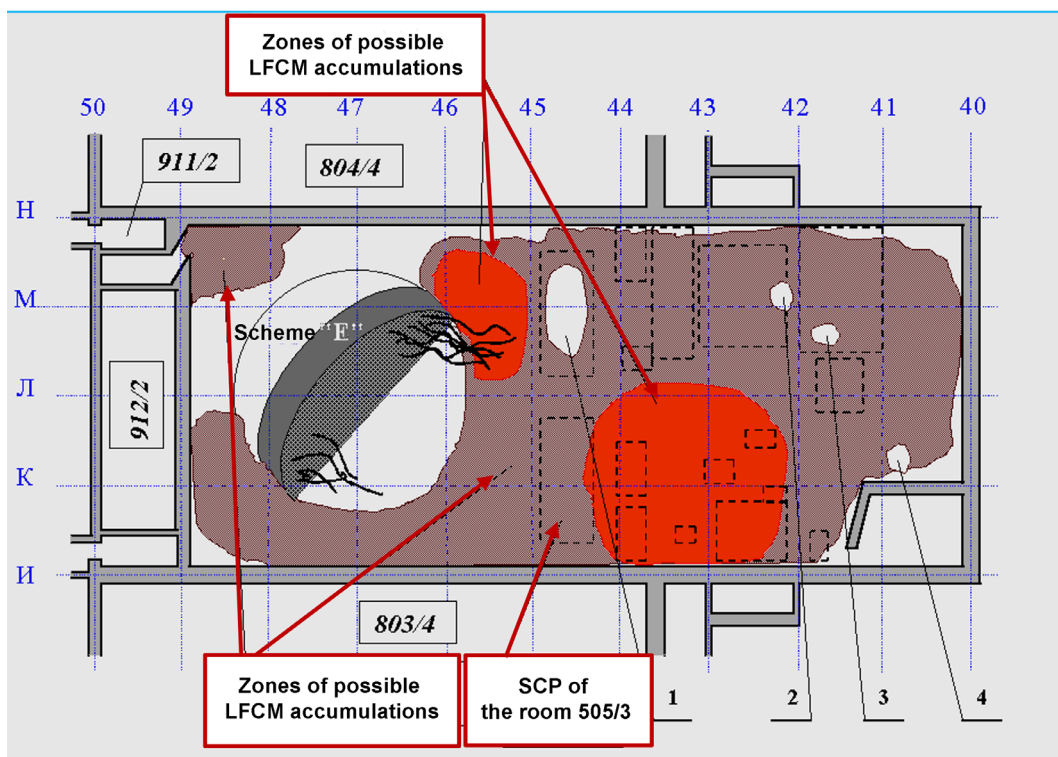


Fig. 2.12 — Location of the areas of expected accumulations of LFCM in the CH:

- 1 — room 505/4 (SCP of spent fuel); 2 — room 219/2;
3 — room 061/2; 4 — room 821/2

Currently, there is no effective control of the FCM subcriticality level and monitoring of neutron activity in the CH. Although the backfill materials should contain neutron absorbers (about 40 t of boron carbide and gadolinium compounds), which were periodically dumped in the ruins of the CH in 1986, ensuring the nuclear safety of FCM accumulations in the CH requires to conduct additional experimental and computational studies and organize at least two or three effective monitoring points for NFD. This must be done before dismantling the unstable building structures of the Shelter object.

2.2 Nuclear hazardous accumulations

The third group includes FCM accumulations, whose nuclear safety is not guaranteed due to insufficiently effective safety barriers, monitoring and control of the subcriticality level. These are potentially the most nuclear hazardous LFCM accumulations in the south-eastern part of room 305/2, which was the epicenter of the interaction of the melt of the reactor core with structural materials.

Until now, room 305/2 remained insufficiently experimentally studied. Drilling was stopped due to high dose loads and a lack of technology for extraction and handling of highly active cores. In 1990, a remote device was constructed (Fig. 2.13), which performed a video recording of the south-eastern part of room 305/2.

According to the materials of photography and video, technical drawings and schemes made by several reconnaissance groups, as well as the results of numerous laboratory studies of samples, it was possible to reconstruct the general appearance of the rubble from various materials contained in room 305/2. To describe the FCM localized here, they were conditionally divided into 7 subzones (Table 2.4, Fig. 2.14) [39, 26].



Fig. 2.13 — Transporting of the remote device to the sub-reactor room 305/2 [38]

**Table 2.4 — Expert assessment of the FCM distribution
in room 305/2 [26]**

Room	Subzone number	Brief description of FCM in the accumulation	FCM volume, m ³	The amount of fuel for uranium, t
305/2	1	Black LFCM, CF, products of interaction of corium melt with concrete	150—180	36 ± 12
	2	Brown and black LFCM, CF (probably)	80—100	25 ± 6
	3	LFCM, lava charge, CF	5—10	3 ± 2
305/2 and 504/2	4	Loose FCM	40—60	3.5 ± 2
	5	LFCM, lava charge, CF, loose FCM	70—100	12 ± 7
	6	Stalactite – LFCM	0.7—1.4	0.2 ± 0.1
305/2	7 (below the mark +9.7)	LFCM, products of interaction of corium melt with concrete	About 20	About 1.5

Subzone 1 — the place of formation of the bulk of LFCM. In this part the south-eastern sector of the reactor support plate was located, which melted during the active stage of the accident. This part of the LFCM array is characterized, in general, by black lavas. The accumulation may contain a site with a high concentration of uranium (up to 50%). At the bottom of this area probably lies a layer of metal. The maximum amount of fuel in the accumulation can be approximately 50 t.

Subzone 2 — the place of formation of brown LFCM. From here, during the active stage of the accident, lava flowed and later formed a large vertical flow. The concrete of the sub-reactor plate was destroyed by the thermal impact. This accumulation contains mostly the brown LFCM. The maximum amount of fuel in the accumulation can reach 30 t.

Subzone 3 — the rubble along the southern wall of room 305/2, formed after the collapse of metal structures. The proposed type of FCM is FE fragments, black and brown LFCM. The volume of the rubble is about 60 m³. Approximately from 1 to 5 t (U) of fuel lies in the rubble — mostly FE fragments.

Subzone 4 — FCM, which were formed during the remelting of the south-eastern sector of the reactor support and the lava charge. The volume is 40...60 m³. This accumulation may contain from 1.6 to 5.4 t of uranium.

Subzone 5 is an accumulation of 50—100 FA. The mass of fuel is from 3 to 6 t. Probably, a layer of LFCM with unmelted fuel was to be formed on the upper plate of the rest of the reactor support in the process of interaction of CF with structural materials. Part of these FCM could get inside the reactor support circuit, due to which there is visual thermal damage to its top plate. The total volume of FCM in the accumulation is 70—100 m³, fuel weight is 12 ± 5 t.

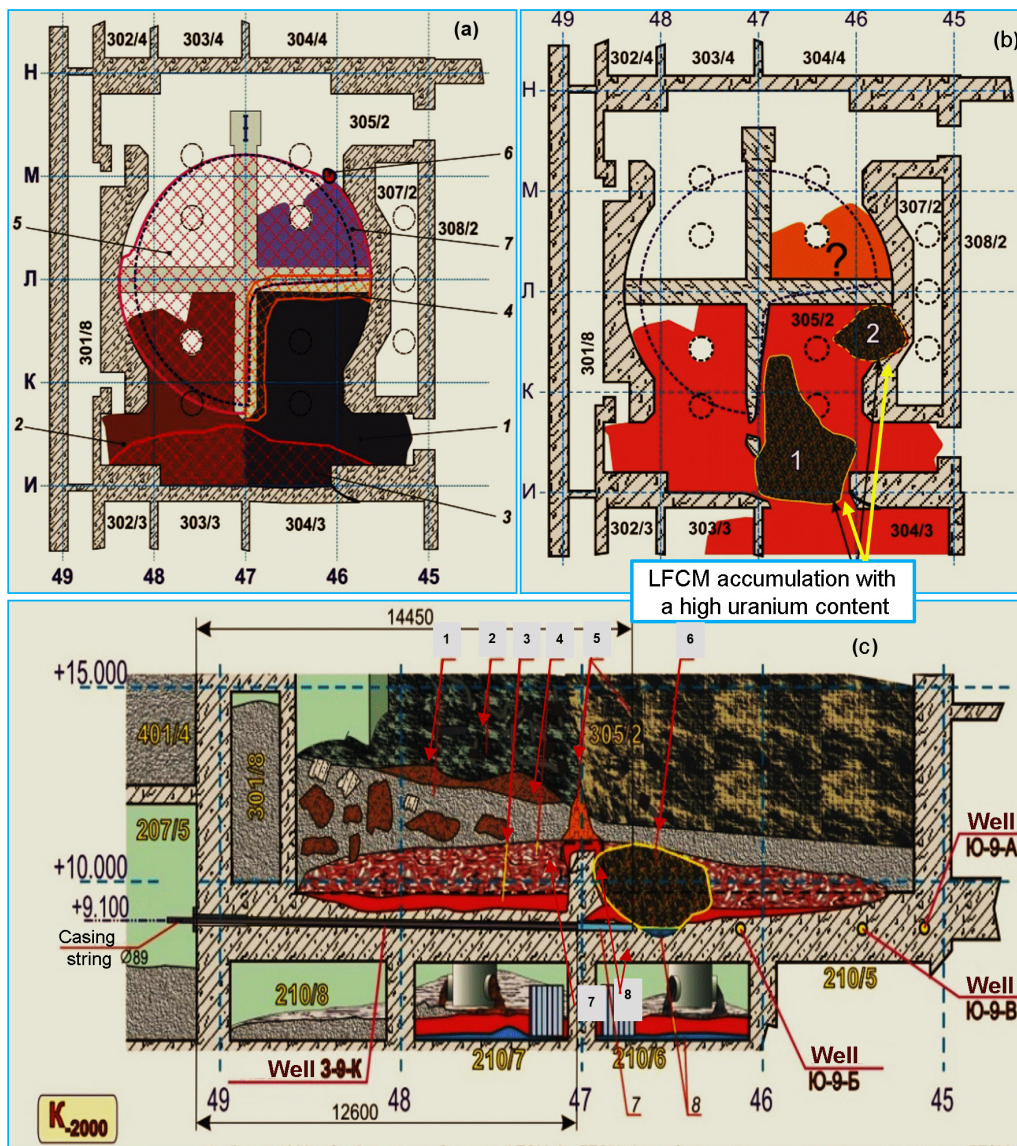


Fig. 2.14 — Location of hypothetically nuclear hazardous LFCM accumulations in room 305/2:
 a — location of subzones 1–7 with LFCM; b — nuclear hazardous zones 1 and 2;
 c — vertical section of the accumulations structure in room 305/2: 1 — concrete in 1986;
 2 — rubble with FCM; 3 — LFCM; 4 — estimated limits of the LFCM spread; 5 — loose FCM,
 6 — LFCM accumulations with a high uranium content; 7 — RW; 8 — radioactive metal

Subzone 6 — polychrome LFCM. This is a LFCM lapping “stalagmite”. The uranium content in the blue samples is approximately 5.7%, in the yellow and brown samples it is 7 and 7.6%, respectively. The total volume of “stalagmite” is about 0.7 m³. The mass of fuel in the accumulation is 100—300 kg (U).

Subzone 7 — LFCM with the products of interaction of the corium melt with concrete.

Accumulations of mostly black and brown LFCM (subzones 1 and 2), formed at the final stage of the accident due to the long high-temperature process of interaction of the melt materials of the core (corium) with structural materials (concrete, serpentinite, gravel, metals), are an integral LFCM array on the floor of room 305/2 (Fig. 2.15). The local nature of the residual heat release of the fuel mainly provided the required heat balance in the area of LFCM formation.

On the temperature cartogram (Fig. 2.16) two epicenters of heat release are clearly distinguished, which determine the temperature regime around two accumulations of fissile materials localized in the zones of concrete penetration of the sub-reactor plate. The epicenter no. 1 is located in the open part of the south-eastern quadrant of room 305/2, opposite the southern sliding gate. The epicenter no. 2 is located in the space between the wall of the pedestal of the support tank of biological protection and the scheme of “support of the reactor” under the pedestal of its base.

Estimation of the boundaries and volume of two accumulations with high concentrations of fissile materials was performed based on experimental data of temperature, neutron, γ -fields, video observations and sampling in 1988—1990 (Fig. 2.17).

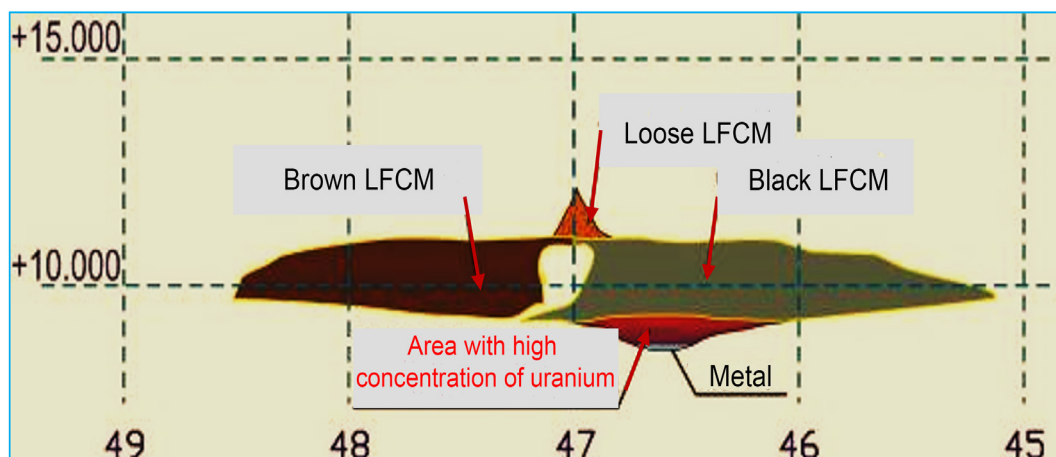
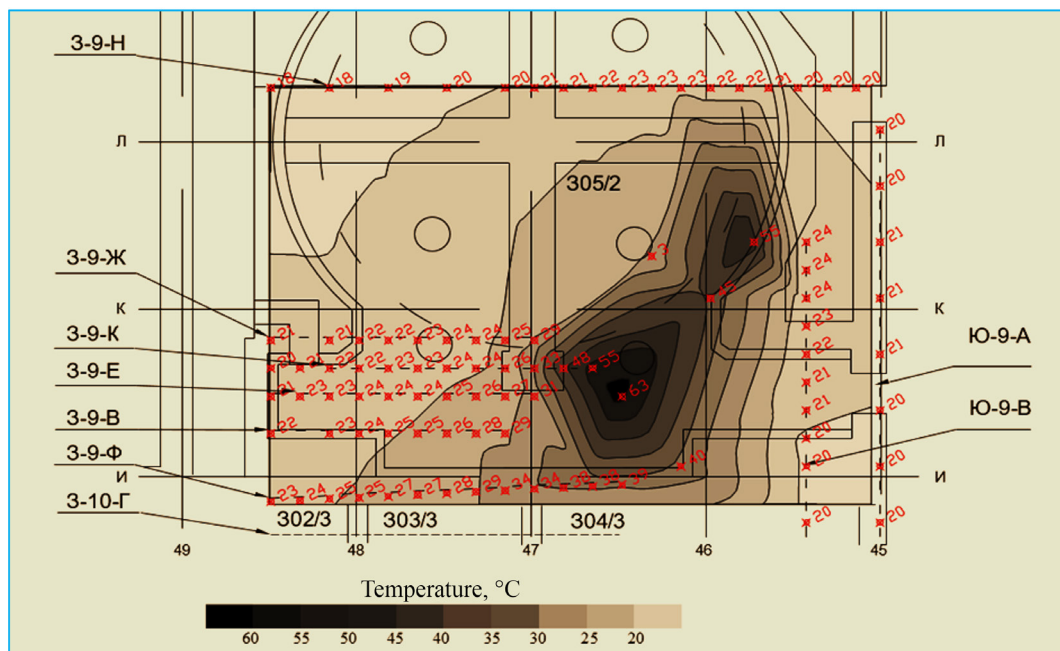


Fig. 2.15 — Layout of LFCM location with a high content of fissile nuclear materials in room 305/2, series K-3000 [26]



The “southern” accumulation with a high concentration of fissile materials is located in the array of the sub-reactor plate directly near the gap in room 304/3 (Fig. 2.18). The data obtained in the process of studying the accumulation periphery show that the steel beam (1) of the emergency support of the “L” scheme is fired at the level of 3—4 m from the plate surface. This indicates the presence of a center of powerful heat generation in this area [40].

The “northern” accumulation with a high concentration of fissile materials is located in the array of the sub-reactor plate in the immediate vicinity of the smelting in the direction of room 307/2 and in the smelting itself. It was formed in the place where the thermodynamic conditions in the front of the interaction of the fuel melt with concrete caused the penetration of the sub-reactor plate. The epicenter of this accumulation lies in the gap between the wall of the support column of the biological protection tank and the support scheme of the reactor under its base (see Fig. 2.18, b). The niche that was visually smelted in the semicircular concrete pedestal support indicates the presence of a heat source under the support of room 307/2. Based on estimates of the nuclear fuel amount and analysis of temperature fields, it is shown that the concentration of fissile material in this area is not less than 30% [41].

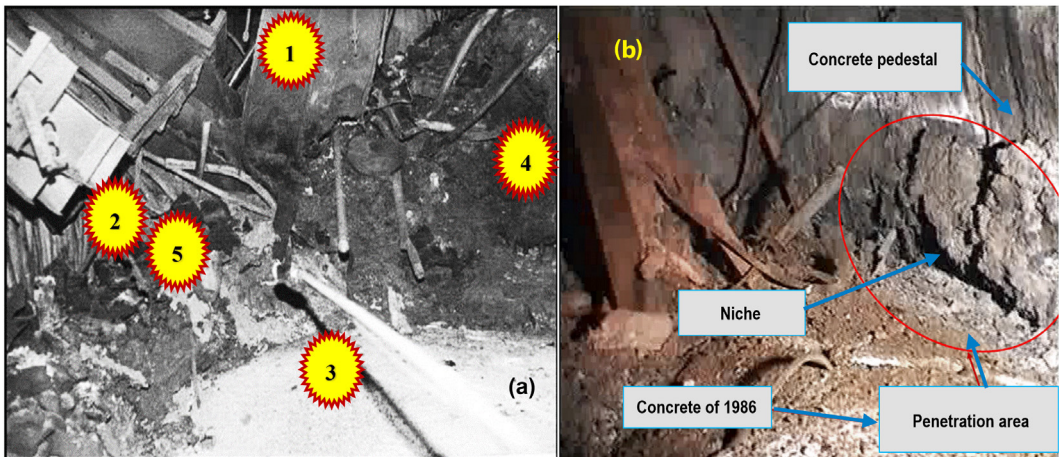


Fig. 2.18 — The results of the external inspection of the localization zones of the LFCM accumulations with high uranium concentration in room 305/2:

a — “southern” LFCM accumulation with a high concentration of fissile materials:

1 — steel beam of additional support scheme “L”; 2 — fragments of lower water communications;
3 — “fresh” concrete of 1986; 4 — loose LFCM; 5 — graphite blocks and fragments of technological channels;

b — “northern” accumulation with a high concentration of fissile materials

The geometry and contours of nuclear hazardous LFCM accumulations were evaluated by the configuration and coordinates of wells drilled in the sub-reactor plate (Fig. 2.19), taking into account the results of the analysis of the material composition of the selected cores [42].

From the west, the “southern” accumulation is limited (drilling was stopped due to a high core activity) by the coordinates of five wells, from the east and north — by drilling

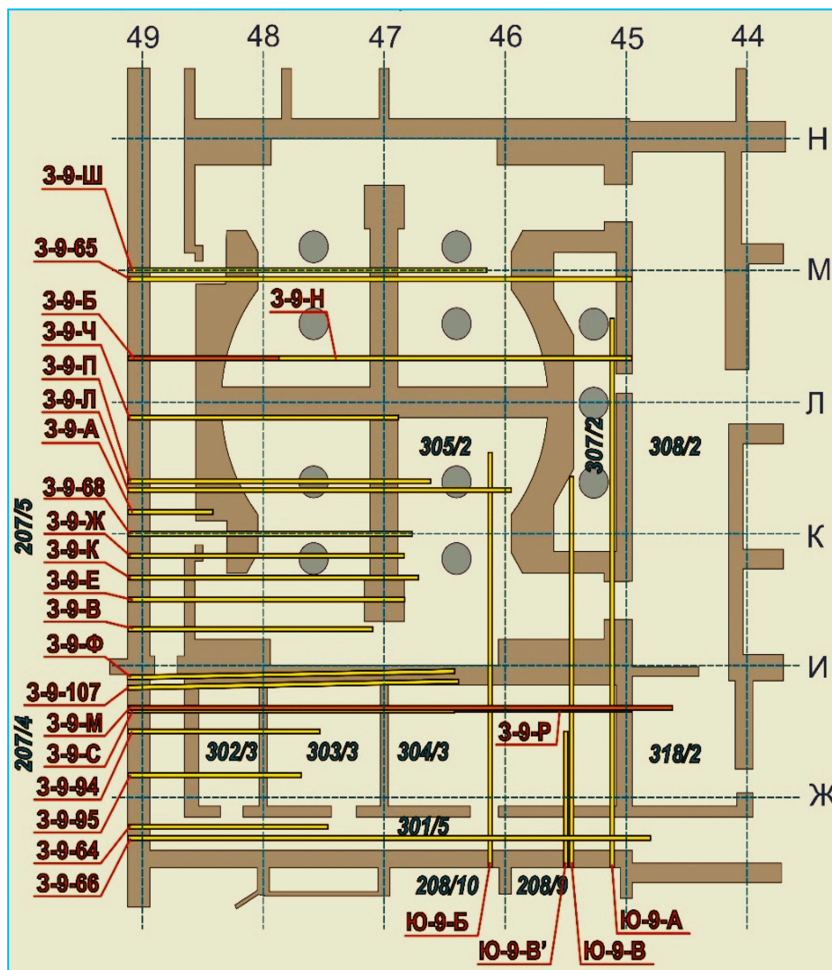


Fig. 2.19 — Horizontal projections of wells drilled in the sub-reactor plate in the area of the mark +9.00 m

wells, from the south — by a wall of room 304/3 and wells drilled in it (see Fig. 2.19). As we approached the boundary of this accumulation, fast growth in NFD (up to $1,000 \text{ n/cm}^2 \cdot \text{s}^{-1}$) was observed in almost all wells. This confirmed that further deep into the well there is a powerful source of neutrons, which could only be accumulations with a high concentration of fissile materials.

According to the results of a set of calculation and experimental studies, it is shown that the LFCM accumulation in two zones of the sub-reactor plate penetration can have a three-layer structure: LFCM at the top, fissile materials of high concentration in the center, and a metal layer at the bottom (Fig. 2.20).

According to the estimation, the total volume of the “southern” accumulation with an increased concentration of fissile materials may be approximately 50 m^3 , and the volume at the epicenter can be $9 \dots 12 \text{ m}^3$. The results of estimates of the characteristics of the epicenter of the “southern” accumulation of fissile materials are given in Table 2.5.

To assess the probability of the existence of a critical composition, the priority task was to determine the amount of nuclear fuel within each LFCM accumulation, so first it was analyzed the experimental data and the results of instrumental measurements [20, 42, 43].

The first measurements of the fuel amount remaining after the accident in the lava were made in 1988—1990 by the integrated thermometric method [44], in 1992 by the balance of ^{137}Cs in the lava [45], and in 1993 by the balance of magnesium [28]. The amount of fuel

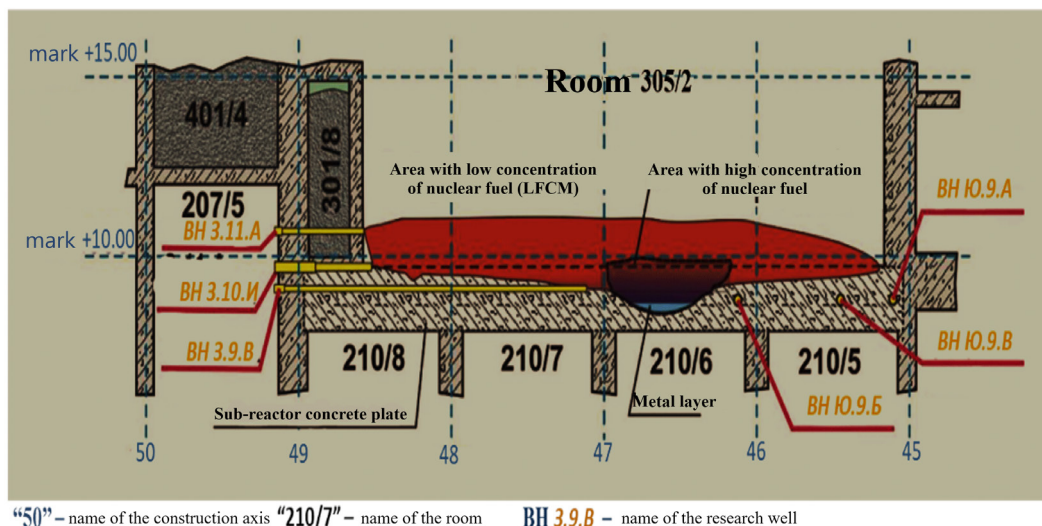


Fig. 2.20 — Three-layer structure of accumulation of nuclear hazardous fissile materials in room 305/2 [41]

in the lava of the sub-reactor rooms was estimated by the visual method [32]. New research, collection and verification of available materials [39, 46] regarding LFCM contained in room 305/2, took place in 1996—1998 (according to the lower estimate, the mass of fuel in room 305/2 is not less than 60 t [46]). The research method consisted of the generalization of direct visual observations (all photo and video shootings) and further complex analysis taking into account the results of elemental and radiochemical analysis of selected samples (more than 100 samples), as well as measurements of NFD, ER and temperature. This enabled to build an album of the most likely profiles for room 305/2 and its cross-sections (a total of 13) every 2 m and estimate the total amount of fuel in room 305/2 [47].

Table 2.5 — Characteristics of the epicenter of the “southern” accumulation of fissile materials [27]

Parameter	Calculation variant		
	1	2	3
FCM density, g/cm ³	6.83—7.95	6.47—7.51	6.34—7.01
Density at the FCM maximum porosity, g/cm ³	3.92—4.48	3.73—4.25	3.67—4.00
Cavern volume in concrete ($h = 1.4$ m)*, m ³	14.10—16.40	14.90—17.30	16.00—17.70
The volume of the accumulation with a high concentration of fissile materials ($h = 0.9$ m)*, m ³	9.05—10.53	9.60—11.13	10.28—11.35
Cavern radius at the mark +9.10, m	1.79—1.93	1.84—1.98	1.91—2.00

* h — height (thickness) of the concrete layer.

In 2002—2010, several theoretical and computational works were carried out, as a result of which adjustments were made to the scenario of Chornobyl lava formation [34—36, 38, 39, 47, 48], a more complete understanding of the mechanism of LFCM formation was provided and the scenario of zones formation with a high content of fissile materials was substantiated. Regardless of the approaches used in estimating the total amount of fuel in room 305/2, quite comparable results were obtained:

according to the Technological Regulations of the Shelter object [49], the FCM accumulations localized in the sub-reactor room contain 75 (+25, –35) t of SFM with an average fuel content of about 26% with an average burnout of 10.8 MW days/kg (U);

nuclear fuel mass according to the results of experimental thermometric studies [50] is 75 ± 25 t (U);

according to the results of the visual-analytical method (division into separate accumulations, averaging of the analyzes data of samples taken from room 305/2) [39] is 85 ± 25 t (U);

the estimate of the amount of fuel given in [47] coincides with the data given in [50];

according to the results of [26], the amount of fuel in room 305/2 is equal to 80 ± 30 t (U).

Consequently, room 305/2 may contain about 80 t of SFM. Of these, only 25 t were detected by visual inspections [32], which indicates the possibility of the existence of “hidden” SFM accumulations weighing 40—50 t.

According to the data obtained during many years of research [41], the balance of the material model of the formation of SFM accumulations in the room 305/2 was compiled and the discrepancies were eliminated between the experimental data obtained from thermometric measurements and the available analytical estimates. After performing additional works (including thermophysical calculations [26, 41]), the material balance was compiled for the room 305/2 (Fig. 2.21) and the FCM amount was estimated in two zones with a high concentration of SFM: 18 ± 5 t (U) in the “southern” accumulation and 5 ± 3 t in the “northern” one.

It is estimated that the critical mass of low-enriched uranium up to 2% (^{235}U) varies widely: from 0.2 t to tens of tonnes, depending on the material composition, especially humidity, density, geometry, etc. [48]. At the same time, the document ПБЯ-06-00-88 [51, p. 2.18] regulates the possibility of self-sustaining chain reaction (SSCR) in the accumulation of fissile materials, the enrichment of which at ^{235}U exceeds 1%, if the total isotope mass is more than 300 g.

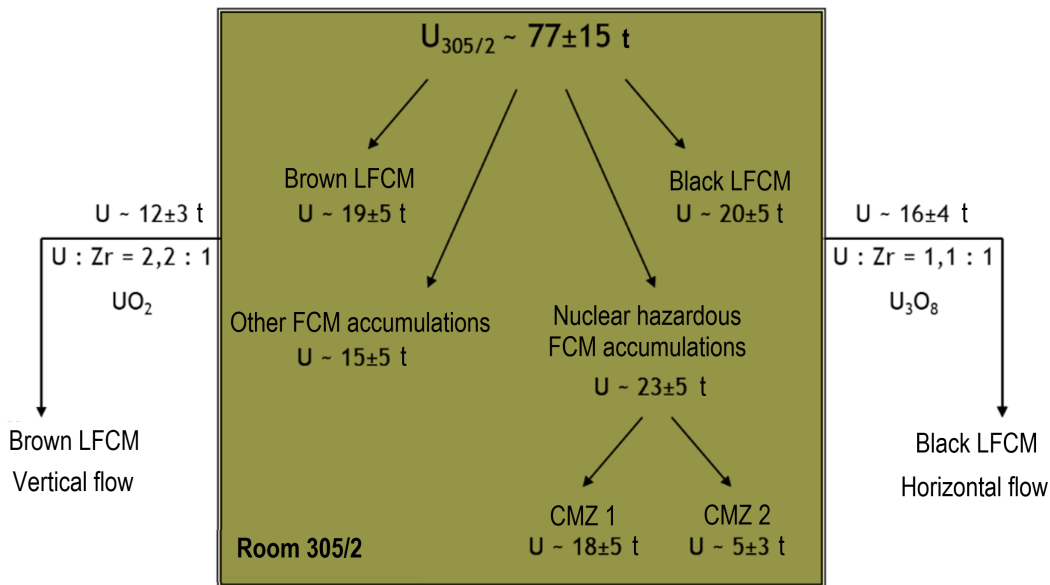


Fig. 2.21 — Scheme of nuclear fuel balance in the room 305/2
(CMZ — critical mass zone)

According to the calculations of the neutron-physical parameters of the humidified silicate fuel mixture and the analysis of temperature fields in the concrete of the support plate in the south-eastern sector of the sub-reactor room 305/2, the fuel mass in FCM accumulations is up to 20 t (U) with enrichment of about 1.15% (^{235}U). Within such limits, the existence of a critical composition and, as a consequence, the SSCR emergence is possible. In June 1990, a critical incident was reported after water penetration.

Regarding the “northern” accumulation with a high concentration of fissile materials, preliminary estimates of the fuel amount give reason to believe that the existence of a critical composition in this FCM accumulation is unlikely. However, based on the version of the corium origin of this accumulation, an elemental composition is obtained, at which the mass of uranium required for the existence of a critical composition may not exceed 5 t. Then the “northern” FCM accumulation can also be potentially nuclear hazardous.

So, in room 305/2 two compositions of SFM can be located with a high probability. Therefore, there is an urgent need to develop and implement measures to improve the control of their subcriticality level and technical solutions for preventive suppression or elimination of the possibility of SSCR occurrence there [39].

2.3 Destruction of lava-like fuel containing materials and predictive estimates of their behavior

Analyzing the LFCM state for 35 years after the 1986 accident, we can conclude that compared with surveys conducted in the early years [21, 52], the mechanical strength of black and brown LFCM has been decreased slightly, and the mechanical strength of polychrome LFCM remains stable. The main factors contributing to the LFCM destruction are water, temperature changes and self-irradiation during γ -, β -, α -decay of fission products and transuranic elements.

Mechanical destruction of the black LFCM occurred in places of their contact with water, which is typical for several rooms. For example, during observations, the “stalactites” properties in room 217/2 almost did not change. This is because the “fresh” concrete that flowed in room 217/2 from north to south, solidified and formed a kind of inclined plane that prevents water from coming into contact with the “stalactites”.

Another situation is with the “elephant’s foot” (Fig. 2.22), which is located in the same room and is constantly exposed to water. In 1992, an experiment was conducted to investigate the properties of dust generated on its surface. A gauze swab impregnated with a special adhesive was placed on the lava surface. After hardening of glue and gluing of gauze to a surface, an effort was made to tear off the swab, as well as FCM particles with it. However, with the detachment of the swab, a large part of the surface layer of lava in the form of fragments of several centimeters in size was easily separated together with it. The result was unexpected, because during the sampling of the “elephant’s foot” that was carried out in the first years after the accident, small arms had to be used because of the FCM location.

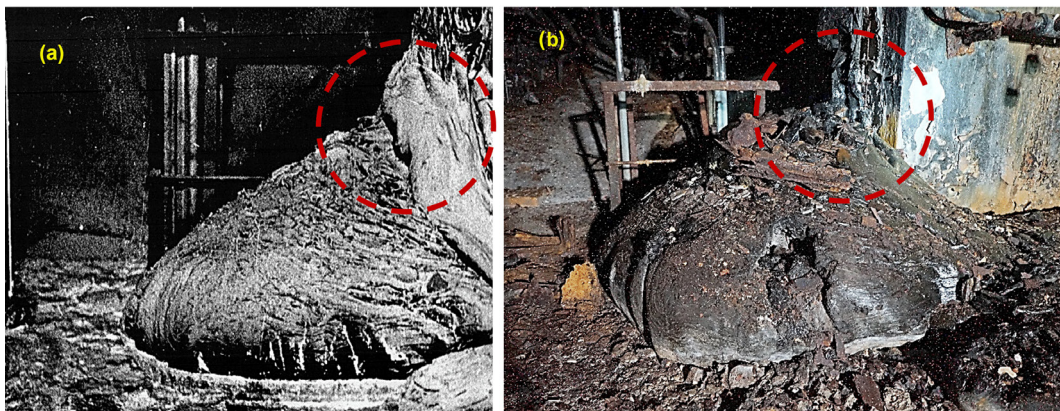


Fig. 2.22 — Destruction of the LFCM accumulation “elephant’s foot” (room 217/2):
a — photo of 1993; *b* — photo of 2013

A similar pattern is observed in PSP-1 (Fig. 2.23). After inspecting this area in 1988, the presence of a lava layer in the form of a solid mass was spotted. A few years later, under the influence of water, which periodically flooded this area of the floor, the lava was decomposed.

The destructive effect of moisture and temperature differential on the mechanical properties of LFCM is confirmed by the fact that in the dry and relatively stable temperature in room 304/3 the black LFCM fragments did not undergo noticeable changes and remained the same as during the first surveys in 1988—1990.

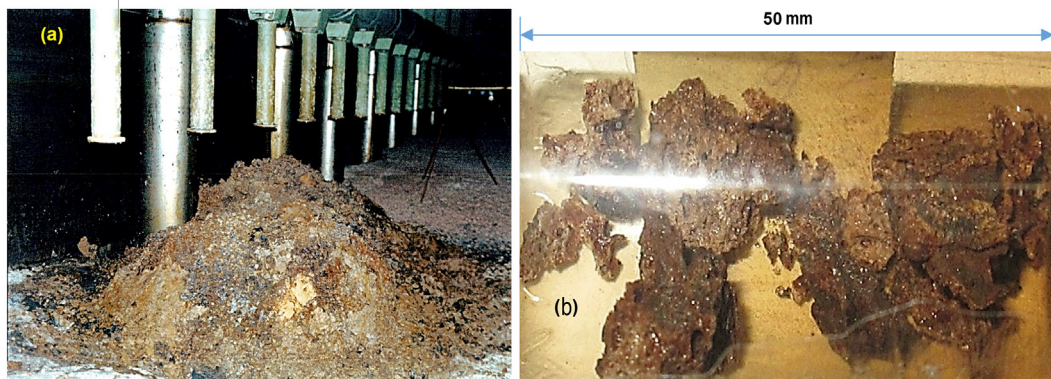


Fig. 2.23 — Destruction of the LFCM accumulation on the first floor of the PSP (room 012/7):
a — photo of 1993; *b* — photo of 2020

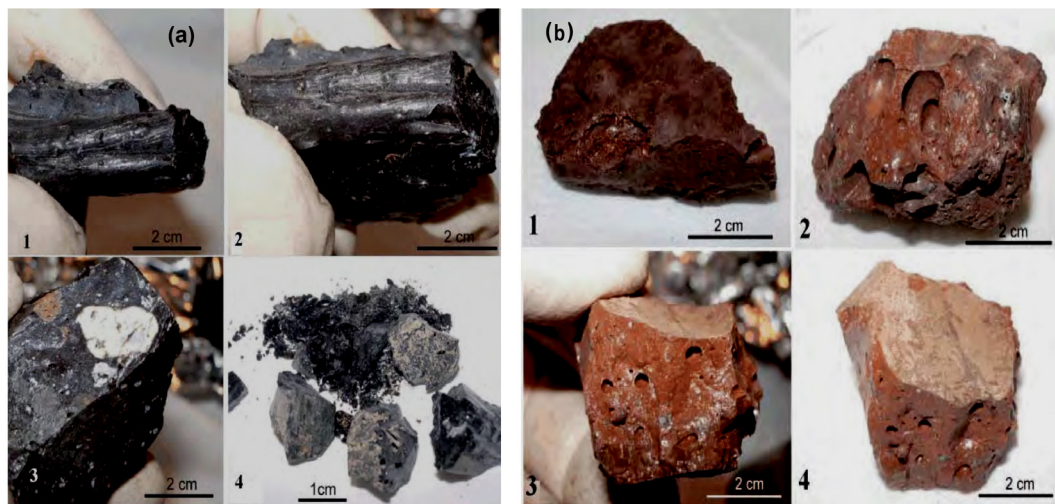


Fig. 2.24 — Appearance of LFCM samples taken in 1990 and stored at the V. G. Khlopin Radium Institute: *a* — black LFCM; *b* — brown LFCM



Fig. 2.25 — Brown LFCM in the valve of room 210/7

It is to be recalled that in rooms with high humidity in 1990 on a surface of black LFCM the “yellow spots” were found which gradually occupy the area more and more. This phenomenon is also explained by chemical changes in the LFCM material under the influence of water or its vapor.

The main part of LFCM samples, which were stored in laboratory premises and were not exposed to temperatures and humidity, did not change virtually (Fig. 2.24). As of 2011, only a sample of black ceramics was destroyed (number 4 in Fig. 2.24, *a*) [52, 21].

Analysis of the data shows that the brown LFCM have undergone the slightest changes in their properties: the strength of the brown LFCM samples during storage has been hardly changed. The same can be said about room 210/7, as special changes of the brown LFCM are noticed neither in the fourth valve nor on the floor (Fig. 2.25). There is an increase in cracks in the solidified mass of the brown LFCM, which can be caused by seasonal temperature fluctuations.

The pumice-like LFCM on the first and second floors of the PSP were changed most noticeably due to temperature differences and direct contact with water (Fig. 2.26).

Approximately 10 years after the accident, the properties of slag-like LFCM changed significantly [53]. First, the vitreous crust cracked, became brittle and lamellate. Secondly, the slag accumulations on the ground and first floors of the PSP have lost their monolithic and become brittle — when pressed, the granules crumble. Inside them, the slag strength is greater than on the surface. However, this strength assessment is very subjective. It is established that where the contact of the heap with the environment is less, its strength is greater.

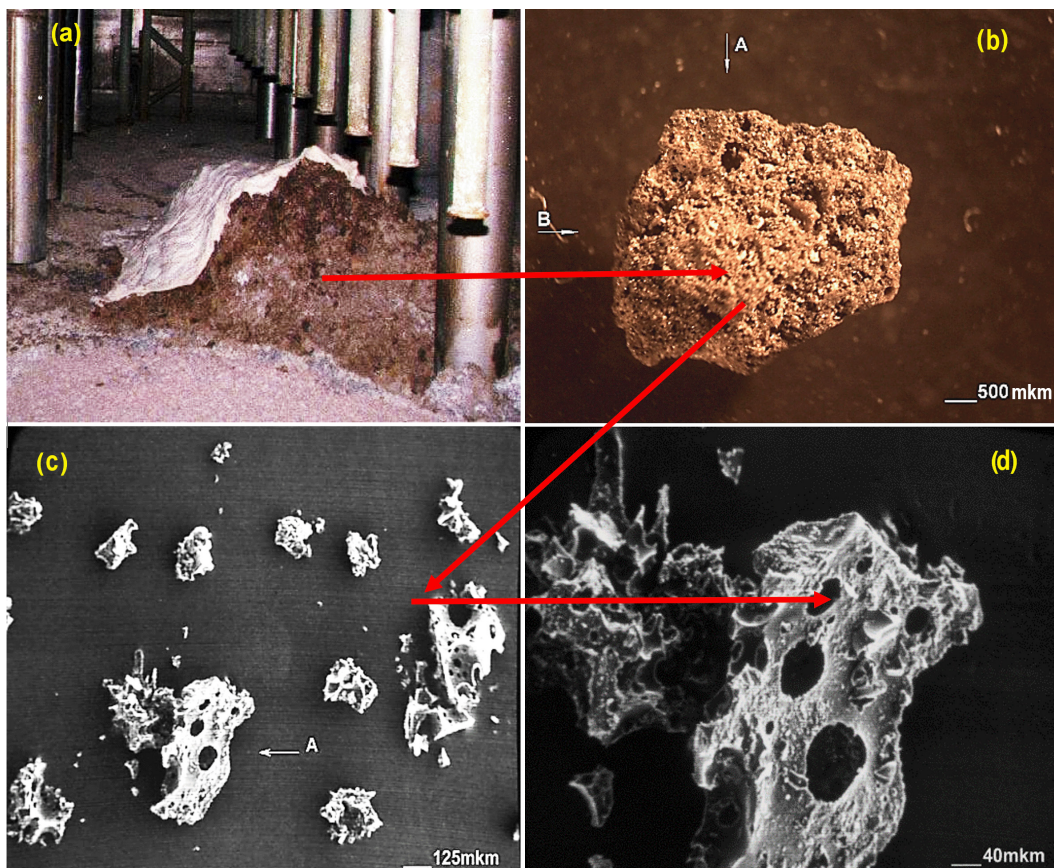


Fig. 2.26 — General view of the pumice-like LFCM accumulation in room 012/7:
a — accumulations of pumice-like LFCM in room 012/7 on the ground floor of PSP;
b — an LFCM sample from this accumulation; *c*, *d* — the destruction of the LFCM sample
 from room 012/7 into fragments of 10—100 μm in size

As can be seen in Fig. 2.26 at high magnification, on the surface of LFCM particles there are crystalline formations with sizes from 1 to 5 μm . This is due to the recrystallization of some compounds and the deposition of trace amounts of salts on the LFCM surface under the influence of water and temperature gradients.

The review [54] shows the possibility of LFCM destruction in the case of freezing water in the pores. Indeed, the pores in LFCM are accessible for water, which can freeze in winter, significantly increasing in volume. It is known from practice that this kind of process is the cause of the destruction of rocks. But this is not the case with LFCM, because the lavas have molecular sieve properties, and most of the available porosity is occupied by water molecules embedded in silicate cycles. Such water at low temperatures does not form ice crystals and does not destroy silicate cycles. This point of view has been experimentally confirmed: after several hundred cycles of repeated cooling and heating of water-saturated LFCM in the range from -20 to $+50$ $^{\circ}\text{C}$ with simultaneous optical microscopy of existing (specially grown) microcracks [53, 54] no crack growth was observed. Another thing is that the presence of frozen water in large cavities of the accumulations can lead to their wedging and the division of the accumulation into smaller fragments, which happens regularly in the Shelter object and is confirmed by many visual observations.

Observations and analysis of literature data show that the main factor influencing the transformation of LFCM accumulations is water. Under its influence, the largest structural changes underwent “pumice”, slag (accumulations of the ground and first floors of the PSP) and black LFCM. Brown and polychrome LFCM underwent minimal structural changes because they were the least in contact with water and were not exposed to significant temperature changes. We should note that the destruction of accumulations in the object occurs at the macro level also. Due to the heterogeneous composition, different cooling conditions, etc., many of them easily break down into separate, more homogeneous and more resistant to external influences fragments.

Another confirmation of the negative effects of moisture was given by the study of LFCM leaching. It is proved that the fast-dissolving part of LFCM characterizes the amount of submicron fraction on the surface of LFCM samples, which is washed away at the first moment of contact with solutions. The slowly soluble fraction (dissolved radionuclides on the surface of microcracks) characterizes the direct dissolution of the LFCM matrix and the process of diffusion of radionuclides from the depth of the fragments to the surface and dissolution.

Analysis of the obtained data shows that under adverse conditions, in the case of the LFCM destruction into fragments of 3–5 mm in the water of the Shelter object, black LFCM will dissolve in about 1,400 years, brown ones in 5,800 years, and polychrome ones in more than 10,000 years. At the same time, about 0.08–0.2% of brown and black LFCM were dissolved in the first months of contact with water.

After the NSC construction, the main factors of the LFCM destruction have been eliminated. Precipitation intake stopped, the temperature stabilized, and the amount of condensing moisture decreased. The process of the LFCM degradation will slow down and will be determined mainly by the formation of microcracks and pores due to self-irradiation with α -particles.

The dynamics of the LFCM state is closely related to the influence of processes that cause their dispersion and leaching of radionuclides. Over time, this increases the amount of radioactive dust in the Shelter object. Despite the significant amount of research, the mechanisms of FCM degradation can not yet be considered well-established.

Studies of the oxidation process of nuclear fuel in the air [55] using magnetic susceptibility measurements determined the degree of oxidation of irradiated and unirradiated nuclear fuel. The degree of U_3O_8 formation on the surface of UO_2 was calculated experimentally. The results showed that the oxidation process for irradiated fuel is slower than for fresh one.

Today, it is considered that nuclear fuel, which is in the Shelter object in the form of CF (fuel pellets, FA and their fragments), is quite stable given the environmental conditions of the facility.

Previous studies of LFCM have considered only three main mechanisms of their degradation: the destruction of the LFCM surface and, as a consequence, generation of the RA; the appearance on the surface of LFCM new growths in the form of uranium compounds; radionuclides leaching with LFCM water. Over time, under the influence of various factors due to physicochemical processes, the state and properties of fuel containing materials change, which worsens the state of radiation safety of the Shelter object. Currently, there are three main processes of LFCM degradation are observed [3, 56]:

- cracking of lavas into rather rough pieces (see Fig. 2.22);

- destruction with the formation of radioactive dust;

- radionuclides leaching in the interaction of lava with water and the formation of new soluble chemical compounds.

The dust-generating capacity of LFCM and irradiated nuclear fuel is their inherent property and takes place without the action of additional external factors [54, 56]. At least several tens of kilograms of irradiated fuel are converted into dust annually at the Shelter object through a spontaneous dust generation mechanism. The physics of this phenomenon is quite complex and not fully understood. The probable cause of such spontaneous dust generation is the specific nature of objects. LFCM and irradiated nuclear fuel is highly radioactive dielectrics that produce a flux of β -particles from the surface with a current density of up to 0.1 nA/cm^2 , which causes the presence of noticeable gradients of electric potential and mechanical stress on their surface. Electrostatic interactions provide both dust-generating ability and high mobility of the dispersed phase separated from the surface [57]. The phenomenon of spontaneous dust formation by the surface of LFCM and irradiated fuel was first reliably recorded experimentally in 1997 [58].

As an example, we consider the results of studies of samples taken in 2014 in room 012/7. The LFCM sample had the highest specific radioactivity. Particles localized by digital and track autoradiography were isolated and studied by a set of methods [59]. The size of the detected particles reached 200 μm . According to their morphology, it can be assumed that these are fragments of mechanically destroyed porous glass. Inside the glass matrix, inclusions of the U-Zr-O phase ranging in size from units to tens of microns with different ratios of U and Zr were observed (Fig. 2.27). According to electron microscopy and X-ray tomography, these inclusions are dendrites of uranium dioxide mixed with structural zirconium. Examination of one of the samples on a single crystal diffractometer showed that the dendrites probably consisted of several (at least five) UO_{2+x} single crystals. Accumulations of needle crystals containing Na-U-S-O (without Zr), and they are probably water-soluble uranium sulfates, were found on the surfaces of cavities (probably bubbles) (Fig. 2.27, b).

The obtained results show that spontaneously destroyed fragments of LFCM in room 012/7 were the source of radioactive particles that got into the cuvette. Observation and detailed analysis of them are needed to study and predict the behavior of materials formed as a result of the accident.

Attempts to experimentally study the LFCM by X-ray diffraction analysis have not helped to elucidate in detail the mechanisms of LFCM degradation [60], so LFCM cannot be studied by standard techniques and with conventional equipment. For this purpose it is necessary to develop special methods, and also to use modern research equipment. After modernization of the X-ray diffractometer DRON-4M in the ISP NPP the phase structure

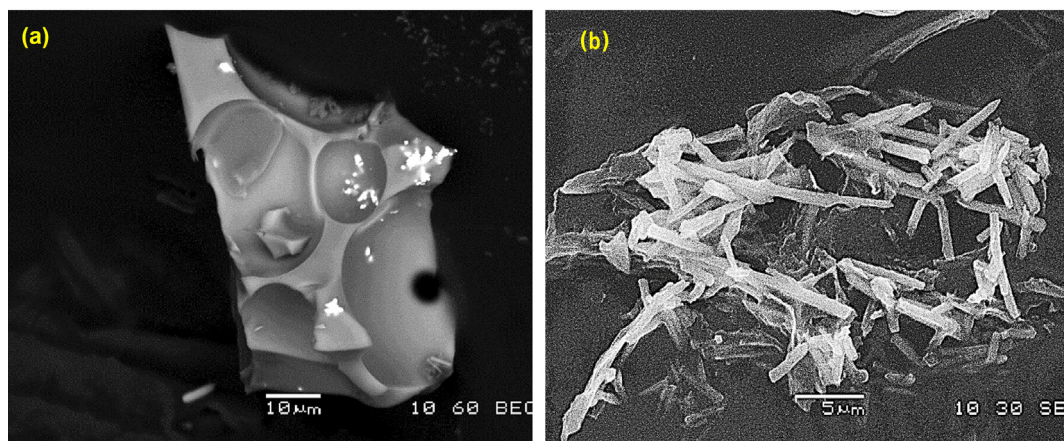


Fig. 2.27 — SEM images of fine-sized samples collected on a planchet in room 012/7:
a — a fragment of a vitreous matrix with inclusions of U-Zr-O phase;
b — needle-shaped crystals on the surface of the glass fragment

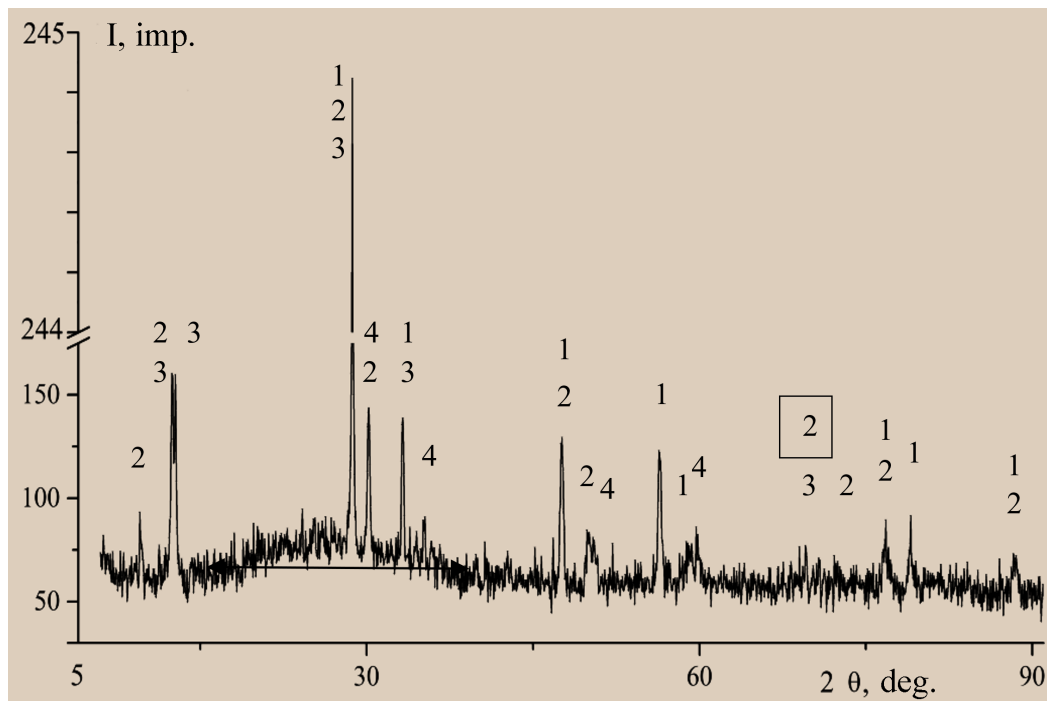


Fig. 2.28 — Diffraction pattern of brown ceramics:

1 — uranium oxide $\text{UO}_{2,34}$; 2 — uranium silicate USiO_7 ; 3 — orthorhombic silicon oxide SiO_2 ;
4 — cubic zirconium oxide ZrO_2

of crystalline phases in all types of lavas was investigated. The example of brown ceramics [61] shows the presence not only of uranium oxide but also uranium silicate, silicon oxide and cubic zirconium oxide (Fig. 2.28).

Due to the developed method of detection of low-intensity X-ray lines using X-ray phase analysis of materials that contain many (more than eight) crystalline phases with low content (from several percent to several tenths of a percent by weight), it was possible to significantly expand the list of crystalline phases in the LFCM. This method is based on the calculation of correlations using computer statistical approaches. The correlation diffraction pattern is shown in Fig. 2.29 [62].

The data of the correlation diffraction pattern allowed not only to increase the reliability of identification (number of reflections) of the mentioned crystalline phases ($\text{UO}_{2,34}$, USiO_7 , orthorhombic SiO_2 and cubic ZrO_2) but also to establish the presence of a sample of tetragonal zirconium oxide ZrO_2 , several phases of silicon oxide SiO_2 , zirconium silicate ZrSiO_4 , calcium silicate Ca_2SiO_4 and aluminum silicate Al_2SiO_5 (Fig. 2.29).

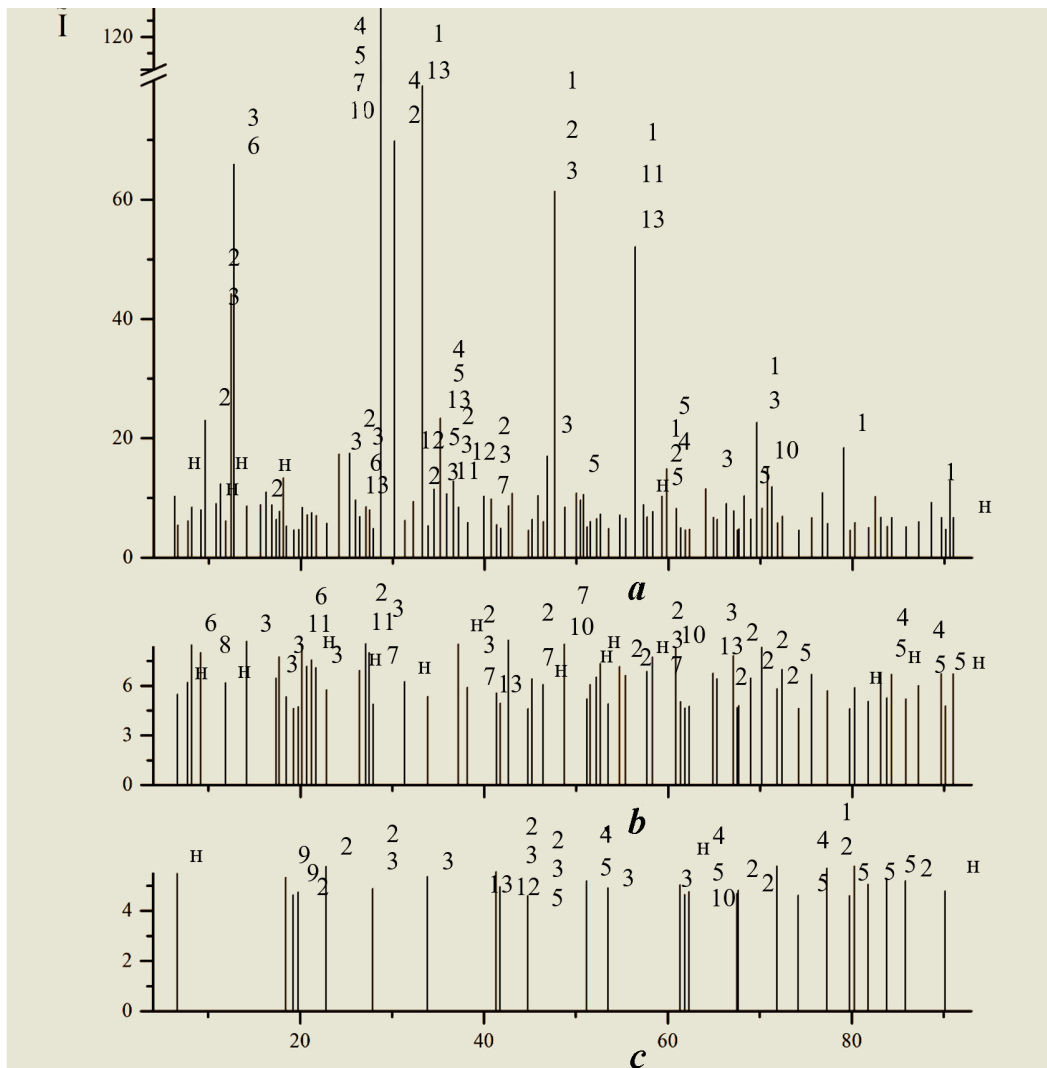


Fig. 2.29 — Diffraction pattern of the sample of brown ceramics:

a — correlation diffraction pattern; *b* — areas of correlation diffraction pattern with reflections less than 8 impulses; *c* — the area of the correlation diffraction pattern with reflections less than 5.5 imp: 1 — $\text{UO}_{2.34}$; 2 — USiO_7 ; 3 — orthorhombic (1) SiO_2 ; 4 — cubic ZrO_2 ; 5 — tetragonal ZrO_2 ; 6 — orthorhombic (2) SiO_2 ; 7 — trigonal (1) SiO_2 ; 8 — tetragonal (1) SiO_2 ; 9 — trigonal (2) SiO_2 ; 10 — tetragonal (2) SiO_2 ; 11 — ZrSiO_4 ; 12 — Ca_2SiO_4 ; 13 — Al_2SiO_5 ; *H* — unidentified reflections

According to the obtained data of the phase composition of brown ceramics, the model of the evolution of the LFCM microstructure was updated. It has been established that the behavior of LFCM is determined not by one or more physical and chemical processes, but by their relationship and interaction.

Schematically, the microstructure of brown LFCM ceramics, taking into account the new data, is presented in Fig. 2.30. Inclusions of uranium oxides are now represented by uranium oxide $\text{UO}_{2,34}$. Instead of zirconium-uranium-oxygen phase $(\text{U,Zr})\text{O}_x$, there are zirconium oxide inclusions that have a cubic and tetragonal structure. The crystalline phases of zirconium oxides are the result of crystallization (at least the part) of the amorphous zirconium-uranium-oxygen phase $(\text{U,Zr})\text{O}_x$ after the accident. There are also inclusions of zirconium silicate, known as chernobylite $(\text{Zr,U})\text{SiO}_4$. Recently discovered uranium-silicate-hydrate of potassium-sodium $(\text{K,Na})_2(\text{UO}_2)_2(\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$ (mineral weeksite), is most likely located in the contact zone of uranium oxide UO_x and silicate glass phase on the surface of uranium oxide inclusions. It was formed as a result of the interaction of uranium oxide, inclusions of uranium oxide and oxides of silicon, sodium and potassium of the glass

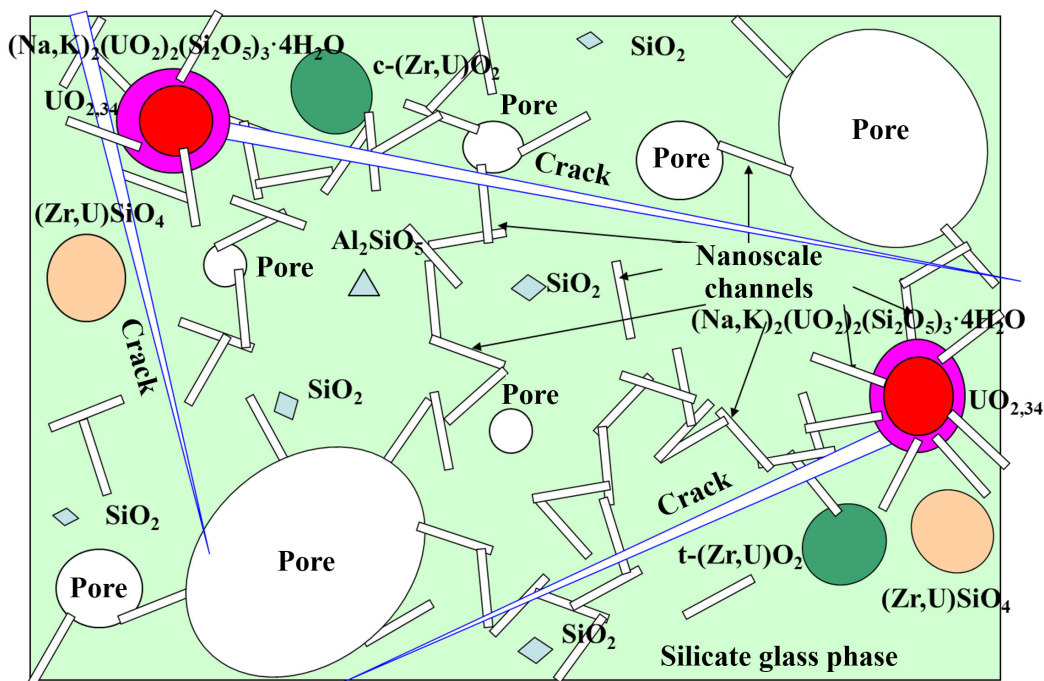


Fig. 2.30 — Scheme of the microstructure of the brown LFCM ceramics taking into account the new data

phase of LFCM and water. The silicate glass phase of LFCM contains several previously unknown phases of silicon oxide SiO_2 : orthorhombic (1), orthorhombic (2), trigonal and possibly tetragonal. Also in the silicate glass phase, there is aluminum silicate Al_2SiO_5 and possibly calcium silicate Ca_2SiO_4 . All phases of silicon oxide and silicates were formed partly due to the crystallization of the multicomponent silicate melt during its cooling at the time of the accident and partly due to the crystallization of the glass phase for a long time after the accident.

The pore space of brown ceramics is represented by large and small gas pores, cracks and nanosized pore channels (see Fig. 2.30) [63, 64]. The volume of gas pores has not been changed. There is no significant increase in the volume of cracks and nanosized pore channels. Nanosized pore channels penetrate the glass phase and all crystalline inclusions of brown ceramics. They connect gas pores and cracks with the external environment.

In 2016, under creating a model of the evolution of the LFCM microstructure, among the large number of physical and chemical processes that took place in LFCM for 30 years after the accident, the following processes were identified that determined the formation of their microstructure [65]:

- formation of open pore channels in LFCM due to the combination of at least part of the tracks of α -particles formed during the α -decay of radionuclides;

- penetration of oxygen of air into inclusions of uranium oxides through open nanosized pore channels;

- oxygen oxidation of uranium oxide UO_2 in inclusions;

- formation of the LFCM cracks due to increased volume of uranium oxide inclusions;

- penetration of water into the LFCM through cracks to inclusions of uranium oxides;

- destruction of the LFCM with temperature fluctuations due to changing the physical state of water which is contained in gas pores and cracks;

- interaction of water and dissolved in it salts and gases with uranium oxides and products of activation, formation of hydrates and soluble compounds of uranium and transuranic elements.

Updating the model of the evolution of the LFCM microstructure, to the already identified physical and chemical processes we should add two more:

- radiation-stimulated phase formation of uranyl silicate of sodium-potassium hydrate $(\text{Na,K})_2(\text{UO}_2)_2(\text{Si}_2\text{O}_5) \cdot 4\text{H}_2\text{O}$;

- crystallization of the phases of silicon oxide SiO_2 (orthorhombic (1), orthorhombic (2), trigonal and possibly tetragonal), aluminum silicate Al_2SiO_5 and possibly calcium silicate Ca_2SiO_4 in silicate glass phase and possible crystallization of cubic and tetragonal zirconium or uranium-oxygen phase $(\text{Zr,U})\text{O}_x$.

In 2016, in the model of the evolution of the LFCM microstructure, the stages of evolution of the microstructure of the LFCM internal volume were identified, their sequence was determined and their duration was estimated.

Stage 1 — the formation of open porosity, which is the result of combining closed spherical pores with newly formed nanosized pore channels. They are also the result of combining α -particles tracks accumulated in the material. The stage began after the accident, the duration is up to 10...12 years.

Stage 2 — oxidation of uranium oxides UO_x in the LFCM inclusions due to the penetration of air through open nanosized pore channels. The stage began after the end of stage 1 (1996—1998), duration is from three to five decades up to the LFCM destruction.

Stage 3 — formation of the LFCM crack due to the increase in the volume of inclusions of uranium oxides UO_x during their oxidation. It began in 2004—2011, the duration is from three to five decades up to the LFCM destruction.

Stage 4 — penetration of water into the LFCM through cracks and its interaction with the inclusions of uranium oxides; release of uranium salts from inclusions into the environment; destruction of the LFCM part due to repeated freezing and thawing of water in pores and cracks; release of uranium oxide particles UO_x in the environment. Beginning — 2004...2011. After the completion of the NSC construction, this stage has practically been stopped. Atmospheric precipitation does not penetrate the NSC, and the processes of stage 4 are significantly slowed down.

According to the new data on the LFCM phase composition, obtained in 2016—2020, there are two more stages in the evolution of the microstructure of the internal volume of LFCM.

Stage 5 — radiation-stimulated phase formation of uranyl silicate of sodium-potassium hydrate $(\text{Na,K})_2(\text{UO}_2)_2(\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$. Beginning — 1996...1998 (probably later, 2004...2011). The gradual development of the process of radiation-stimulated phase formation of uranyl silicate of sodium-potassium hydrate will take five to seven decades until the full “use” of uranium oxide in the inclusions.

Stage 6 — crystallization of amorphous phases of LFCM: glass phase with the formation of several phases of silicon oxide SiO_2 , aluminum silicate Al_2SiO_5 and possibly calcium silicate Ca_2SiO_4 , as well as the amorphous phase $(\text{Zr,U})\text{O}_x$ with the formation of cubic and tetragonal oxides. Beginning — after the accident, it will last from four to six decades up to the transition to the crystalline state of the glass phase of LFCM and the amorphous phase $(\text{Zr,U})\text{O}_x$.

Brown ceramics is currently in stages 2, 3, 5 and 6.

The proposed updated model of microstructure evolution makes it possible to predict the LFCM behavior in the short and long term. The LFCM self-irradiation will continue. It is difficult to say whether the volume of nanosized pore channels will increase; it has hardly changed in the last five years. The oxidation process of uranium oxide UO_x in the inclusions will continue. The volume of cracks, their length and possibly the number will increase with the volume of uranium oxide inclusions. The penetration of water into the LFCM through the cracks to the inclusions of uranium oxides in the NSC has already significantly slowed

down. The interaction of water with uranium oxide UO_x , the formation of hydrates and soluble uranium compounds were almost stopped. Radiation-stimulated phase formation of uranyl silicate of sodium-potassium hydrate $(\text{Na,K})_2(\text{UO}_2)_2(\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$ will continue. Crystallization of the phases of silicon oxide SiO_2 and silicates in the silicate glass phase will also continue, as well as the possible crystallization of cubic and tetragonal zirconium oxides ZrO_2 in the amorphous zirconium-uranium-oxygen phase $(\text{Zr,U})\text{O}_x$.

According to the equilibrium stable diagram “uranium — oxygen”, uranium oxides have a cubic lattice from uranium oxide UO_2 to oxide $\text{UO}_{2.25}$. In the inclusions of brown LFCM ceramics, uranium oxide $\text{UO}_{2.34}$ exists with a cubic lattice because these inclusions have a compressed state of the glass phase. However, during the oxidation process, the stoichiometric oxygen factor will increase, the volume of inclusions will increase, and the number and length and width of cracks will increase. After reaching the threshold values of the concentration of cracks and their length, LFCM will begin to break down into particles of material with an average size of 100—200 μm (size range — from 50 to 500 μm) because they can not withstand even its own weight. These glass phase particles will contain uranium, products of fission and activation. All inclusions of uranium oxides will get outside the LFCM. There will be no stresses compressing the inclusions in the destroyed material, cubic uranium oxide UO_x with a value of x greater than 2.34 will pass into a mixture of oxides: cubic uranium oxide $\text{UO}_{2.25}$ and orthorhombic uranium oxide U_3O_8 . With the transformation of the cubic lattice into an orthorhombic one, the grains of uranium oxide will break down to the size of a few microns, and some of them, possibly, to the submicron level. These particles of uranium oxide UO_x are the most dangerous.

When the value of x reaches 2.66, uranium oxide in the inclusions will completely turn into uranium oxide U_3O_8 with orthorhombic lattice. This will reduce the density of uranium oxide in the inclusions to 8.39 g/cm^3 and increase their volume accordingly (by 23.5%). As a result, the LFCM will be destroyed completely. All inclusions of uranium oxide U_3O_8 will get outside the LFCM.

The value of x increased from 2.25 to 2.34 (by 0.09) over 7—14 years, for the period from 2004—2011 to 2018. At the current oxidation rate, with an increase in the stoichiometric coefficient of oxygen to 2.66 (by 0.32), the LFCM destruction can be expected in 25—50 years, i.e. between 2043 and 2068. However, the oxidation rate may increase due to the increase in the thickness of the cracks in case of increasing the size of the uranium oxide inclusions.

In 2018, the content of uranyl silicate of sodium-potassium hydrate $(\text{Na,K})_2(\text{UO}_2)_2 - (\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$ in the LFCM was 3—4% (wt.), or 3—4 g per 100 g of the LFCM. This amount of uranyl silicate was formed during about 7—14 years (for the period from 2004—2011 to 2018); 1.5—2 g of uranium oxide UO_2 was used to obtain it. According to the current rate of the uranyl silicate hydrate formation, all available uranium oxide, i.e. 4.5—5.5% (wt.), will be consumed in 20—41 years, i.e. by 2038—2059.

However, it should be noted that although after heat treatment of brown LFCM ceramics (600 °C, 10 h, air) the content of anhydrous sodium-potassium uranyl silicate increased from 3—4% (wt.) to 10—14% (wt.), and the LFCM destruction did not happen. The volume of uranyl silicate hydrate will increase in 9—16 years, consequently, by 2027—2034 there will be no LFCM destruction.

The behavior of two processes (oxidation of uranium oxide UO_x in inclusions and radiation-stimulated phase formation of uranyl silicate of sodium-potassium hydrate $(\text{Na,K})_2(\text{UO}_2)_2(\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$) affect each other. Both processes lead to an increase in uranium oxide or uranyl silicate inclusions, increased crack formation and LFCM destruction. Uranium oxide and uranyl silicate hydrate from the inclusions will leave the LFCM. The combined course of these processes can reduce the duration of stages 5 and 6 and lead to the destruction of LFCM earlier.

Having applied the dependence of the relative volume of the crystalline phase on time (s-shaped crystallization curves) in the assumption that not six phases crystallize, but one, it was estimated the time until the beginning of the LFCM destruction due to the development of the glass phase crystallization. The estimations show that the crystallization process can approach a rapid (or avalanche-like) stage in 14—21 years (up to 2032—2039). In this case, a significant part of the glass phase in the LFCM can be broken down into particles with average sizes of 20—50 μm (in the range of sizes from 10 to 120 μm).

Crystallization of several phases can lead to the fact that the rapid stages of crystallization can be several (up to six, according to the number of currently known phases that are the result of crystallization). But a few rapid stages may not change into an avalanche stage. Multiphase crystallization of LFCM requires further study.

When working on the transformation of the Shelter object into an ecologically safe system, experts approach the need to develop a technology for the treatment of LFCM, such as solid-state air conditioning. Studies of the microstructure, physicochemical properties of LFCM and prediction of their evolution have contributed to the accumulation of experience in working with these materials. Similarly, the microstructure of LFCM tells us some ways to deal with them. The LFCM are thermodynamically metastable materials because their main (by mass) phase — glass phase — is an amorphous material in which the crystallization process takes place, i.e. the transition from metastable amorphous to stable crystalline state. If the material tends to transform into a more stable state, we can help him in this by conducting a managed crystallization of the glass phase of LFCM. That means to conduct its heat treatment, to control the formation of the crystal nucleus, to organize their controlled growth, to prevent destruction due to the activation of the sintering process of the already crystalline material, and to determine, if possible, required for the crystallization phase and crystallization sequence, which can be implemented.

Analysis of the LFCM microstructure and the physical and chemical processes that determine it indicates that the problem element of the microstructure is the inclusion

of uranium oxide UO_x . They increase their volume by uranium oxide UO_x oxidation and radiation-stimulated formation of uranyl silicate of sodium-potassium hydrate $(\text{Na,K})_2(\text{UO}_2)_2(\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$. Therefore, any effects on LFCM that allow the conversion of uranium oxide UO_x to compounds that do not interact with oxygen and water can be considered useful for converting LFCM to a more stable state. It is also important, if possible, to reduce the size of the UO_x inclusions (preferably to a size of less than $1\text{ }\mu\text{m}$) by redistributing them in the LFCM: to redistribute the uranium oxide and its compounds in the pore space, cracks and gas pores.

When heat treatment of LFCM is performed, it is possible to activate the radiation-stimulated phase formation of uranium potassium-sodium silicate, thereby binding uranium oxide UO_x to a compound that may have greater corrosion resistance than uranium oxide. Heat treatment of LFCM also makes it possible to achieve complete closure of nanosized pore channels (at $150\text{--}400\text{ }^\circ\text{C}$) and complete closure of cracks (at $200\text{--}530\text{ }^\circ\text{C}$), which will close the pore space and, accordingly, reduce the LFCM surface.

2.4 Assessment of the level of nuclear safety of the Shelter object

The main principle that determines all activities for the technical provision of safety of nuclear fuel accumulations at the Shelter object is the *principle of exclusion*, or prevention of the SSCR in existing conditions and any expected changes in existing conditions [66]. In this case, SSCR is always considered as a hypothetical event that is the result of the existence and/or occurrence of some conditions, which at the level of available knowledge and existing experience can not be predicted. Therefore, if SSCR cannot be ruled out as a hypothetical event, the facility remains potentially nuclear hazardous and, accordingly, the monitoring of the main parameters (NFD, ER, temperature and humidity) of these accumulations and the operational control of their subcritical level are required.

Monitoring the neutron activity of SFM accumulations has always been a priority. Nuclear safety control systems named Shater and Finish were developed in the first years after the accident (Fig. 2.31). *The Shater complex* was put into operation in 1987, was designed to record the current parameters of the FCM: NFD, ER of γ -radiation, temperature, heat fluxes, and was to become the main regular control system of the Shelter object. However, the detectors of the complex were located for objective reasons on the periphery, far from the FCM accumulations, and gave an insufficiently informative indication. After working out its resource, the system was decommissioned in 2000 and replaced by the *information-research system Finish*.

IRS Finish-I was formed by careful selection of informative channels and had the status of pure research. In December 1998, an independent set of technical means was singled out from the Finish research system to ensure the regulatory control of the subcritical state of FCM, which was named Finish-R.

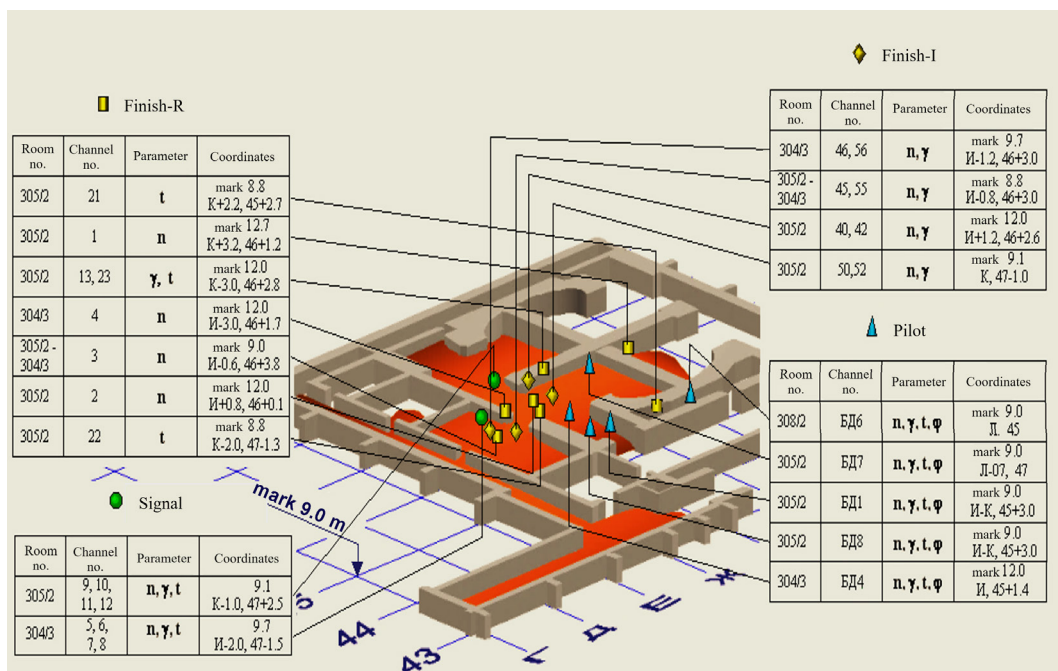


Fig. 2.31 — Location of nuclear safety control systems of the FCM at the Shelter object at +9.00 m

The *Finish-R* system included 21 control channels and consisted of 40 measuring channels, in particular three channels of control of NFD, four channels of measurement of ER, 26 channels of temperature measurement, six channels of control of heat flux, one channel of measurement of humidity (see Fig. 2.31). As the *Finish-R* system was singled out from the research system, the latter was used as a test site and a hot reserve. The main tasks of the research system are:

- providing experimental and research work on the assessment of the subcriticality of nuclear hazardous areas in room 305/2, CH and reactor space;
- providing alternative control of the state of FCM in room 305/2;
- testing of new technical solutions and control procedures;
- research and testing of organization of new routes of information channels.

To expand the control points in parallel with these systems, the *Signal control system for FCM* was developed and implemented. Its first construction stage was put into trial operation in late 1994. Initially, it consisted of four control channels and secondary measuring equipment. In 1995, the number of control channels of NFD and ER was increased

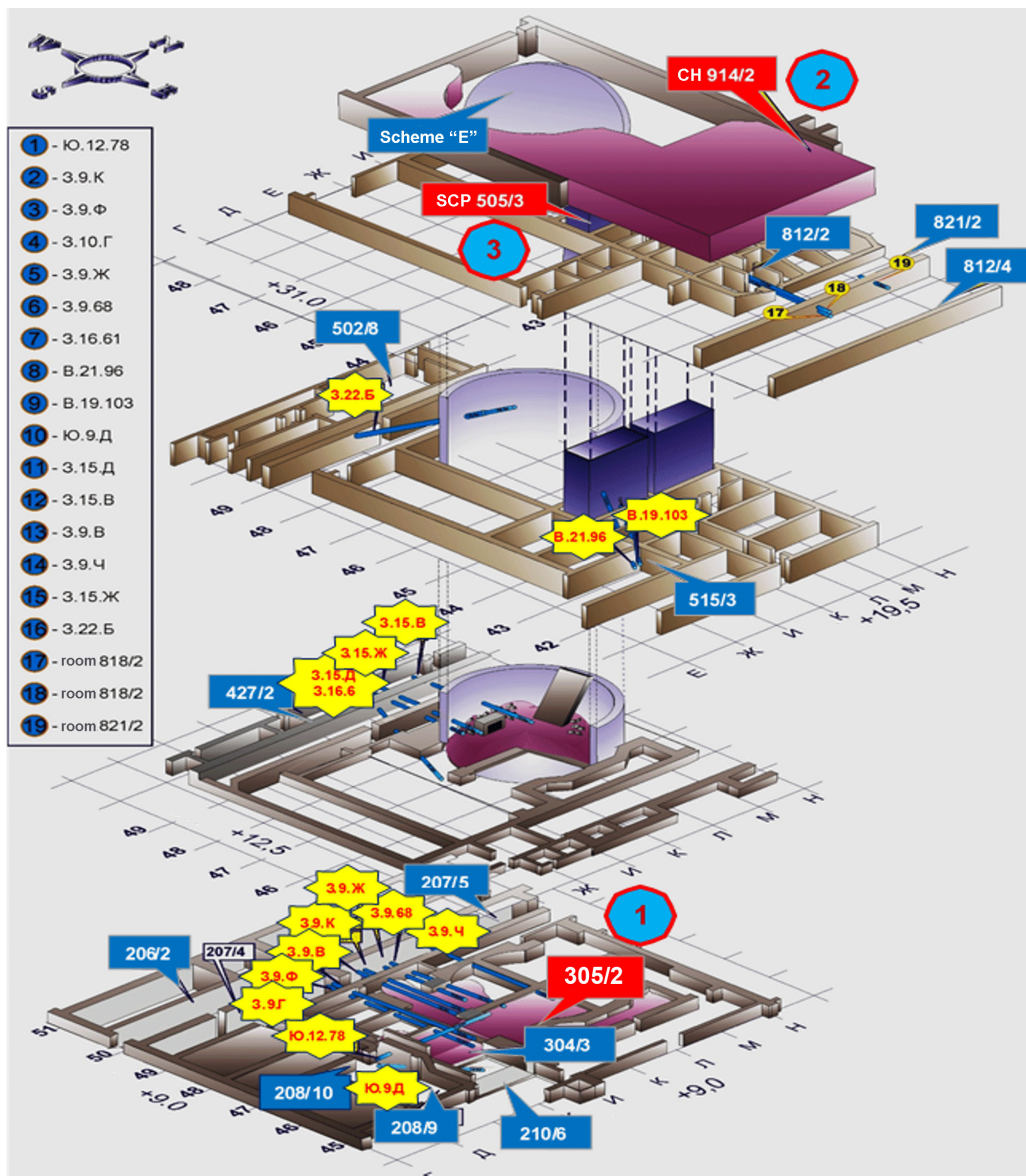


Fig. 2.32 — Layout of detection units (NFD, ER)
of the nuclear safety monitoring system:

- 1 — potentially nuclear hazardous accumulations of FCM in room 305/2;
2 — the same, in the CH; 3 — the same, in the SCP of the spent nuclear fuel

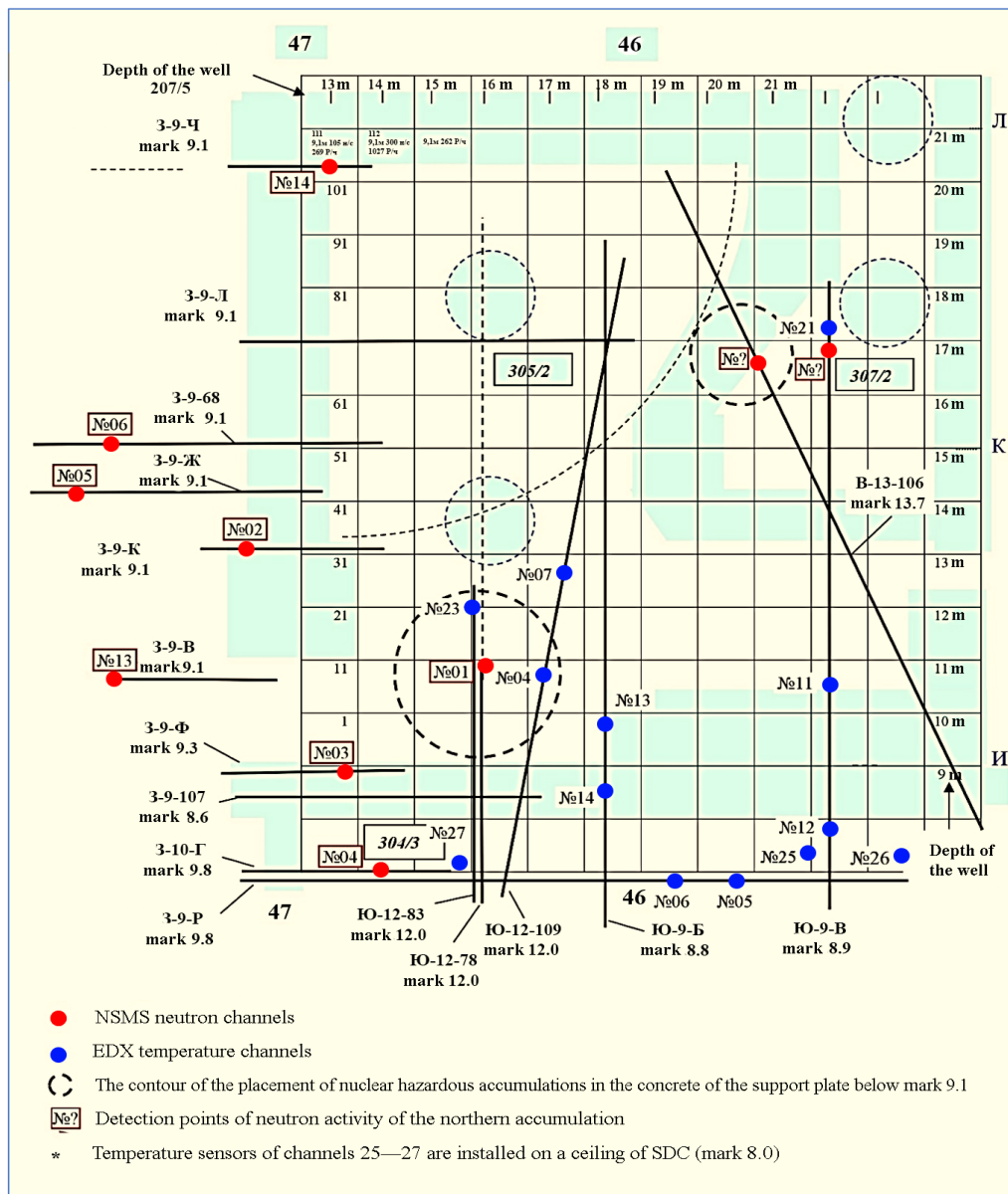


Fig. 2.33 — Layout of detectors of the nuclear safety monitoring system IACS NFD no. 1, 2, 3, 6 with the recommended placement of detectors for monitoring the northern LFCM accumulation in room 305/2

by another sixteen. Additional channels in the CH were installed through the technological access doors in the roof of the Shelter object. In 2000, the system was put into a normal operation state. Today, the Signal system has been decommissioned, and the disparate control systems have been replaced by a single system for monitoring the facility — an ICS.

The Nuclear safety monitoring system (NSMS), which contains 19 channels for control of NFD and ER, was put into operation in 2018 (Fig. 2.32). To date, the monitoring of neutron activity on the periphery of the “southern” SFM accumulation in room 305/2 is carried out in three points of NFD detection. The NSMS detection units are located on the periphery of the “southern” accumulation with a high SFM concentration (at least at a distance of 2.5 m from the epicenter), respectively, their efficiency and informativeness are low. Currently, accumulations in the CH are not actually controlled. The NSMS detection units are installed in the penetrations under the lower floor of the CH and are uninformative due to the weakening of the response more than 100 times. The situation is similar to the “northern” SFM accumulation (room 305/2).

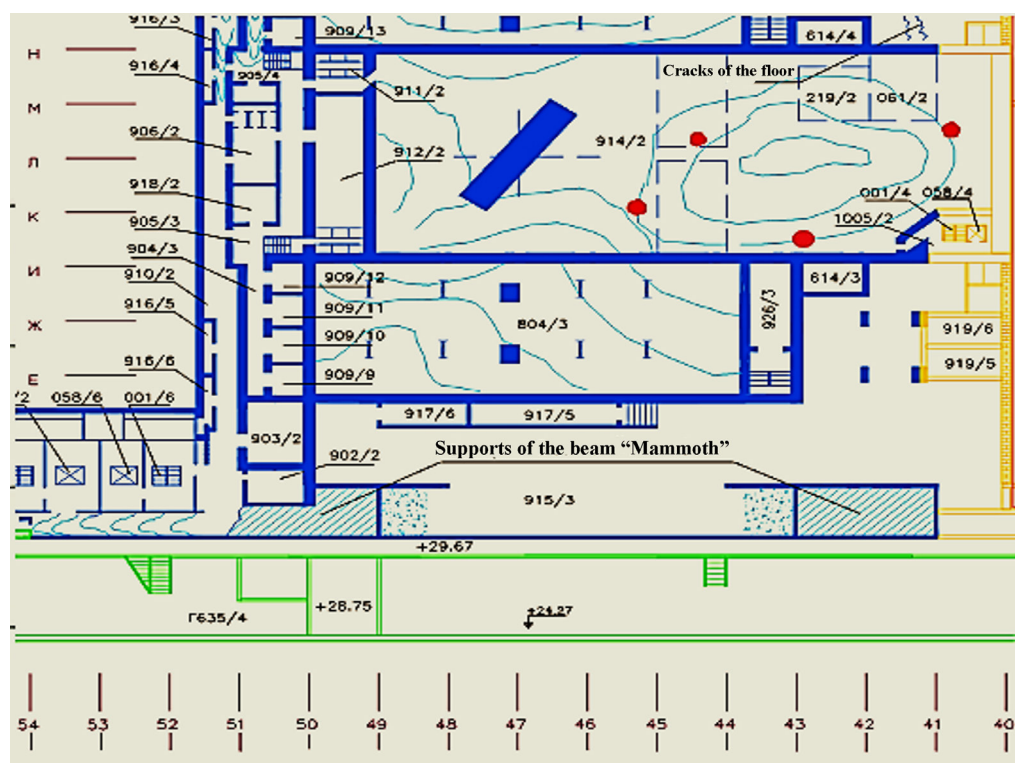


Fig. 2.34 — Scheme of the recommended placement of LFCM monitoring detectors in the CH

Thus, the current location of the 19 neutron detection points of the NSMS does not provide a sufficient level of nuclear safety of the NSC, as it does not provide effective monitoring of neutron activity of potentially nuclear hazardous accumulations in the CH, the SCP and room 305/2 [67]. In addition, the NSMS design did not provide for temperature control, so in 2018 the ISP NPP developed and implemented an expert research system at the Chornobyl NPP, which contains 19 temperature channels and five additional channels of NFD. As most detection points in the NSMS are not very informative, the system needs to be adjusted to increase efficiency: to decommit non-informative neutron measurement channels, as well as to use equipment (channels no. 12, and 15 of the reactor space; detection units no. 13 and 14 of the south-west quadrant of room 305/2, detection units no. 17, 18 and 19 of the penetrations under the CH) for more informative control points (Fig. 2.33).

The layout of detection points and routes of access to them in the areas of potentially nuclear hazardous FCM accumulations in the CH, which can provide monitoring of the state of subcriticality, is shown in Fig. 2.34 [68]. One neutron detection unit is located at each detection point. The optimal routes for delivery of detectors to the detection points are penetrations in the pipe rolling of the roof. Delivery of detectors to the lower floors is possible through a well from room 515/3.

Monitoring of neutron activity on the periphery of the “northern” accumulation with an increased concentration of nuclear hazardous fissile materials is possible after the installation of neutron energy dispersive X-ray spectroscopy (EDX) detectors in room 305/2.

2.5 Assessment of existing safety barriers and effectiveness of operational control of subcriticality of accumulations of nuclear hazardous fissile materials

The current “Technological Regulations...” [49] states that the guarantor of the safety of the Shelter object is the existing system of barriers (formed naturally or created in the process of elimination of the beyond design-basis accident) on the way of spread of radioactive products and ionizing radiation, as well as purposeful activity of the personnel in the course of operation. The system of physical barriers includes building structures of the fourth power unit (primarily the walls and ceilings of the premises with FCM inside); NSC building structures; FCM with mechanical properties holding them in the form of separate local accumulations. In addition, as the barriers that prevent the SSCR occurrence there are specified: neutron-physical characteristics and geometrical parameters of FCM accumulations (for example, non-compact arrangement of SFM accumulations), due to which the formation of critical masses is impossible under normal conditions; lack of water in the accumulations of FCM; the presence of neutron absorbers in the area of localization of SFM accumulations; the impossibility of water retention in the volume of FCM accumulations.

The results of a comprehensive analysis of the available data and the results of experimental and computational studies of potentially nuclear hazardous LFCM accumulations

at the Shelter object have shown a lack of justification for the current safety barriers. First, the strength parameters of both the Shelter object and the NSC were not calculated in case of the SSCR occurrence. Second, the statement about the properties of the LFCM accumulations themselves, which prevent the formation of critical masses, is based on calculations in which the concentration of nuclear hazardous fissile materials in the LFCM did not exceed 18%, which corresponded to the results obtained for samples taken at the periphery of SFM accumulations. However, in the epicenter, the SFM concentration may be higher. In addition, in the Technological Regulations regarding room 305/2, it is stated that the average concentration of the SFM in it is about 26%. Due to this fact and the results of temperature measurements, which indicate two centers of high concentrations of fissile materials, it is necessary to review or verify the existing safety barriers.

The nuclear safety of the Shelter object is ensured by the routine operational control of the FCM in the subcritical state through the introduction of solutions of neutron-absorbing materials (NAM) [49, 69—73]. The NAM solution (0.1% solution of gadolinium nitrate) is fed by:

- gadolinium solution feed system (GSFS), which is designed to reduce the K_{ef} in the accumulations of FCM in the demolished reactor shaft of the fourth unit of the Chornobyl NPP;

- modernized dust suppression system (MDSS), using which in case of the GSFS inoperability or exceeding of critical levels the K_{ef} value is reduced by the spraying of NAM on a surface of accumulations contained in the CH;

- installation “System of operative feed of aqueous solution of gadolinium” (henceforth — gadolinium feed system) which is intended for the K_{ef} reduction in the FCM accumulations in room 305/2. The supply of about 40 liters of gadolinium solution from the installation is carried out through a pressure pipeline laid in the casing pipe of the backup well. The location of the nozzle allows the injection of NAM in the south-eastern sector of room 305/2.

With sufficient frequency of operation of these systems, in 2004—2009 [70], the content of gadolinium in soluble and colloidal forms was 0.2—1.6 g/m³, and in the form of a solid phase, it reached 10 g/m³ at an initial concentration in the washing solution of about 1,000 g/m³. According to the results of measurements in 2005, it was concluded that “...gadolinium accumulates in room 305/2 as a result of deposition...” [74]. However, recently the number of MDSS sessions has decreased significantly, and according to new experimental studies [75], the concentration of gadolinium in the water of some wells usually did not exceed 1 mg/l, which has practically no influence on the level of subcriticality of the reproductive system.

A short-term increase in the concentration from 2 to 5 mg/l is associated with dust suppression sessions (Fig. 2.35), but such a concentration of NAM is not enough, because the gadolinium concentration in the area of the SFM accumulation is three orders of magnitude lower than necessary for effective control of the subcriticality level of this accumulation. Therefore, now at the Shelter object, it is necessary to increase the efficiency of operational control of the subcriticality level of the SFM accumulations in room 305/2.

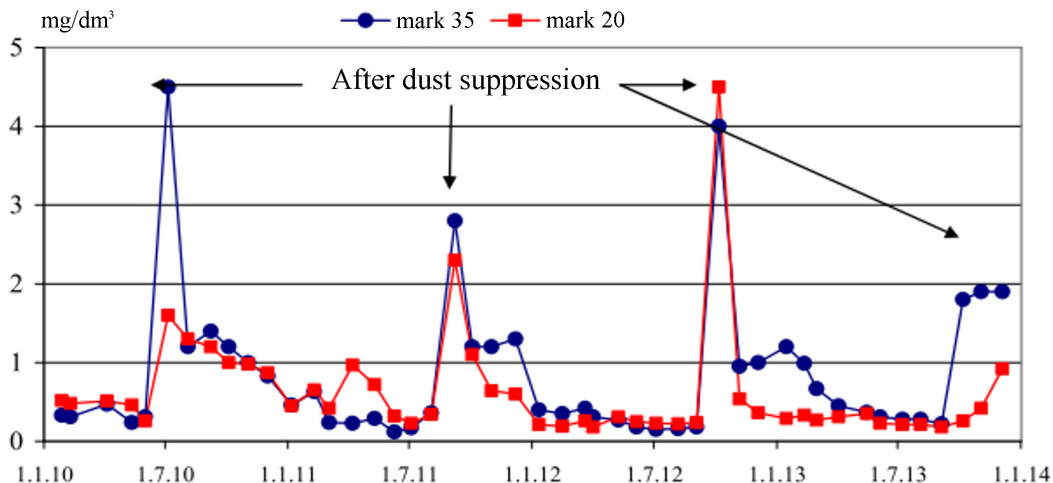


Fig. 2.35 — Gadolinium concentrations in the area of localization of the SFM accumulations after the MDSS operation [41, 76]

The GSFS and MDSS operation affects the level of subcriticality of the SFM accumulations at the lower marks of the Shelter object very inertially because the supply of NAM solution is provided in the space of the reactor shaft from above. In the path of such water flows there is a cascade of pools, which affects the inertia of the solutions flow to the SFM localization zone and determines the minimum required volume of the NAM solution.

Since there is no access directly to the epicenter of the nuclear hazardous accumulations of the LFCM, the effectiveness of the gadolinium feed system for influencing the level of subcriticality of the SFM accumulations in room 305/2 is insufficient, as the system supplies the NAM solution only to the near periphery of the accumulations (Fig. 2.36).

The volume and the feed rate of the absorber must be estimated by calculation and experimental methods individually for each specific route and the method of delivery. It is estimated that the state of readiness of the technological suppression system should be determined equals to three hours if the rate of reactivity insertion in the case of subcritical anomaly does not exceed $10^{-4} \beta/s$, and a maximum of 20 minutes if the rate of reactivity insertion is $10^{-3} \beta/s$ [77]. Taking into account these criteria, additional studies of gadolinium feed systems are required.

The effectiveness of the MDSS or the GSFS as systems for influencing the subcriticality of nuclear hazardous accumulations of LFCM in room 305/2 is also insignificant due to the long delivery time of the NAM. For example, if before the NSC installation the reaction of

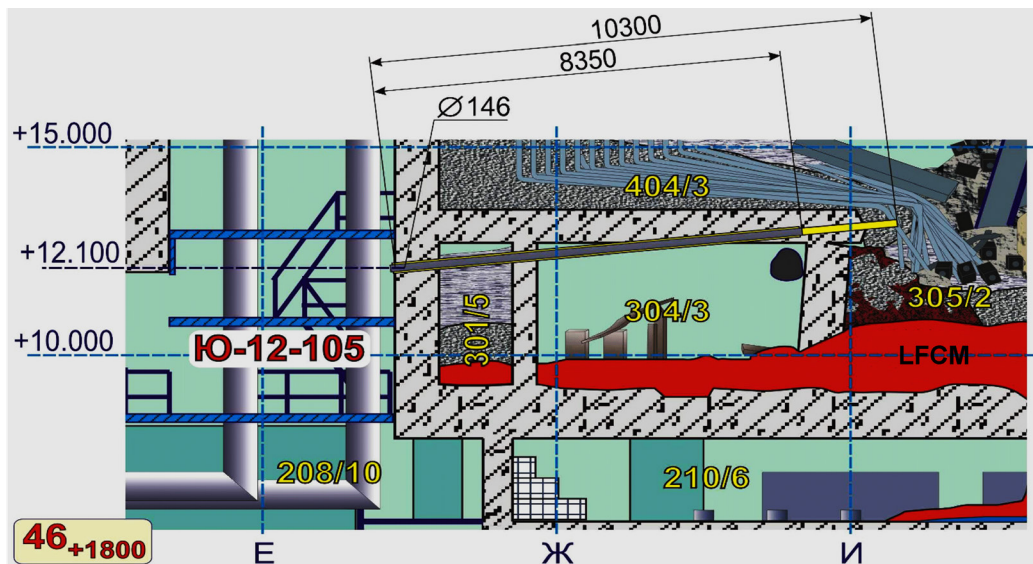


Fig. 2.36 — Scheme of gadolinium introduction for influence on the level of subcriticality of the SFM accumulations in room 305/2 (the well Ю-12-105)

NFD measuring channels to a significant inflow of water due to heavy rainfall was after five to six hours [41], then, due to the current drying of the cascade of water accumulations in the NSC conditions, NAM will reach the SFM localization zone not earlier than in ten hours. In addition, it will be needed to estimate experimentally the minimum volume of solution required to fill the entire cascade of pools. According to preliminary estimates, to restore the water regime of the “southern” SFM accumulation, which will ensure its subcriticality, about 3—4 t of water must be fed directly through the western wells to the localization zone of these LFCM, creating a new system of pipelines and pumping system. In the case of using the regular systems MDSS or GSFS, at least 50 t of water must be supplied.

2.6 Current state of nuclear safety of the Shelter object

Analysis of the results of experimental work [78] showed that the SFM accumulation in room 305/2 is a two-layer porous structure: the upper layer consists of black and brown LFCM, the lower layer is a potentially critical composition with a high concentration of SFM (Fig. 2.37).

Before the NSC commissioning, the LFCM were completely wetted, and the dynamics of NFD was kept within the seasonal trends by a regular inflow of moisture from precipitation and condensate. Seasonal deviations did not exceed 10% of the average annual values;

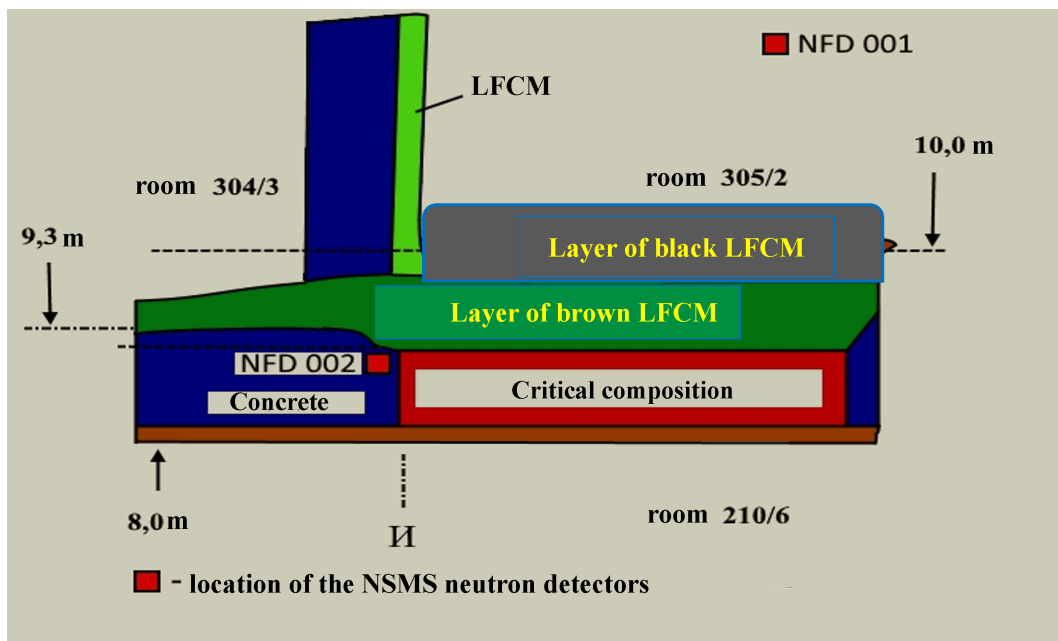


Fig. 2.37 — Model of the potential nuclear hazardous FCM accumulation in room 305/2

they are not informatively significant in the process of controlling dangerous changes in the level of the SFM subcriticality.

After the NSC installation and its commissioning, significant changes in the humidity and temperature regime took place. Due to the lack of precipitation input into the Shelter object, the process of evaporation and loss of moisture by the porous structure of the LFCM has begun.

Significant changes have also taken place in the dynamics of temperature in the premises of the Shelter object. According to the monitoring results, the temperature in all controlled places increased by about 1—3 °C in 2018 and lagged behind the increase in ambient temperature by about 5—10 °C. On the periphery of the LFCM accumulations in rooms 305/2 and 304/3, it lay in the range of 19—23 °C at the ambient temperature of about +2...12 °C in the daytime. Noticeable changes took place for moisture also. If before the NSC installation the period of condensate formation in these premises began in May and ended in September, then in 2018 the period of condensate formation began in late September or early October. As of October 31, 2018, the intensity of condensate formation was significant, the floor and walls of the premises of the PSP and the SDC were quite moist.

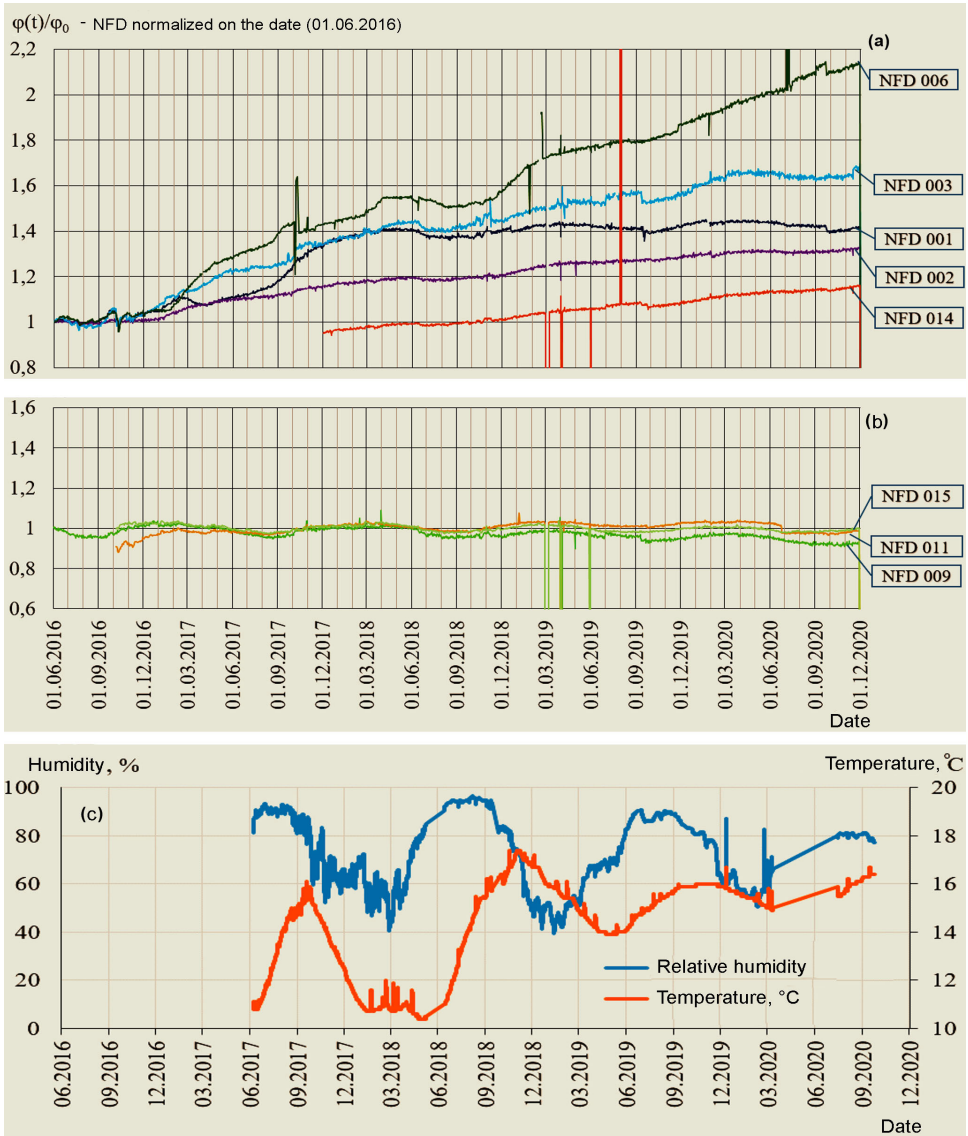


Fig. 2.38 — Dynamics of NFD in room 305/2 as well as temperature and humidity conditions at the lower marks of the Shelter object in room 210/7:

- a* — NFD near a nuclear hazardous accumulation in room 305/2 of the Shelter object;
- b* — NFD on the remote periphery; *c* — temperature and humidity at the lower marks of the Shelter object in room 210/7

Dynamics of NFD on the periphery of accumulations with the high concentration of SFM in room 305/2 for 2016—2020 is shown in Fig. 2.38. The research results showed that seasonal trends in neutron flux dynamics are observed only at detection points located on the accumulation surface, as they are determined by the periods of appearance (condensation) and loss (evaporation) of the shielding layer of the water reflector and fully correspond to the temperature and humidity conditions in the NSC.

Statistical processing of the NFD data showed that the correlation coefficients at these detection points are more than 0.8, and the increase in neutron activity is determined by the neutrons of the forced fission, i.e., the increase of K_{ef} . In contrast to nuclear hazardous accumulations of LFCM, on the periphery and in clearly subcritical accumulations the values of NFD lie at the same level (Fig. 2.38, *b*).

Another pattern is observed in the “southern” accumulation of room 305/2 with the increased concentration of fissile materials. The neutron activity of the accumulation increases due to changes in humidity (Fig. 2.38, *a*). According to the obtained data on the dynamics of parameters on the periphery of the LFCM accumulation, calculations of its structure, geometry, as well as following the observations of NFD, a forecast was made for further growth of neutron activity due to moisture loss in the layer of the humidified medium of the black LFCM (total volume up to 54 m³) and growth of K_{ef} .

The growth of NFD will continue until the optimal water concentration is reached with the maximum K_{ef} in the layer of black LFCM. Next, the neutron activity will fall until complete dehydration of this upper layer. Also, assuming that the critical LFCM composition will retain moisture until the LFCM layer is completely dry (excluding the capillary effect), the time before the start of the process of water loss by the critical composition will be approximately 700 days. The beginning of the process of moisture loss can be determined by the change in the gradients of the NFD at the detection points in the south-eastern square. The criteria for expert assessment of the level of subcriticality are the rate and multiplicity of the NFD growth.

2.7 Recommendations for preventing the occurrence of uncontrolled self-sustaining chain reaction

The effectiveness of the NSC nuclear safety depends on the following conditions:
availability of reliable experimental and calculated data, which are guaranteed to prevent the SSCR probability;

the ability of organizational and technical means to ensure effective operational control of the subcriticality level of all SFM accumulations (subject to effective operational neutron monitoring);

implementation of means of preventive suppression of criticality parameters of SFM accumulations (implementation of measures that exclude the conditions necessary for the SSCR occurrence).

For the SFM accumulations in room 305/2, the first two conditions for nuclear safety are unacceptable. An available experimental data not only does not exclude the possibility of SSCR occurrence but, on the contrary, indirectly confirms such a risk. Currently, there are no means of effective operational influence on the subcritical level of accumulations. The current access routes can provide operational control of the level of subcriticality (with a guarantee of early detection of anomalies at $K_{\text{ef}} < 0.95$) of SFM only in the presence of reliable individual quantitative and qualitative criteria for early detection of anomalies in the responses of detectors that can be identified as dangerous changes of K_{ef} .

An algorithm for early identification of dangerous changes in the criticality level has been developed [79], which in case of its application in the NSMS software and implementation of the proposed recommendations for adjusting the NSMS monitoring point scheme will allow implementation of the second condition of nuclear safety.

Today, the task of effectively ensuring the SFM nuclear safety is generally reduced to implementing the principle of preventing the SSCR occurrence. For the SFM accumulations localized in room 305/2, the third condition, which consists of the implementation of means of preventive suppression of criticality parameters, becomes especially relevant.

First of all, it is necessary to determine the spatial distribution and concentration of NAM to ensure that the safe level of $K_{\text{ef}} < 0.95$ is not exceeded at any expected change in the state of the SFM accumulation. It is equally important to determine and ensure effective routes of NAM delivery directly to the SFM accumulations and to evaluate experimentally the time characteristics of the processes of neutron absorbers introduction in the propagation medium, as well as the duration of the required concentration holding. For this purpose, the following works were performed:

- collection and analysis of available experimental data to create a spatial and physico-chemical model of nuclear hazardous FCM accumulations;

- analysis of model calculations of the influence of neutron absorbers on reducing the probability of a critical incident;

- preparation of technological recommendations (including decisions on the introduction of neutron absorbers in the SFM accumulation) to prevent the occurrence of critical incidents at all stages of the NSC further transformation.

Requirements for the technological process of suppression of criticality parameters (exclusion of the SSCR probability) can be formulated as follows:

- the basis of the proposed solutions should be technologies mastered at the Shelter object, the minimum possible financial costs and the minimum collective radiation dose of personnel performing work;

- the implementation of decisions on the introduction of neutron absorbers in the SFM accumulations in the Shelter object should be effectively monitored to minimize the RAW amount;

such solutions should not lead to a decrease in the stability of structures, should ensure guaranteed stabilization of the LFCM conditions (ensure nuclear safety of the FCM in normal and emergency modes) and provide for the possibility of the further dismantling of the Shelter object structures.

Because of these requirements, technical solutions acceptable to the NSC to prevent the risks of SSCR have been identified:

- introduction of the liquid NAM in the SFM accumulation;

- controlled reduction of the concentration of moderator (water) in the area of localization of the SFM accumulation in case of guaranteed impossibility of water access to the reactor plate;

- introduction of the solid NAM.

A guaranteed way of preventive suppression of the criticality parameters is the introduction of the solid NAM in the volume of accumulation. However, the technology (method) of NAM delivery must be determined individually for each SFM accumulation. Studies of the possibility of using NAM have shown that they can be introduced in the form of special masses (for example, rods that pass through drilled wells) or as special solutions that are guaranteed to impregnate the LFCM volume to achieve an acceptable level of risk at any initial event. Boron (regular RBMK emergency protection rods), cadmium, europium and gadolinium were considered as absorbing materials.

The effectiveness of operational control of the neutron anomaly strongly depends on the delivery routes of the absorber, which should ensure the placement of NAM directly in the environment of fissile materials. According to the current routes, NAM get only on the accessible periphery of the SFM accumulation, i.e. on the boundary “detector — source”. In this case, the process of suppression of the neutron anomaly is simulated (the regular NSMS registers a false decrease in NFD), i.e. does not correspond to reality. A similar situation occurred during the 1990 neutron incident.

Therefore, after the NSC is set to the design position, the LFCM behavior is influenced by the humidity and temperature conditions. According to the results of experimental and computational model studies, the level of nuclear safety of all SFM accumulations was re-evaluated. The epicenter, localization zone of potentially nuclear hazardous FCM accumulations, their mass and volume, composition and structure, and the probability of critical compositions were estimated.

Due to the uncertainty and unpredictability of the mechanisms of dehydration of the SFM accumulations, the primary mandatory task is the implementation of effective local (on the available periphery of the SFM accumulations) monitoring of neutron activity, as well as the implementation of an expert procedure for identifying dangerous changes in subcriticality into the NSMS software.

Chapter 3. RADIATION SAFETY

All nuclear and radioactive materials of the facility are radioactive waste by nature and should be removed from it for future disposal. The physical and chemical characteristics of the RAW differ significantly depending on their origin. The Shelter object is represented by almost the entire spectrum of RAW, and a significant part of it belongs to the highly active one. The radioactivity of materials in the facility is determined by the activity of radionuclides that have formed either as a result of neutron activation in the reactor core of the destroyed power unit or due to surface contamination of materials with radioactive substances.

The Shelter object contains a significant amount of finely dispersed fuel as a result of physical and chemical effects on the fuel during and after the accident. Fuel dust poses a risk of internal human exposure and the dispersion of radioactive substances outside the location. In the post-accident period, secondary fuel dust appears due to the destruction of lava-like fuel containing materials. In addition to fuel dust, there is a significant amount of dust in the facility, the formation of which is associated with the degradation of building structures and the destruction of dry dust-suppressing coatings under the influence of aging and climatic factors. Because these structures and dust suppression coatings are contaminated with radionuclides, this dust is often radioactive.

During the active stage of the accident, most of the graphite stack burned out and was scattered by radioactive release, and the other part was discharged into the reactor hall, on the site, and the roof of the power unit. Part of the graphite is dispersed due to the explosion and distributed in the form of dust in the reactor compartment.

The main volume of RAW at the Shelter object consists of various types of building materials. The radionuclide composition of their surface contamination is characterized by the presence of ^{134}Cs , ^{137}Cs , ^{90}Sr , $^{239+240}\text{Pu}$, ^{241}Am , and ^{60}Co . The level of contamination of concrete and building structures varies in a wide range. The main potential source of metal waste that will be generated during the dismantling process are pipelines, ventilation ducts and other technological equipment of the power unit. The materials used in the active stage of emergency response to backfill the reactor shaft are also a significant part of RAW.

One of the main factors of danger at the Shelter object is the presence of radioactive water, which affects the state of radiation safety, and interacting with FCM, dissolves and transports radionuclides that may enter the environment. Part of the activity is concentrated in silty sediments and, drying out, poses a threat as a source of aerosols.

3.1 Change of gamma radiation fields after installation of the NSC into the design position

Measurement of dose rate (DR) and angular distribution of γ -radiation intensity in some areas was performed in 2016 before and after the NSC was set to the design position [80]. The DR was measured with a radiometer-dosimeter MKS-07 “Poshuk” (Fig. 3.1), and the angular distributions of the intensity of γ -radiation — using the device ShD-1 [81] and the installation “Ekran” (Figs. 3. 2 and 3.3).

This equipment was previously tested and repeatedly used at the pre-project research stage and during the implementation of several projects at the Chornobyl NPP site, such as:

- stabilization of building structures of the Shelter object;
- construction of a NVS of the second stage of the Chornobyl NPP;
- final closure and conservation of the first — third power units of the Chornobyl NPP;
- reconstruction of the main building of the Chornobyl NPP with reinforcement and sealing of building structures that perform the functions of the NSC EP;
- restoration of the EP of the turbine island in the fourth power unit of the Chornobyl NPP;
- reconstruction of part of the turbine island of the Chornobyl NPP to create a high-level waste (HLW) storage facility.

The research sites were chosen taking into account the location of the areas of the future dismantling of unstable structures of the Shelter object and their subsequent treatment, as well as due to: the minimum distance to the main sources of γ -radiation of the Shelter object; the minimum possible distance from the place of installation of the ShD-1 device to the NSC structures for maximum registration of γ -backscattering; availability of access to research sites before and after the NSC setting in the design position.

Based on this, four research zones were selected, which are shown in Fig. 3.4.

The results of DR measurements using MKS-07 “Poshuk” for areas 1—4 before and after installing the NSC into the design position are given in Table 3.1. Comparing the data at all points of the study areas, we see a decrease in the DR value after setting the NSC in the design position from 1.8% (point 2) to 53.8% (point 7E) from the initial value (before setting the NSC in the design position).



Fig. 3.1 — Radiometer-dosimeter MKS-07
“Poshuk” with the detection unit BDBG-07

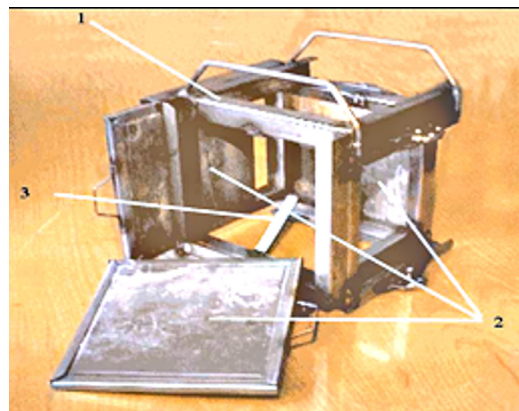


Fig. 3.2 — “Ekran” installation:
1 — the casing of the installation; 2 — lead
screens; 3 — bracket for mounting the detector

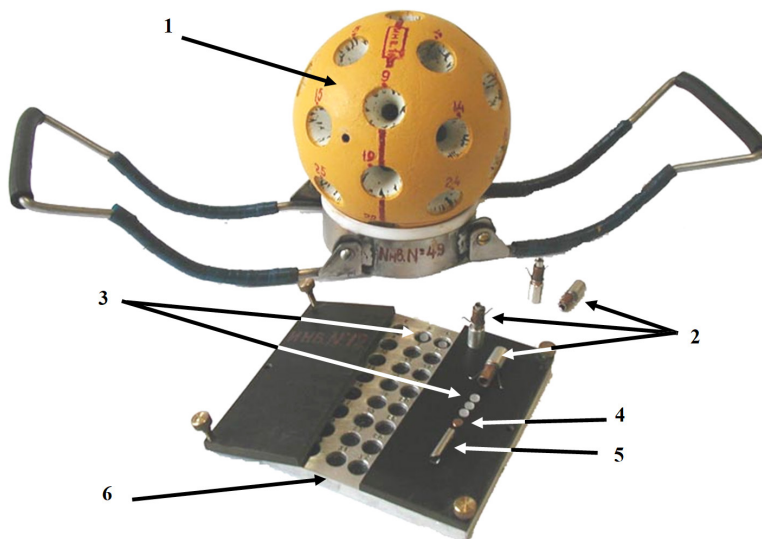


Fig. 3.3 — Device ShD-1:
1 — the lead case with the collimated apertures; 2 — capsules with detectors;
3 — thermoluminescent detectors; 4 — copper filters; 5 — clamps;
6 — the case for transportation of detectors

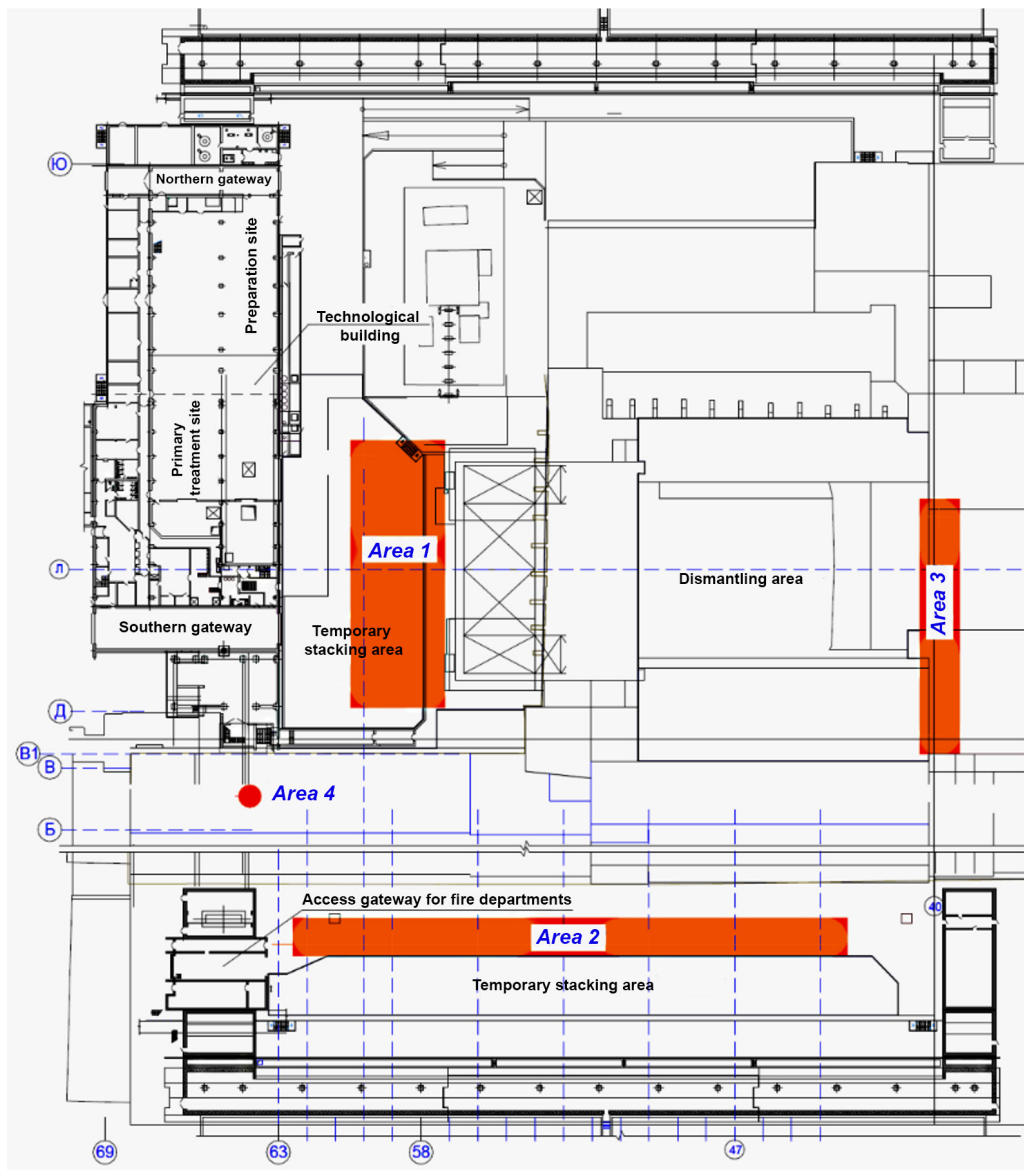


Fig. 3.4 — Research areas:

1 — the local area of the Shelter object, temporary stacking site; 2 — the local area of the Shelter object, temporary storage site; 3 — unit B coating; 4 — deaerator stack coating

Table 3.1 — Dose rate of γ -radiation in areas 1—4

Area no.	Point no.	Coordinates of the measuring point	DR, $\mu\text{Sv/h}$		Deviation from the initial value, %
			before installing the arch	after installing the arch	
1	1	$\Gamma/58_{-3}$	237	202	-14.8
	2	$M/58_{-3}$	34	33.4	-1.8
	3	$H/58_{-3}$	21	14.0	-33.3
	4	$\Pi/58_{-3}$	11.5	7.1	-38.3
	5	$P-2/58_{-3}$	8.5	5.6	-34.1
	6	$E/58_{-0.5}$	35.5	26.4	-25.6
	7	$\mathcal{K}/58_{-0.5}$	38	23.7	-37.6
	8	$I/58_{-0.5}$	26	22.7	-12.7
	9	$K/58_{-0.5}$	21.4	16.0	-25.2
	10	$\mathcal{L}/58_{-0.5}$	21	17.6	-16.2
	11	$M/58_{-0.5}$	20	14.8	-26.0
	12	$H/58_{-0.5}$	21.5	13.4	-37.7
	13	$\Pi/58_{-0.5}$	19.4	14.8	-23.7
2	1E	$A_{-15}/44$	45.2	32.6	-27.9
	2E	$A_{-15}/47$	82.8	65.2	-21.3
	3E	$A_{-15}/50$	105	87.3	-16.9
	4E	$A_{-15}/53$	117	92.8	-20.7
	5E	$A_{-15}/56$	79.9	78.1	-2.3
	6E	$A_{-15}/59$	63.8	50.6	-20.7
	7E	$A_{-15}/62$	50.9	23.5	-53.8
1	8E	$E/60$	99.2	68.1	-31.4
	9E	$\mathcal{K}/60$	84.4	65.0	-23.0
	10E	$I/60$	63.2	61.2	-3.2
	11E	$K/60$	69.3	62.0	-10.5
	12E	$\mathcal{L}/60$	62.7	52.5	-16.3
	13E	$M/60$	53.8	43.9	-18.4
	14E	$H/60$	50.0	40.4	-19.2
	15E	$\Pi/60$	42.3	39.6	-6.4
	16E	$P/60$	40.0	32.4	-19.0
4	1III	$B_{+7}/64$, mark +42.800	280	255	-8.9
3	2III	$I_{+1}/40_{+1}$, mark +74.500	2,370	2,280	-3.8
	3III	$\Gamma_{+1}/40$, mark +71.200	460	450	-2.2
	4III	$H_{-1}/40_{+1}$, mark +74.500	1,900	1,700	-10.5

When the DR is determined with the “Ekran” installation in areas 1 and 2 (Fig. 3.5), the detector was placed in a lead container with one open side facing up, and all other directions were shielded. The purpose of the research was to evaluate the effect of the backscattering of γ -radiation on the NSC structures. The results of the investigation (Table 3.2) showed that after setting the NSC in the design position, the DR, which forms from the upper direction, increased at the points of area 1, and at the points of area 2, on the contrary, decreased (Fig. 3.6). This can be explained as follows. In area 1, the “Ekran” installation was placed on a site near the reactor unit. Therefore, direct γ -radiation from the main sources in the CH of the fourth power unit after scattering from the NSC structures fell on the detector placed in the installation, which, accordingly, increased the contribution of the component from the “up” direction (see Fig. 3.6, *a*). In area 2, there is no direct radiation from radiation sources located in the CH, because between the study area and the CH there are structures of the DS and the turbine island. In this zone, a decrease in DR from the direction “up” was recorded (see Fig. 3.6, *b*).

Table 3.2 — The dose rate indications of the “Ekran” installation at the measurement points located in zones 1 and 2, $\mu\text{Sv/h}$

Area no.	Point no., coordinates	Before installing the NSC	After installing the NSC into the design position	Deviation from the initial value, % ($\pm$)
1	8E, E/60	29.9	33.5	+12.0
	9E, Ж/60	31.0	30.6	+1.3
	10E, И/60	24.4	25.2	+3.3
	11E, K/60	20.5	25.3	+23.4
	12E, Л/60	18.2	19.3	+6.0
	13E, M/60	15.2	17.3	+13.8
	14E, H/60	15.1	17.4	+15.2
	15E, П/60	10.9	15.6	+43.1
	16E, P/60	10.9	13.5	+23.9
2	1E, A ₋₁₅ /44	15.8	13.2	-16.5
	2E, A ₋₁₅ /47	31.8	21.1	-33.6
	3E, A ₋₁₅ /50	34.4	31.2	-9.3
	4E, A ₋₁₅ /53	34.4	31.1	-9.6
	5E, A ₋₁₅ /56	24.7	24.9	-0.8
	6E, A ₋₁₅ /59	20.2	15.7	-22.3
	7E, A ₋₁₅ /62	13.8	9.1	-34.1

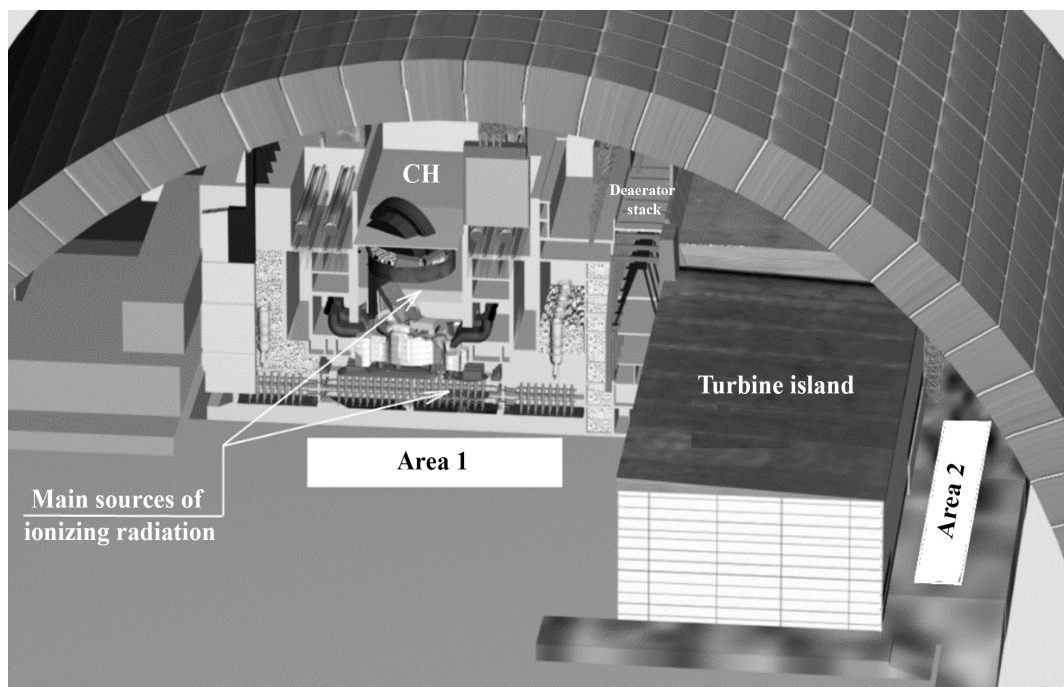


Fig. 3.5 — Measurements of dose rate in areas 1 and 2 using the “Ekran” installation

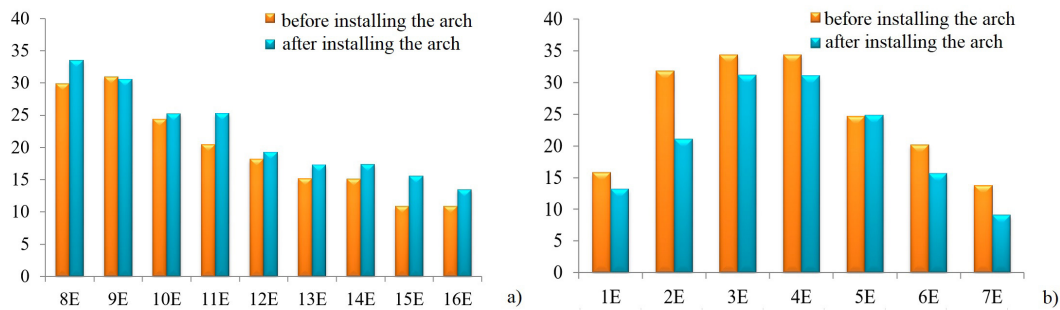


Fig. 3.6 — Measurement data by the “Ekran” installation from the “up” direction before and after the setting of the NSC arch, $\mu\text{Sv/h}$:
 a — at the points of area 1; b — at the points of area 2

The study of angular distributions of γ -radiation using the ShD-1 device did not reveal significant changes in angular distributions at selected points (Fig. 3.7). It should be noted that there is a tendency to increase the intensity of γ -radiation from the upper direction with a general decrease in intensity values, but such an increase lies within the error of registration in thermoluminescent dosimeters (TLD-500K) and requires additional data analysis. Although the study points are selected with the minimum possible distance to the NSC surface (for example, at point 4H the distance to the NSC structures is only 15 m), there are still enough factors that affect the ability to register the backscattering effect. In particular, the backscattering effect, according to various assumptions, is not more than 15% of the DR value, and the error of thermoluminescent dosimeters, which is due to the heterogeneity in the dosimeter sets and energy sensitivity, is $\pm 30\%$.

Thus, the studies showed that after installing the NSC into the design position at all measurement points a decrease in DR from 3 to 50% depending on the survey area was recorded.

The study of the characteristics of the γ -radiation spectrum in the specific research areas will increase the accuracy of estimating the contribution of backscattering from the NSC building structures to the total DR value. It will also allow calculating more accurately the estimated dose load on personnel dismantling unstable structures of the Shelter object as well as to model biological protection. These studies should be performed in the framework of the Program of scientific and technical support at the stages of commissioning and operation of the NSC [82].

The equivalent DR of γ -radiation in the near zone of the NSC was measured in 2017–2018 [83]. The purpose of the studies conducted from June to September 2017 was to evaluate the effectiveness of radiation protection after setting the NSC to the design position, comparing the results of the DR with the results of studies in 2003–2004 [84, 85].

The DR was measured in three vertical planes located at distances from the western buttress wall of the Shelter object in the western direction (Fig. 3.8): plane 1 — at a distance of 120 m; plane 2 — 265 m; plane 3 — 355 m. For each plane, the DR was determined at nine points at heights of 30, 60 and 90 m above the ground. A total of 27 height measurements were performed. There were used a set of three electronic dosimeters DMC 2000S, reader LDM 2000 by company MGPI, the device MKS-07 “Poshuk” with a detection unit BDBG-07 and an unmanned aerial vehicle. The results obtained are given in Table 3.3 and Fig. 3.9.

The analysis of the obtained data shows that as a result of preparatory works at the NSC construction site (dismantling of radioactively contaminated buildings and structures, removal of technological materials and solid RAW, concreting of the assembly area, covering the work area with “clean” rubble), construction of the technological building and other ancillary buildings and structures, as well as after the installation of the NSC in the design position, the ER in the near zone of the NSC decreased on average more than 10 times.

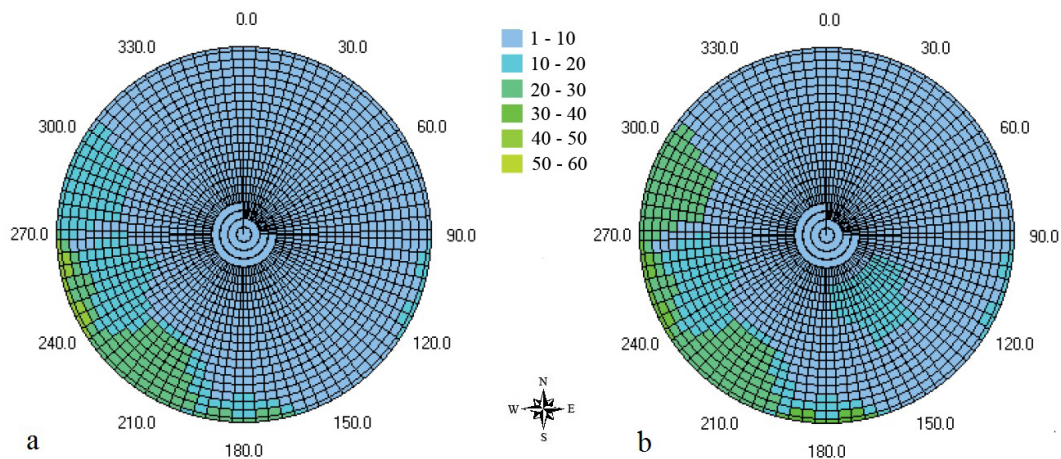


Fig. 3.7 — Cartogram of the angular distributions of the γ -radiation intensity from the upper hemisphere of the measurements of area 3 at point 4III:
a — before installation of the NSC arch, $\text{mR} \cdot \text{h}^{-1} \cdot \text{srad}^{-1}$; *b* — after installation of the NSC arch

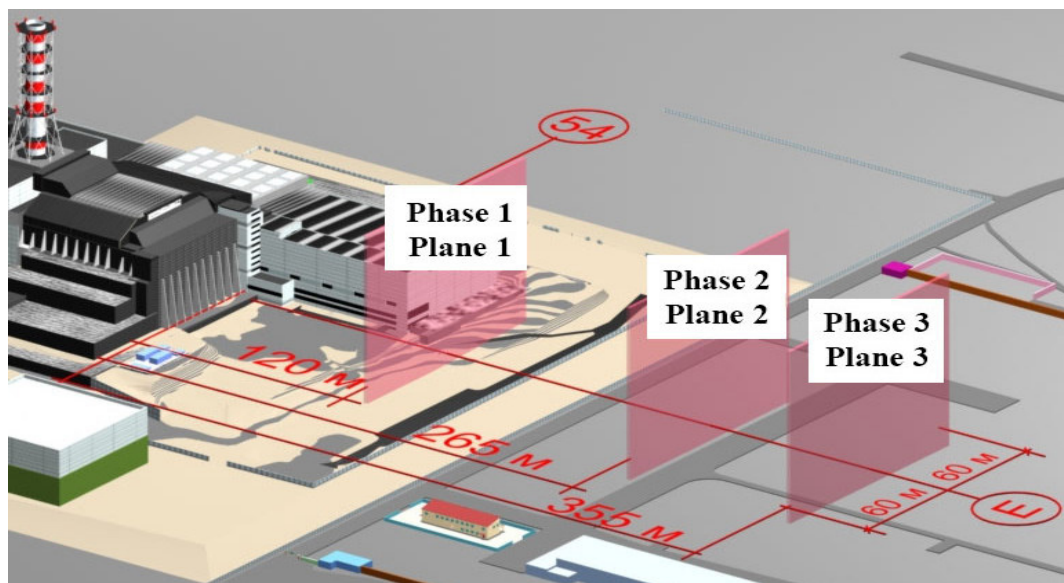


Fig. 3.8 — Areas of equivalent dose rate measurements, 2017

Table 3.3 — Dose rate in the near zone of the NSC, 2017

No. of control points	Coordinates of control points row/axis	Height of the control point, m	DR, $\mu\text{Sv/h}$ (ISP NPP data for 2003—2004)	DR, $\mu\text{Sv/h}$ (SSE “ChNPP” data after installing the NSC arch)	DR attenuation rate	The average DR attenuation rate
Plane 1						
1-1	P/73	30	126	8.6	14.7	9.9
1-2	Γ /73	30	197	45	4.4	
1-3	A/73	30	290	30	9.7	
1-4	P/73	60	182	12	15.2	
1-5	Γ /73	60	320	60	5.3	
1-6	A/73	60	506	51	9.9	
1-7	P/73	90	244	15	16.2	
1-8	Γ /73	90	421	72	5.8	
1-9	A/73	90	482	60	8.0	
Plane 2						
2-1	P/97	30	22	0.8	27.5	20.7
2-2	Γ /97	30	24	6.3	3.8	
2-3	A/97	30	20	2.4	8.3	
2-4	P/97	60	22	1.7	12.9	
2-5	Γ /97	60	33	0.8	41.2	
2-6	A/97	60	31	2.5	12.4	
2-7	P/97	90	34	2.1	16.2	
2-8	Γ /97	90	41	0.8	51.3	
2-9	A/97	90	30	2.4	12.5	
Plane 3						
3-1	P/113	30	9	0.6	15	12.6
3-2	Γ /113	30	11	0.6	18.3	
3-3	A/113	30	11	1.7	6.5	
3-4	P/113	60	11	0.6	18.3	
3-5	Γ /113	60	12	0.6	20	
3-6	A/113	60	12	1.9	6.3	
3-7	P/113	90	13	0.8	16.3	
3-8	Γ /113	90	14	1.9	7.4	
3-9	A/113	90	13	2.4	5.4	

In addition to the above factors that influenced the dynamics of DR changes (DR attenuation ratio), it is necessary to take into account the difference in time of studies [83, 84, 85], which is 14 years, i.e. take into account the half-life of radionuclides forming the DR.

Plane 1 is the closest to the Shelter object. Here the DR is significantly affected by the ionizing radiation sources (IRS) inside the Shelter object, not just the radioactive contamination of the area. Therefore, after decontamination of the area around the Shelter object, the DR attenuation ratio in this area is the lowest compared to other planes, as the IRS inside the Shelter object were not removed. They are only partially shielded by the NSC arch structures.

In plane 2, the DR attenuation ratio is the largest, because this plane lies at a considerable distance from the Shelter object, which reduces the impact of the latter, and decontamination of the territory contributed to a significant improvement in radiation situation, i.e. the DR decrease.

The attenuation ratio in plane 3 is almost twice less than in adjacent plane 2. This can be explained by the influence of the radiation-contaminated area directly adjacent to the NSC construction site on the western side.

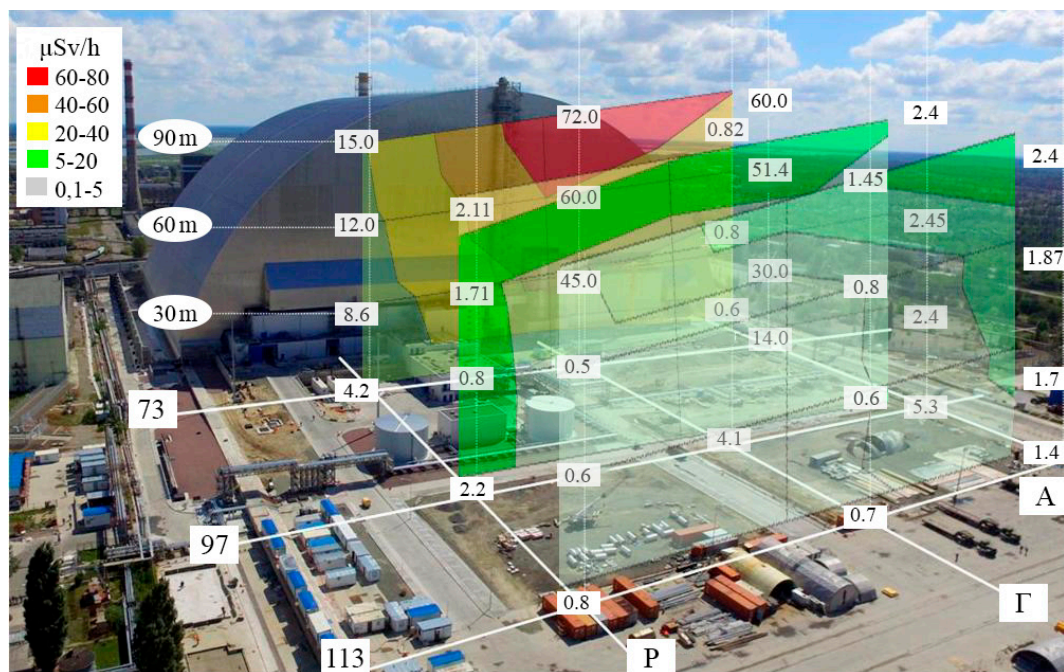


Fig. 3.9 — Dose rate cartogram in the near zone of the NSC, 2017 [83]

From April 17 to June 26, 2018, we continued to measure DR at different heights around the NSC, using the following equipment and tools:

- electronic radio dosimeter MiniTRACE- γ S100R;
- ShortLink. Radio signal transmission module;
- ShortLink. EPC receiver-unit;
- DataEXPERT software;
- MKS-07 “Poshuk” device with the BDBG-07 detection unit;
- unmanned aerial vehicle.

The DR measurements were performed in four vertical planes (Fig. 3.10): plane 1 — at a distance of 45 m from the western side of the NSC; plane 2 — at a distance of 10 m from the southern side of the NSC; planes 3 and 4 — at a distance of 10 and 120 m, respectively, on the northern side of the NSC; in each plane — at nine points at a height of 30, 60 and 90 m above the ground, the total height measurements number is 36 (Table 3.4, Fig. 3.11).

According to the obtained results, areas with maximum and minimum DR values in the near zone of the NSC were identified, which is very important for the organization of the NSC safe operation. The largest DR values were recorded on the southern side of the NSC (plane 2) and southwestern one (southern part of plane 1). The DR increases with height. On the northern side of the NSC (plane 3), the DR values are on average twice lower than in plane 2 on the southern side of the NSC.

Studies have recorded the radiation situation in the near zone of the NSC after installation it into the design position over the Shelter object [83]. Using the obtained data, the dynamics of changes in the radiation situation due to the dismantling of unstable structures of the Shelter object will be studied, and in the future — due to the FCM removal and transferring to the controlled state.

In 2020–2021, radiation studies were conducted at the NSC site to assess the dynamics of the DR changes and the angular distribution of γ -radiation after the completion of the NSC construction compared to the beginning of its construction. The radiometer-dosimeter MKS-07 “Poshuk” (see Fig. 3.1), the ShD-1 device with TLD-500K detectors (see Fig. 3.3), and the radiometer-dosimeter MKS-07 “Poshuk” with a remote collimated detector (Fig. 3.12) were used.

To carry out a comparative analysis of the obtained results with the data of previous radiation studies, measuring points of angular distributions of γ -radiation were selected, which are as close as possible to the measurement sites of previous studies.

When planning the study using the radiometer-dosimeter MKS-07 “Poshuk” with a remote collimated detector, some points were selected at a distance of 120 m from the Shelter object and others at a distance of 265 m. These areas have previously been well surveyed by measurements of aboveground γ -radiation fields before the construction of the NSC arch [84]. The DR research area and the places of measurement of angular distributions of γ -radiation intensity at the NSC site are shown in Fig. 3.13, and the cartogram of the DR distribution as of September 2020 is shown in Fig. 3.14.

Table 3.4 — The dose rate in the near zone of the NSC, 2018 [83]

No. of control points	Coordinates of control points row/axis	Height of control points, m	DR in the control point (data from MiniTRACE-γ S100R), μSv/h
Plane 1			
1-1	P/73	30	17.7
1-2	Γ/73	30	45.1
1-3	A/73	30	71.4
1-4	P/73	60	20.3
1-5	Γ/73	60	76.7
1-6	A/73	60	86.9
1-7	P/73	90	23.9
1-8	Γ/73	90	58.1
1-9	A/73	90	83.7
Plane 2			
2-1	И''/39	30	54.9
2-2	И''/55	30	38.4
2-3	И''/65	30	62.1
2-4	И''/39	60	89.2
2-5	И''/55	60	122.6
2-6	И''/65	60	76.0
2-7	И''/39	90	95.6
2-8	И''/55	90	142.9
2-9	И''/65	90	82.8
Plane 3			
3-1	М'/39	30	33.0
3-2	М'/55	30	17.4
3-3	М'/65	30	20.7
3-4	М'/39	60	59.5
3-5	М'/55	60	29.6
3-6	М'/65	60	22.3
3-7	М'/39	90	88.1
3-8	М'/55	90	47.3
3-9	М'/65	90	23.0
Plane 4			
4-1	ТТ'/39	30	10.4
4-2	ТТ'/55	30	9.2
4-3	ТТ'/65	30	7.1

No. of control points	Coordinates of control points row/axis	Height of control points, m	DR in the control point (data from MiniTRACE- γ S100R), $\mu\text{Sv/h}$
4-4	TT'/39	60	14.4
4-5	TT'/55	60	10.9
4-6	TT'/65	60	10.4
4-7	TT'/39	90	18.0
4-8	TT'/55	90	11.6
4-9	TT'/65	90	10.7

As shown in Fig. 3.14, the DR at the NSC site decreases with distance from the main sources of γ -radiation in the Shelter object and lies in the range from 0.7 to 10 $\mu\text{Sv/h}$, except for the area on the north side of the NSC near the Spent Nuclear Fuel Storage Facility (SNFSF-1), where the DR is approximately 18 $\mu\text{Sv/h}$.

To assess the dynamics of changes in the DR after installation of the NSC into the design position, Fig. 3.15 shows a cartogram of DR before the start of preparation of the NSC construction site [86]. It shows that the range of DR distribution directly near the structures of the Shelter object is from 35 to 125 $\mu\text{Sv/h}$. The DR in the local area is in the same range and the DR at the industrial site is from 5 to 30 $\mu\text{Sv/h}$.

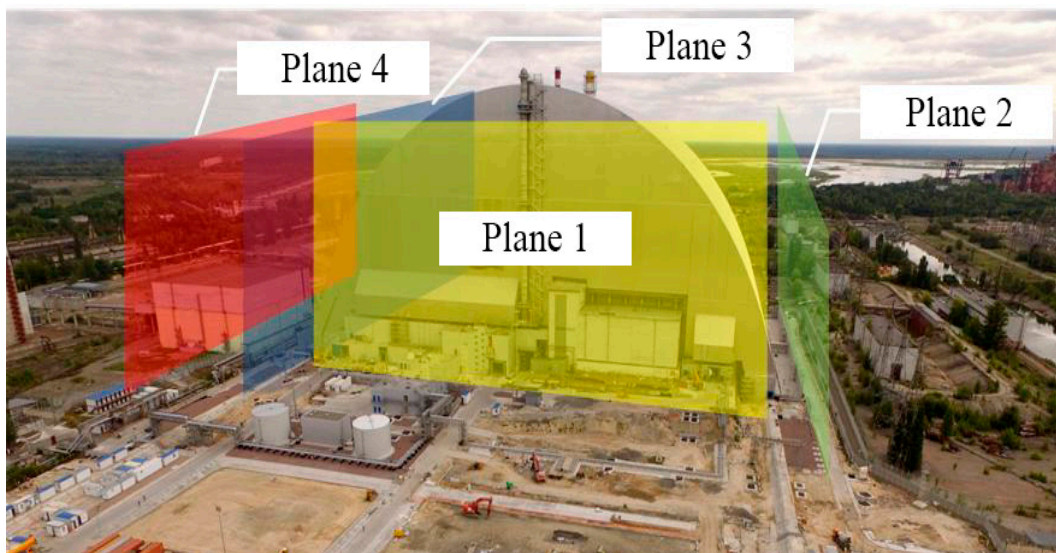


Fig. 3.10 — Dose rate measurement areas, 2018 [83]

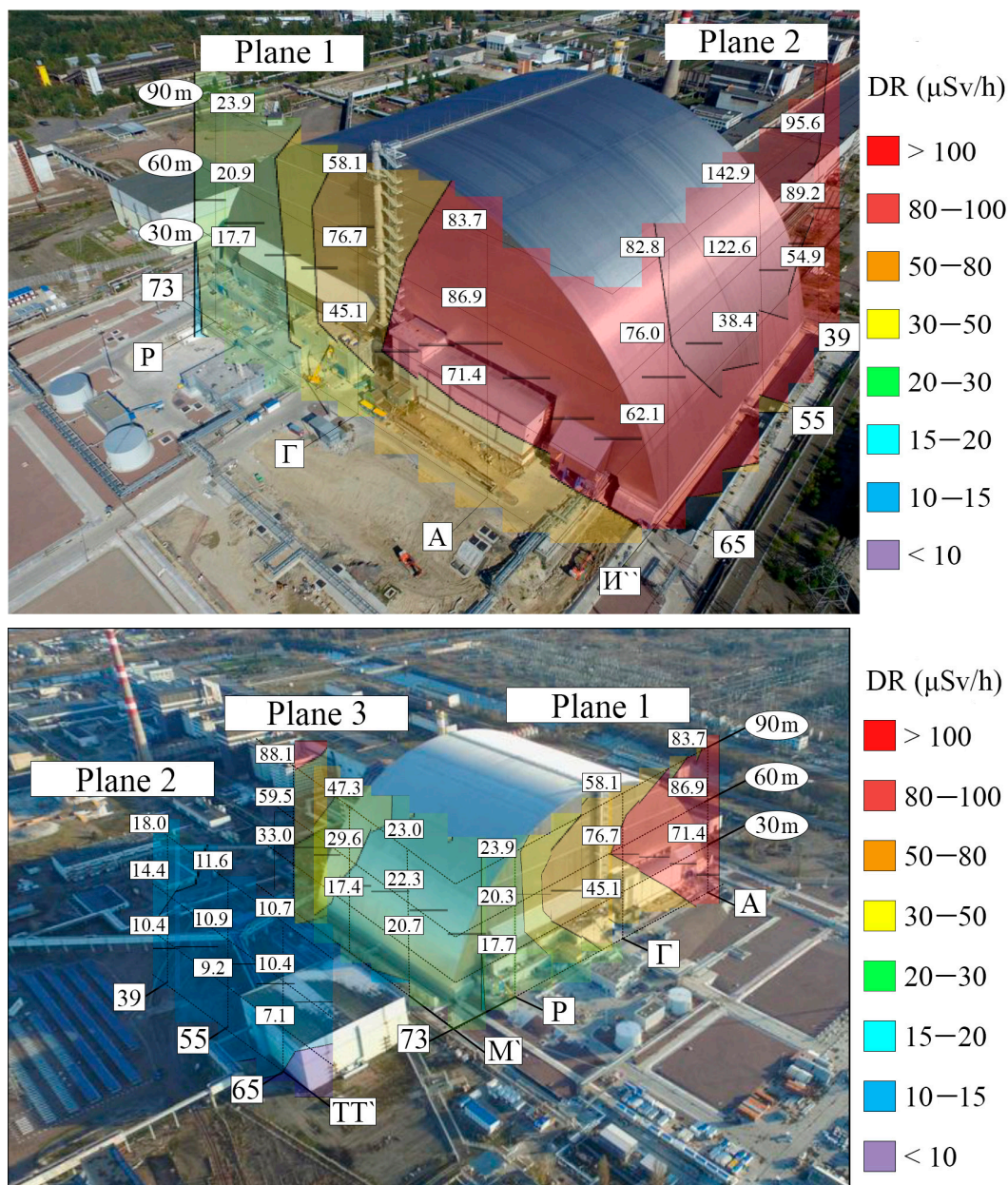


Fig. 3.11 — Cartogram of the dose rate in the NSC near zone, 2018 [83]:
 a — view of the south-western part of the NSC; b — view of the north-western part of the NSC

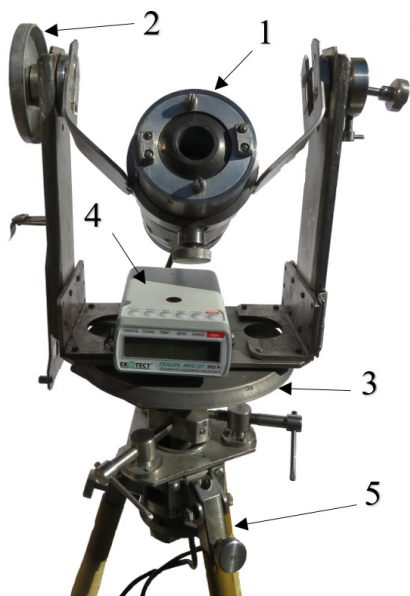


Fig. 3.12 — Radiometer-dosimeter MKS-07 “Poshuk” with remote collimated detector:
 1 — the lead case of the collimator with the detector of γ -radiation BDBG-10;
 2 — limb for installing a collimator with a detector in the vertical plane;
 3 — limb for installing a collimator with a detector in the horizontal plane;
 4 — radiometer-dosimeter MKS-07 “Poshuk”;
 5 — tripod

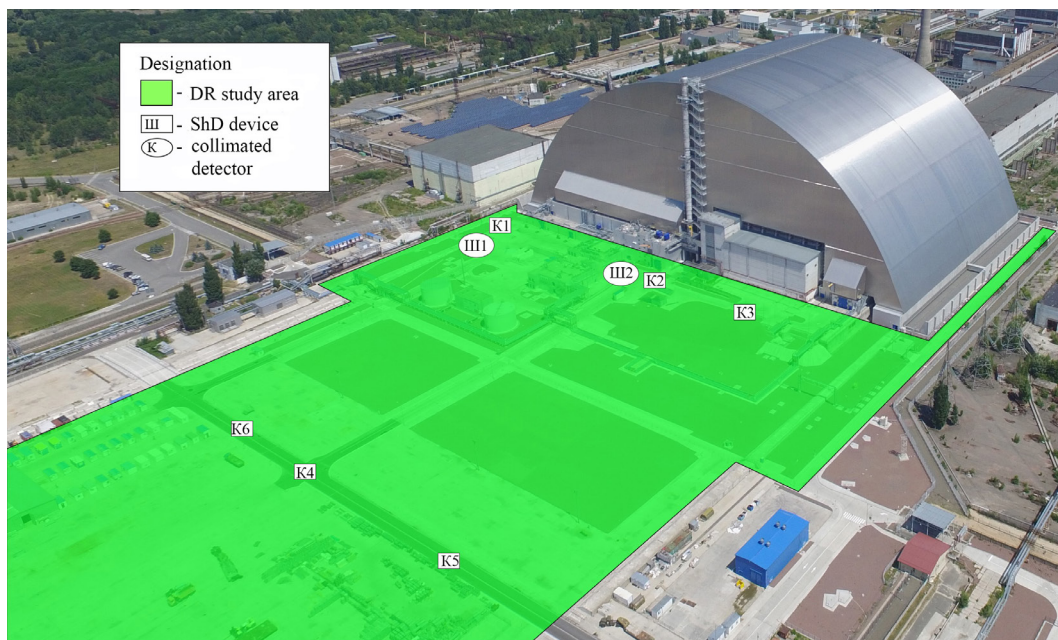


Fig. 3.13 — Research area of the dose rate and place of measurement of angular distributions of γ -radiation, 2020

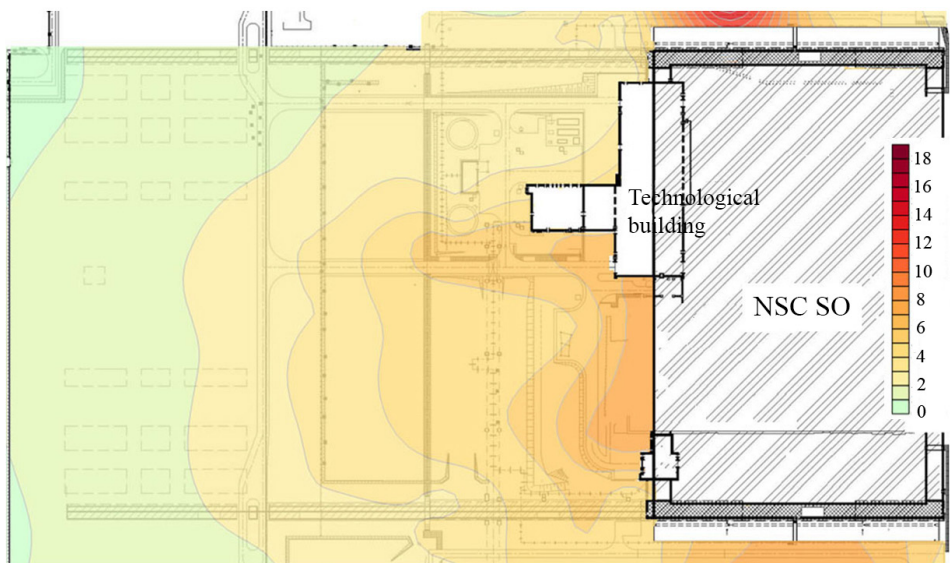


Fig. 3.14 — Dose rate cartogram, $\mu\text{Sv/h}$, at the NSC site, September 2020

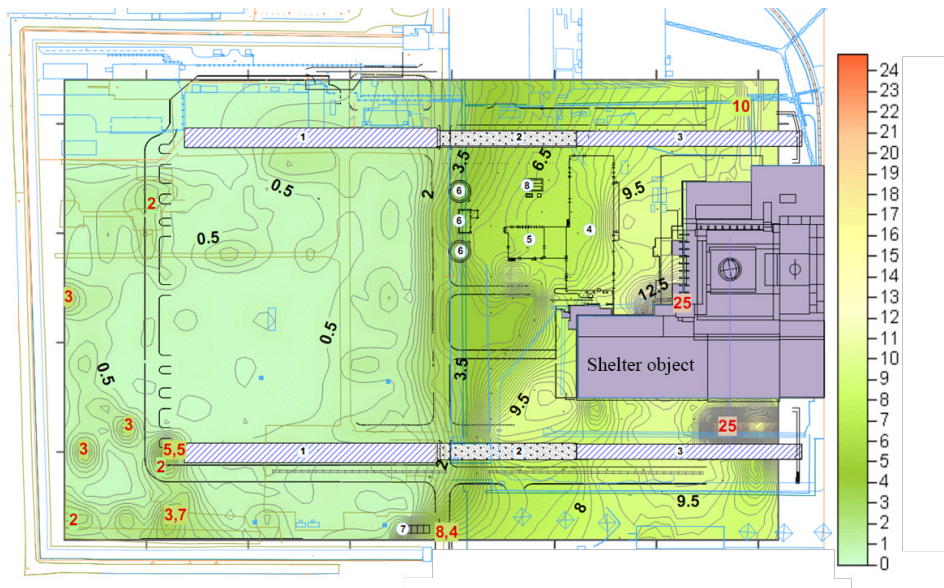


Fig. 3.15 — Dose rate cartogram, $\mu\text{Sv/h}$, before the start of preparation of the NSC construction site, 2008

Comparative analysis of DR before the start of the NSC construction and after its completion was performed for three areas (Table 3.5): arch assembly area; area of its movement; area of the design position of the arch. According to the results of comparative analysis after the installation of the NSC arch into the design position, the DR at the NSC site decreased from 5 to 15 times due to the removal of local sources of ionizing radiation during construction, as well as the construction of new buildings and structures (technological building, buildings of electrical devices, the western wall of the NSC EP), which act as protective barriers against the IRS contained in the Shelter object.

The angular distributions of γ -radiation at individual points at the NSC site were studied after the arch was installed into the design position in early 2021. The obtained data were compared with data from a similar study in 2004 at the same points on the Shelter object site.

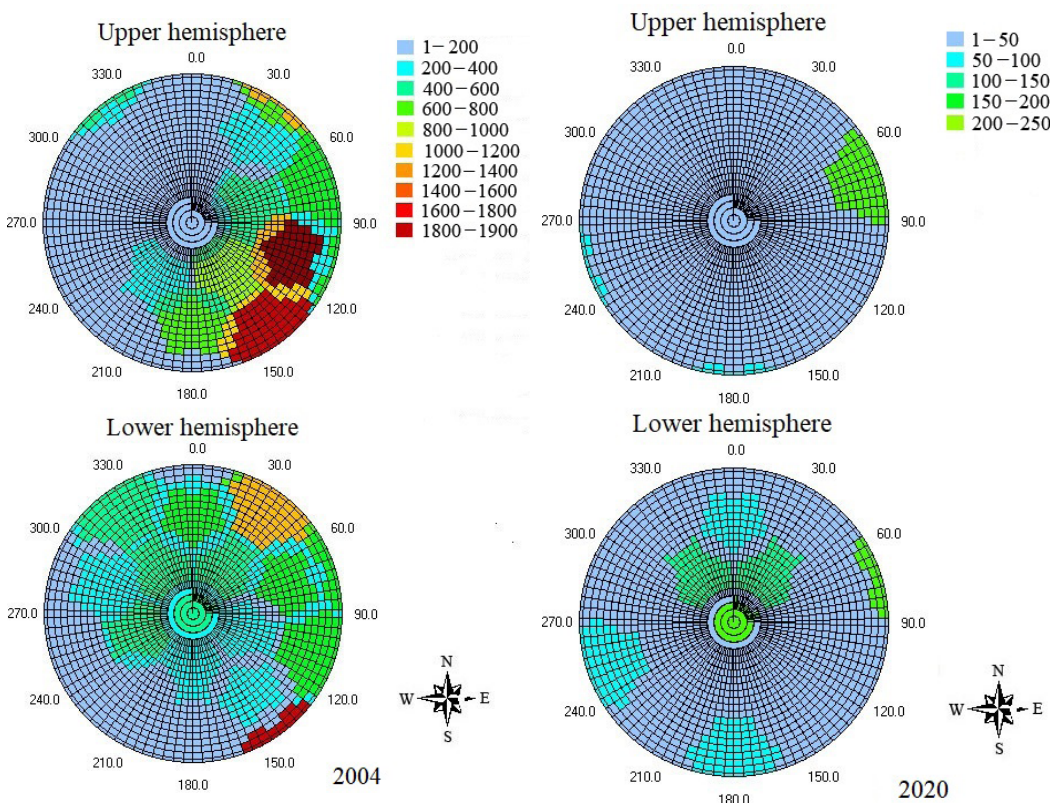


Fig. 3.16 — Cartogram of the angular distribution of γ -radiation at the point III1, $\mu\text{R} \cdot \text{h}^{-1} \cdot \text{srad}^{-1}$

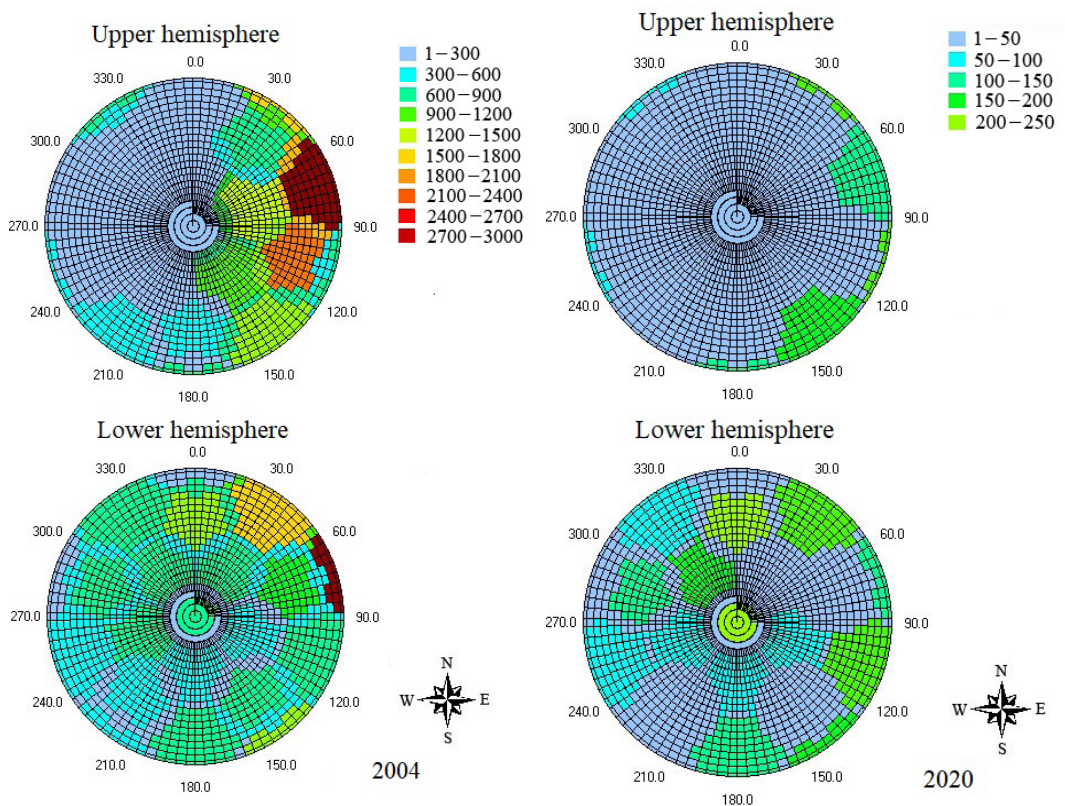


Fig. 3.17 — Cartogram of the angular distribution of γ -radiation at the point III2, $\mu\text{R} \cdot \text{h}^{-1} \cdot \text{srad}^{-1}$

Cartograms of the angular distribution of γ -radiation measured by the device ShD-1 at points III1 and III2 are shown in Figs. 3.16 and 3.17. A comparative analysis of the angular distribution of γ -radiation intensity at points III1 and III2 shows that the radiation intensity in 2020 decreased significantly compared to 2004. In addition, the directions to γ -radiation sources, which make the main contribution to the DR formation, have changed. At point III1, before the construction of the NSC, the largest contribution to the DR value was made by the sources located in the south-eastern direction. After the construction of the NSC, in particular the technological building, this direction was screened, and therefore the sources located in the northeastern direction (near the cascade wall) began to give the largest contribution to the DR value. At point III2, before the construction of the NSC, the

largest contribution to the DR was from the sources located in the eastern direction, and after the construction of the NSC — from the sources located in both northeastern and southeastern directions.

Table 3.5 — The results of a comparative analysis of the dose rate at the new safe confinement site

NSC site area	DR, $\mu\text{Sv/h}$	
	before the beginning of preparatory works	after the completion of the NSC construction
Arch construction area	~ 5	0,7—2
Arch movement area	5—35	4—7
Area of the design position of the arch	35—100	7—10

Table 3.6 — The results of a comparative analysis of dose rate and directions to sources of γ -radiation, which make a major contribution to the dose rate formation

Point no.	Before the NSC construction (2004)		After the NSC construction (2021)	
	DR, $\mu\text{Sv/h}$	direction to the main sources that form the DR	DR, $\mu\text{Sv/h}$	direction to the main sources that form the DR
K1	59	Sources located in the Shelter object	3.6	Sources located in the direction of the SSLRW
K2	83	The same	7.4	Sources located in the Shelter object
K3	150	– » –	14	
K4	23	– » –	4	Sources located in the Shelter object and in the direction of the SSLRW
K5	22	– » –	1.7	Sources located in the Shelter object
K6	22	– » –	1.6	Sources located in the Shelter object and in the direction of the SSLRW

The results of studies using a collimated detector, which indicate the main directions to the sources of γ -radiation, which form the DR at points K1—K6, are shown in Fig. 3.18.

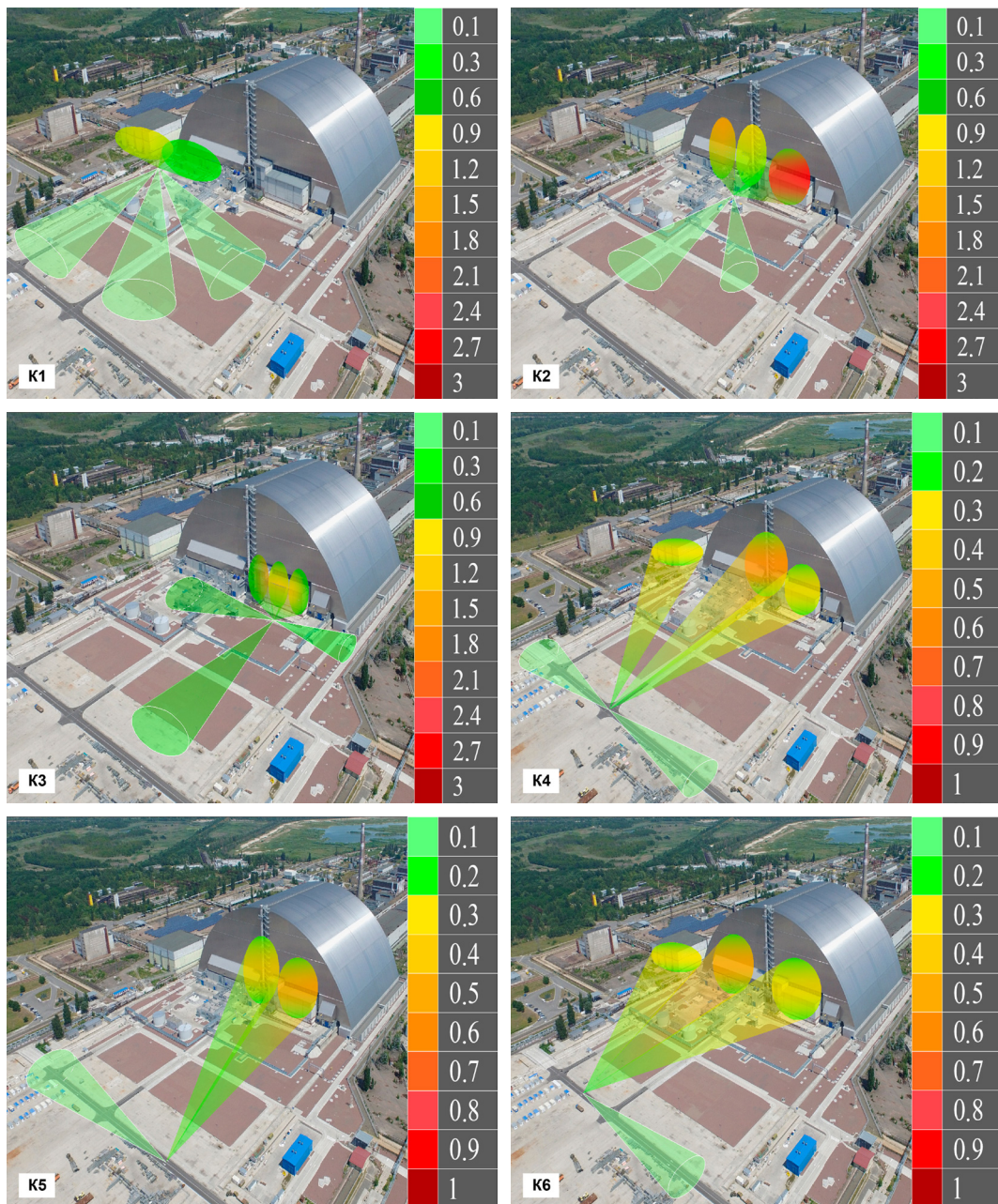


Fig. 3.18 — The main directions to the sources that form the dose rate at points K1—K6

A comparative analysis of DR and directions to γ -radiation sources, which make the main contribution to the DR formation at points K1—K6, before the construction of the NSC (2004 data) and after its construction (2021 data), is given in Table 3.6. As you can see, after the construction of the NSC, the intensity of γ -radiation at the measurement points decreased: the average value of DR in 2004 was 60 $\mu\text{Sv/h}$, and in 2020 it was 5.4 $\mu\text{Sv/h}$, i.e. about 11 times less.

The revealed small changes in the angular distribution of γ -radiation at some points are mainly related to the construction of new buildings and structures on the NSC site, in particular, the technological building and the NSC EP western wall. The influence of the direction, where the Storage of Solid and Liquid Radioactive Waste (SSLRW) is located, on the formation of DR at points K1, K4 and K6 became noticeable. However, the influence of the Shelter object on the formation of the radiation situation at the NSC site remains decisive.

3.2 Radioactive aerosols

Radioactive aerosols of Chornobyl genesis are the most radiologically dangerous. They have a significant impact on the dose load on personnel involved in the 1986 accident response and on the environment. That is why for 35 years special attention was paid to the behavior of RA, and the research was large-scale. Analyzing the work of recent years, we can identify three important stages in the formation and impact of RA.

The first stage (1986) is the active stage of the accident. The core temperature of the reactor, which was established as a result of residual heat release and combustion of graphite, led to additional dispersion and removal from the core of fuel particles of varying oxidation, as well as the emission of several volatile radionuclides. According to various estimates, from 10 to 30 t of fuel dust could be formed. Part of it was dispersed out of the destroyed fourth power unit and formed a fuel component of radioactive contamination of the territories, and the other part remained there in the form of sediments, contaminating the surfaces of building structures.

The second stage (1987—2017) is the construction and operation of the Shelter object. This protective structure made it possible to reduce the RA release into the environment and significantly improve (by several orders of magnitude) the radiation condition of the surrounding area. The introduction of a large-scale DSS reduced the levels of RA air pollution inside the Shelter object and emissions into the environment by several orders of magnitude.

The third stage (2017—2020) is the construction and commissioning of the NSC, which completely eliminated the RA release from the Shelter object into the environment.

Many years of research have shown that the Shelter object contains a significant amount of finely dispersed fuel formed during the accident, and its amount increased further as a result of the mechanical and physicochemical impact on fuel and radioactively contaminated building

structures. The steam explosion caused the release of dispersed fuel particles (ranging in size from units to tens of microns) into the atmosphere. Submicron fractions of fuel dust were estimated to be about 4% of total dust activity. The gravitational sedimentation velocity of dust particles of this size is approximately 85 cm/s. Radioactive dust was carried by air flows and formed radioactive contamination both inside the Shelter object and in the environment [87, 88].

Several mechanisms of the RA formation during the active stage of the accident have been established [28]:

fuel dispergation. Dispergated particles are found inside the Shelter and on the “western trace” formed immediately after the accident;

vapor zirconium reaction. This mechanism could be the reason for the formation of uranium-zirconium particles in the form of fragments of uranium oxides in the zirconium shell;

weathering from LFCM. The upper estimate of the formation rate of wind erosion products on the surface of brown LFCM is about $1.9 \mu\text{g} / (\text{cm}^2 \cdot \text{year})$. The total annual dust generation can reach $7 \cdot 10^{11}$ Bq in terms of α -activity and $4 \cdot 10^{13}$ Bq in terms of β -activity. Taking into account the specific activity of LFCM, the annual formation of radioactive dust by this mechanism could be several tens of kilograms;

high-temperature oxidation of fuel fragments in the air. Oxidized in the air, fuel tablets at temperatures of several hundred degrees in one to three hours disintegrate into U_3O_8 particles 1—15 μm in size;

LFCM destruction in the process of leaching. Atmospheric moisture entering the Shelter object interacted with the LFCM, destroying them and further forming RA smaller than 1 μm . From oxidized particles in neutral or slightly alkaline media (as in the Shelter object) and in the case of constant contact with water, 90% of the activity could go into solution within one year. The subsequent destruction of such microblocks formed submicron particles containing uranium.

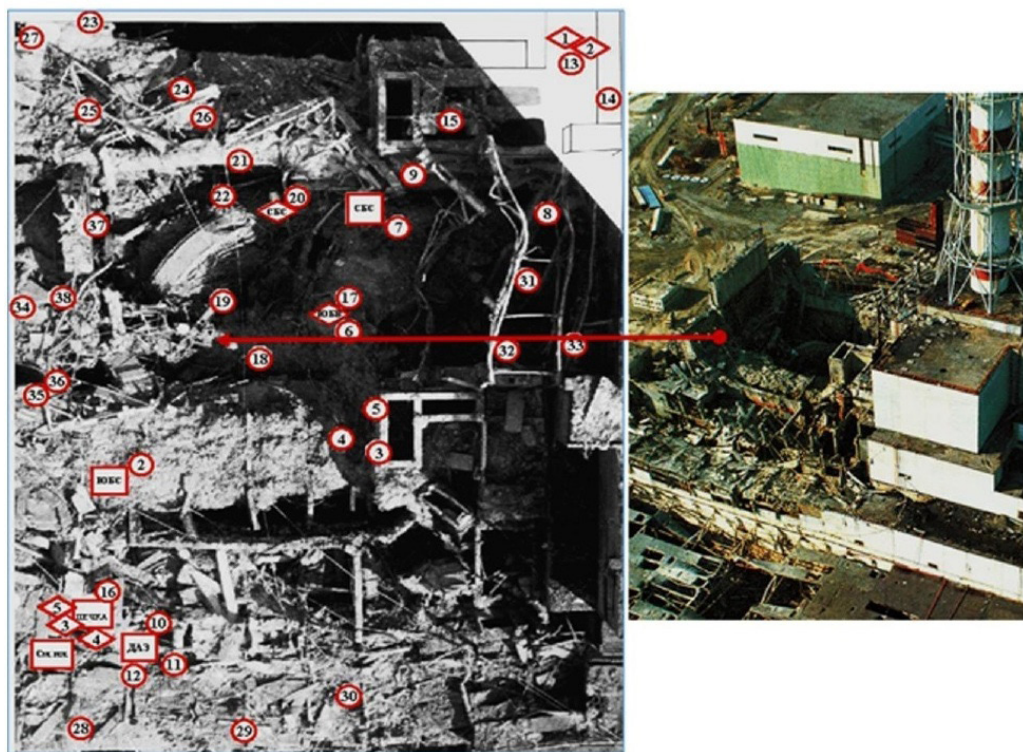
During 30 years (1987—2017) after the construction of the Shelter object, fuel dust was accumulated due to the destruction of open surfaces of LFCM and radioactively contaminated building structures, the formation of new sources of RA due to drying of sediments and their erosion, the destruction of new formations on the LFCM surface [5]. The properties of LFCM changed, which was manifested in their cracking, destruction into large fragments and, as a consequence, increased dust generation. As a result of the destruction, almost 50 kg of fuel dust could be formed annually on the lower marks of the Shelter object: $5 \dots 10 \text{ Bq} \cdot \text{cm}^{-2} \cdot \text{day}^{-1}$ for α -activity, $300 \dots 900 \text{ Bq} \cdot \text{cm}^{-2} \cdot \text{day}^{-1}$ for β -activity. The main contribution to the RA formation in the Shelter object was made by dust resuspension due to technogenic activity and the RA transport by air flows. The part of the dust was released outside the Shelter object through the ventilation stack of Units 3 and 4 of the Chornobyl NPP (until 2013), and then, until 2017, through the NVS and gaps in the walls and the roof of the Shelter object [5, 56].

The first full-scale study of the amount and properties of radioactive dust under the roof of the Shelter object in dozens of samples (Fig. 3.19) took place in 1997 [89, 90].

The generalization of the information accumulated by the end of the 1990s [89] showed: contamination on the surface of the destroyed fourth power unit is characterized by a dust density of 14 g/m^2 ;

the under-roof space of the Shelter object, where the MDSS operates, contains from 4 to 5 t of fuel dust (U) [38, 90, 91];

according to [26], the amount of fuel dust in the rooms that have air communication with the under-roof space, as well as in the reactor shaft (room 504/2) and rooms 305/2, 404/3 and 404/4, which after the accident formed a single space with room 504/2, contains from 2.7 to 3.5 t of radioactive dust, not fixed by dust-suppressing solutions and capable of dust resuspension.



○ — alcohol smear; ◇ — sample; □ — planchet

Fig. 3.19 — Sampling sites under the roof of the Shelter object, 1997

The approximate estimate of the amount of fuel dust (U) within the Shelter object at that time could be about 10 t.

The aerosol particle size composition of fuel particles both in a separate room and in the Shelter object is not constant in general. In contaminated rooms, the contribution of large particles in the aerosol distribution increases during the performance of works accompanied by shaking, a vibration of walls, ceilings, floors, etc. In the case when there are no external influences for a long time, heavy large particles sedimentate, and the distribution shifts to the area of small values. In the process of welding or other fireworks, the contribution of the submicron fraction increases [87].

The density of fuel particles is determined by the presence of uranium oxides UO_2 and U_3O_8 and ranges from 2 to 10.9 g/cm³.

The radionuclide composition of fuel particles depends on their varieties:

UO_2 is the most typical in the composition of most particles;

$\text{Zr}_x\text{U}_y\text{O}_z$ of different stoichiometric composition. In some samples, the contribution of this type of particles is up to 40%;

UO_x with Zr inclusions. The contribution of this type of particles to the total number is insignificant; this indicates that the temperature was above 2,600 °C only in some parts of the core;

particles of higher uranium oxides formed during high-temperature oxidation of fuel in the air. These particles have undergone a maximum degree of transformation in the past due to their small size (units of microns) and high uranium content.

The radionuclide composition of fuel containing particles can be considered as “medium fuel”. The respirable fraction of particles (up to 10 µm) has twice the depletion of cesium isotopes, but one and a half to two times enrichment of the nuclides strontium, plutonium and americium.

Radionuclide composition of fuel particles on 01.01.2015:

Nuclide	Activity, Bq/g (U)
⁹⁰ Sr	$5.97 \cdot 10^8$
⁹⁰ Y	$5.97 \cdot 10^8$
¹³⁷ Cs	$7.23 \cdot 10^9$
²³⁸ Pu	$6.19 \cdot 10^6$
²³⁹ Pu	$5.00 \cdot 10^6$
²⁴⁰ Pu	$8.18 \cdot 10^6$
²⁴¹ Am	$2.41 \cdot 10^7$
²⁴¹ Pu	$2.41 \cdot 10^8$

The ratio of the radioactive component of dust to the non-radioactive one is estimated at 0.5–1%. A large amount of radioactive dust in the under-roof space in the area of the MDSS operation is fixed by dust suppression solutions. But a significant amount of dust (almost 4 t)

is contained in rooms that are connected by air flows to the under-roof space, outside the scope of the MDSS operation, and can form contamination due to dust resuspension. Radioactive dust contains all radionuclides of Chernobyl genesis (^{90}Sr + ^{90}Y , ^{137}Cs , ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{241}Am , and uranium). The activity median aerodynamic diameter (AMAD) of dust particles is in the range of 0.1–250 μm .

3.2.1 Fuel hot particles

In addition to the described morphologies of the fuel dust of the Shelter object, the hot particles (HP) are of special interest. Formed in different periods of the active stage of the accident, at different temperature conditions, they carry information about possible chemical and thermophysical processes of their occurrence, and having a small size and high specific activity, are the most dangerous.

The HPs are divided into weakly and strongly transformed fuel particles [92–94]. Weakly transformed fuel particles (Fig. 3.20, *a*) could be formed in the first stage of the accident and were released mainly in the western direction. They are fragments of nuclear fuel with a well-defined granular structure or individual grains (crystallites) of UO_2 . In Fig. 3.20, there are clearly visible bubbles — the result of diffusion and accumulation of gaseous fission products at a temperature of 1300–1700 K. If the temperature is higher, there is a migration of the bubbles in the intergranular space and their merging, which gives a specific pattern of the grain surface (Fig. 3.20, *b*).

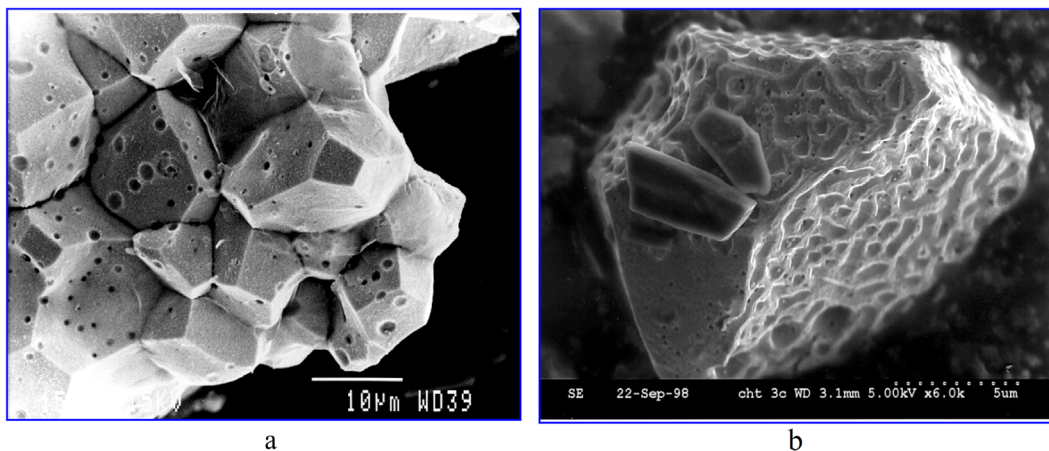


Fig. 3.20 — Appearance of weakly transformed fuel particles obtained by electron microscopy:

- a* — at the Agricultural University of Norway (NLH, Norway);
- b* — at the Institute for Protection and Nuclear Safety (IPSN, France)

In the subsequent stages of the accident, fuel particles with a high degree of matrix transformation were formed. Due to the diffusion of oxygen, the surface of UO_2 cracked due to the different densities of the crystal lattices of the formed higher uranium oxides. At high temperatures, the fuel could partially melt (Fig. 3.21, *a*), in contact with various structural materials (graphite, zirconium, steel, etc.) and materials of the reactor backfill (sand, lead, etc.), which led to the formation of complex chemical compounds, especially on the surface of fuel particles.

Flowed fuel particles contain zirconium. This is obviously due to the higher melting point of uranium oxides compared to their alloys with zirconium and cerium. “Pure” (UO_2) fuel particle flowed with zirconium alloy (U-O-Zr), is shown in Fig. 3.21, *b*.

Studies of the HP characteristics [95] showed that about half of the particles had a matrix of nuclear fuel, and therefore they can be classified as fuel HP. Structural chemical elements were found in the matrix of the remaining particles, so they were classified as fuel and construction hot particles (FCHP).

Fuel HPs are uranium oxide that has retained all the morphological features of irradiated nuclear fuel. During the operation of the reactor, under the influence of high temperatures in the inner zone of the fuel pellet, there is recrystallization of the initial structure of the compressed uranium dioxide powder (particle size approximately $3\text{ }\mu\text{m}$), i.e. an increase in grain size to $25\text{ }\mu\text{m}$ due to recrystallization of them. These grains have the crystal habit of polyhedra, the faces of which are mostly pentagonal. The smooth surface of these faces is

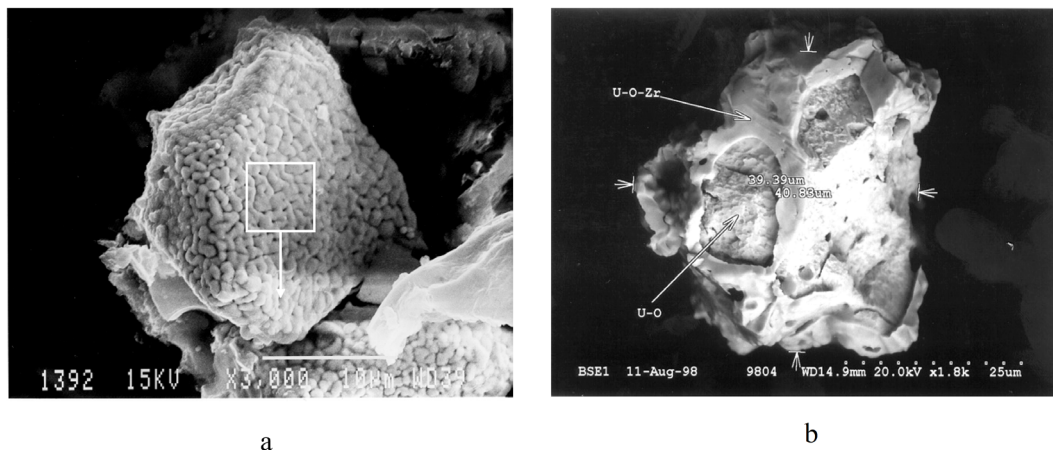


Fig. 3.21 — Typical appearance of strongly transformed fuel particles obtained by electron microscopy:

a — at the Agricultural University of Norway (NLH, Norway);
b — at the Institute for Protection and Nuclear Safety (IPSN, France)

decorated with holes from bubbles of gas atoms (uranium fission fragments), the number of which can be used in the first approximation to estimate the duration of the fuel magazine campaign (Fig. 3.22).

The particles were found among the fuel HP (Fig. 3.23), the surface morphology of which is very different from that shown in Fig. 3.22. Such microtopography of the surface of the irradiated fuel grains is observed after testing the spent FE in a pulse reactor [96], where the FE was affected by a short (about 3 ms) powerful neutron flux pulse. The gaseous fission fragments formed in these circumstances create an excess pressure in the fuel matrix, which causes plastic deformation of the surface of uranium dioxide crystallites with the formation of a characteristic texture that reflects the location of dislocations in the surface layer. The number of such particles with varying degrees of surface damage is approximately 10% of all fuel HP selected on the western trace. The presence of particles with similar surface microtopography clearly indicates the effect of a neutron pulse of an explosive nature.

Fuel and construction HP have a matrix with the elemental composition U-Zr-O. The ratio of uranium and zirconium in the composition of FCHP is very diverse — from zirconium particles with an admixture of uranium dioxide to particles consisting of uranium dioxide with an admixture of zirconium. The structure of FCHP varies from a homogeneous composition (such as a solid solution of $\text{UO}_2\text{-Zr-ZrO}_2$) with an admixture of corrosion-resistant steel to coexistence within one particle of regions of variable composition with an inhomogeneity discreteness of several micrometers or more. X-ray diffraction analysis of some FCHP shows that the material of which they are composed has clearly

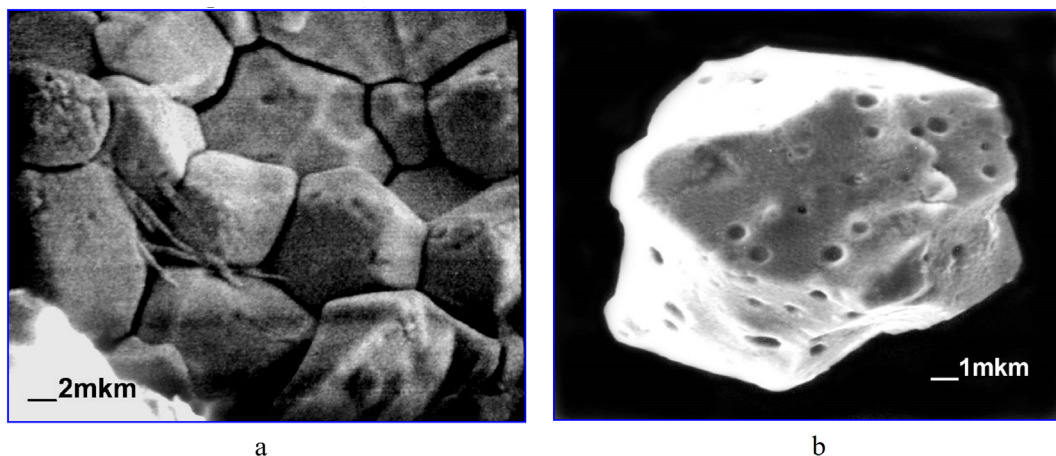


Fig. 3.22 — Fragment of fuel and construction hot particles:
a — the set of equilibrium grains of uranium oxide, *b* — a single grain of UO_2 crystallite

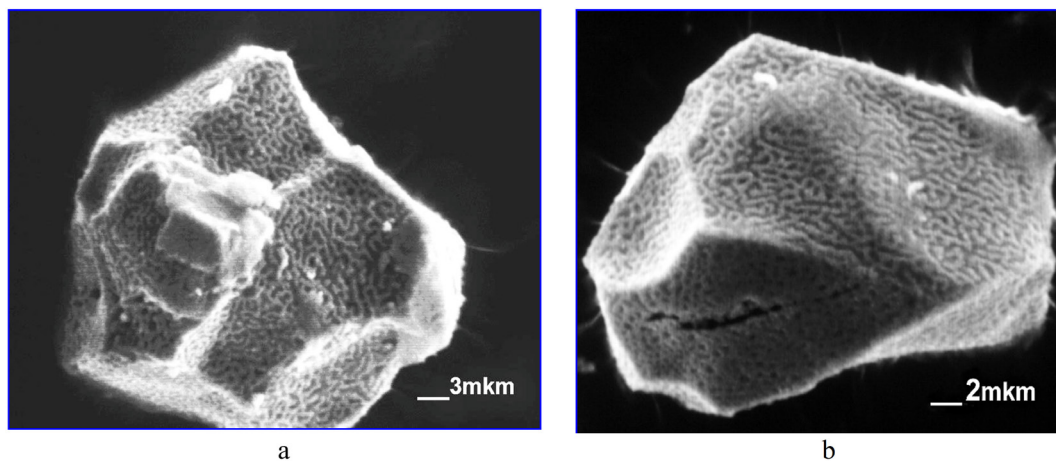


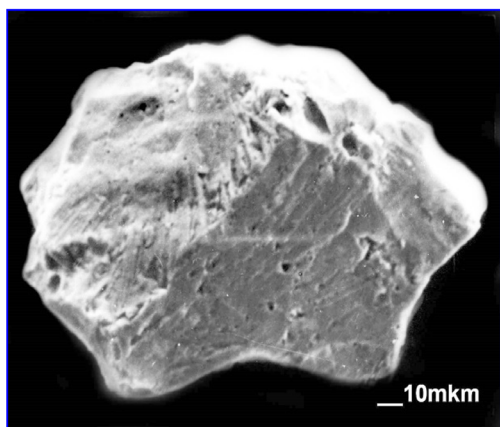
Fig. 3.23 — Fuel and construction hot particles:
a — from the western trace; *b* — from a fuel element fragment of the Shelter object

passed through the stage of rapid crystallization and gives a fairly clear diffraction pattern. Their radiographs cannot be identified with UO_2 , Zr, or ZrO_2 and at the same time are compared well with the reference spectra of $\text{Nd}_2\text{Zr}_3\text{O}_7$, $\text{Ce}_2\text{Zr}_3\text{O}_{10}$ [97]. This confirms the structure of the matrix of these particles as a solid solution of UO_2 -Zr-Zr O_2 .

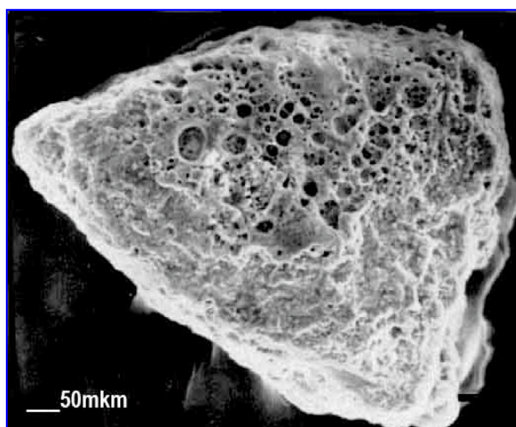
The appearance of FCHP is diverse, the maximum size of the found particles is 850 μm . Typical morphological characteristics of these particles are irregular fragmentary, massive forms, slag-like and flowed surfaces (Fig. 3.24). The particles with a massive structure (Fig. 3.24, *a*) are characterized by a monolithic structure with sharp chips and a smooth surface of the faces, indicating their formation due to grinding of the material in the solid phase.

According to the results of quantitative and structural analyzes, before the reactor explosion, there was oxidation and melting of zirconium parts of FA and fuel alignment plates, melting of fuel rods. The ^{60}Co content in almost all FCHP indicates that during a few seconds there was an intensive mixing of the melt, which should be of low viscosity. The surface of slag-like particles (Fig. 3.25, *a*) contains rounded cavities from gas bubbles of different sizes and concentrations, which indicates the rapid cooling of the material. All FCHP larger than 10 μm have an isometric form; among them, there are no particles formed from the liquid phase, i.e. spherical or drop-shaped.

Small particles (0.5–2 μm) of spherical shape were found on the surface of some FCHP and in the soil (Fig. 3.25, *b*). They could be formed due to condensation from the vapor phase in the epicenter of the explosion with subsequent deposition on various surfaces, in particular on the FCHP.



a



b

Fig. 3.24 — Fuel and construction hot particles:
a — of a massive structure, b — with caverns from intense gas release

The study of FCHP allows establishing the chronology of the development of emergency processes in the reactor. Initially, in the local emergency area of the reactor, there was a melting of the shells of FE, bearing rods, fuel alignment plates and fuel rods of the pellets of the lower FA with the formation of the liquid phase $\text{UO}_2\text{-Zr-ZrO}_2$. Then the melt was

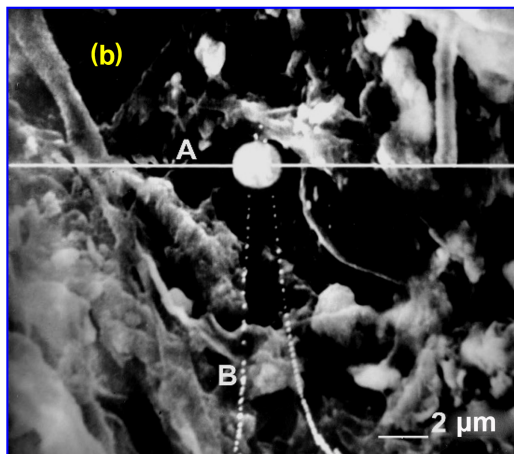
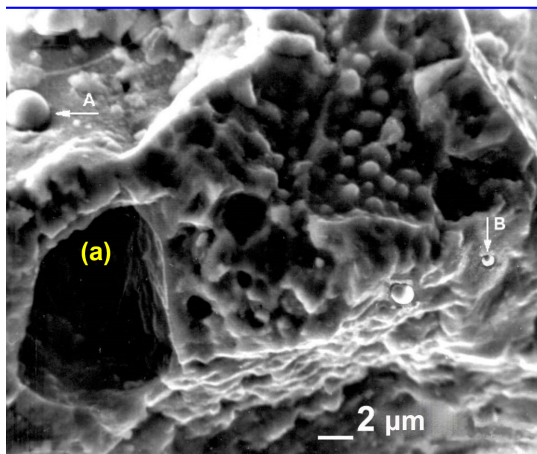


Fig. 3.25 — Photos of fuel and construction hot particles:
a — cavities from gas bubbles and spherical microparticles on the surface of the “large” FCHP;
b — spherical FCHP in the soil; A — probe scanning line; B — distribution of uranium

cooled to a solid phase, after which it was dispersed into micron-sized particles by a powerful explosion and released outside the power unit in the form of aerosol particles.

3.2.2 Radioactive aerosols in the under-roof space of the Shelter object

The main sources of RA in the under-roof space of the Shelter object are the destruction of open LFCM accumulations with the formation of fuel dust, destruction of building structures, destruction of dried bottom sediments of RW, dust resuspension and transport as a result of man-made work (work of MDSS, construction and installation work), dust resuspension and transport due to aging and collapse of unstable building structures.

Before the NSC construction, RA were monitored for many years at various points in the Shelter object space, in particular, RA emissions due to roof gaps (Fig. 3.26, 1), in the bypass system (Fig. 3.26, 2), at the upper marks and the under-roof space, RA generation from open LFCM accumulations.

Regular control of the concentration and particle size composition of RA, released from the under-roof space of the Shelter object into the atmosphere through the bypass system and the ventilation stack, has been carried out since 2002. Samples are taken in room 2016/2 (Fig. 3.27, a) through the hatch (3.27, b). The selection of aerosol particles and their classification by size is carried out using a five-stage impactor IBF-5K. The device sorts aerosol particles in five ranges of aerodynamic diameter: up to 0.5 μm ; 0.5—1.2 μm ; 1.2—3.7 μm ; 3.7—8.5 μm ; 8.5—17.0 μm . To sort particles up to 0.5 μm , a fine filter is used to capture submicron-sized aerosols more fully. The content of ^{137}Cs , ^{154}Eu and ^{241}Am is determined by the γ -spectrometric method.

Before the construction of the NSC, the volumetric activity of $\Sigma\beta$ -radionuclides in the bypass system (see Fig. 3.28) differed in a wide range of readings — from 0.1 to 1,000 Bq/m^3 , which is due to the external influence of man-made activity in the Shelter object [87]. This effect was not the dominant factor, it was episodic, amplitude-intensive and short-lived. The volumetric activity of $\Sigma\beta$ in 2016 ranged from 0.34 to 3.9 Bq/m^3 . As a rule, the carriers of radionuclides (products of the Chornobyl accident) were particles with AMAD of 8—11 μm [98, 99].

After the commissioning of the NSC (Fig. 3.29 [87]), the dynamics of the volumetric activity of $\Sigma\beta$ in the bypass system is constant (in 2020 it was 0.2...0.33 Bq/m^3), and its trend is shifted towards minimum values. Let's pay attention to the increase in the contribution of condensed ^{137}Cs to the total activity, which is due to the significant amount of construction dust that was formed during the construction of the fencing circuit and internal works in the NSC. The AMAD of ^{137}Cs carrier particles ranged from 4 to 14 μm , and the ^{241}Am carrier particles ranged from 4 to 6 μm [100].

To assess the formation of unfixed radioactive dust in the under-roof and inter-but-tress spaces, to control the activity and composition of aerosol fallout radionuclides in

the under-roof space of the Shelter object, two deposition planchets were installed at the control points: one on the south-eastern corner of the western support of the beam “Mammoth”, mark +43,000 m, axis 50, row B, room 2007/3 (Fig. 3.29); other one is in the inter-buttress space. According to the results of the control, the RA deposition density in the under-roof space of the Shelter object in 2017–2019 decreased several times compared to the beginning of observations (July 18, 2014) [100]. The sharp increase in the activity and

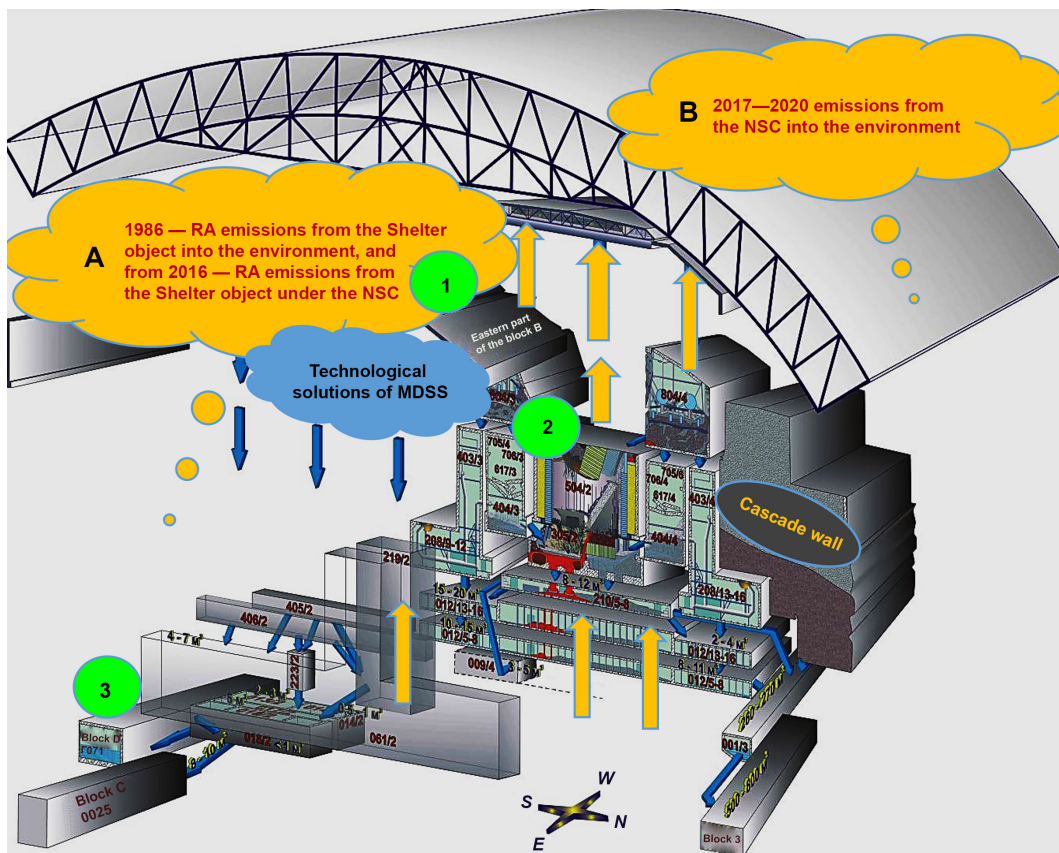


Fig. 3.26 — Scheme of formation and dispersion of radioactive aerosols in the NSC:

A — emissions from the Shelter object; B — emissions from the NSC;

- 1 — control point of the RA emissions into the NSC main volume on the upper marks on the roof of the Shelter object;
- 2 — control of the particle size and radionuclide composition of RA in the under-roof space of the Shelter object (bypass system);
- 3 — control of the surface air in the main volume of the NSC

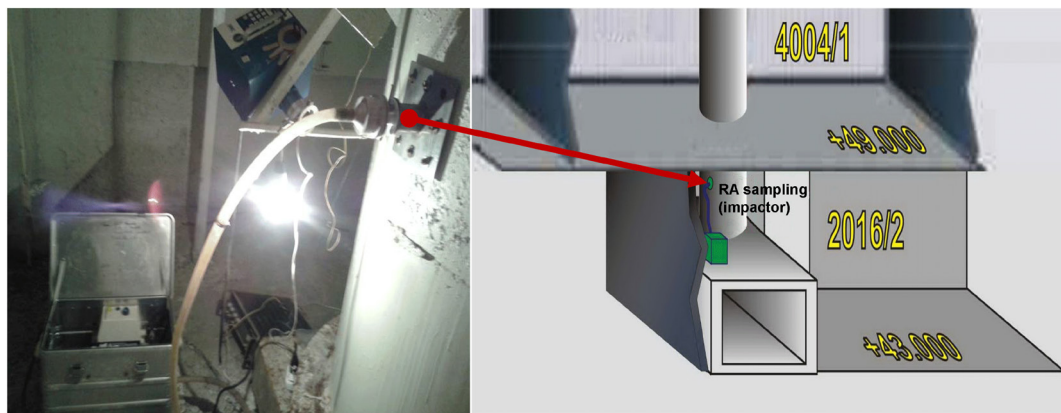


Fig. 3.27 — Location of the radioactive aerosol sampling point in the bypass system (room 2016/2 of the Shelter object)

enrichment of aerosols with condensed cesium in 2016—2017 (Fig. 3.30) was caused by significant dust rise during the sealing of the NSC arch. To compare the nature of the RA behavior in the premises of the Shelter object (Fig. 3.31), we present the data of the deposition density in room 402/3 [100].

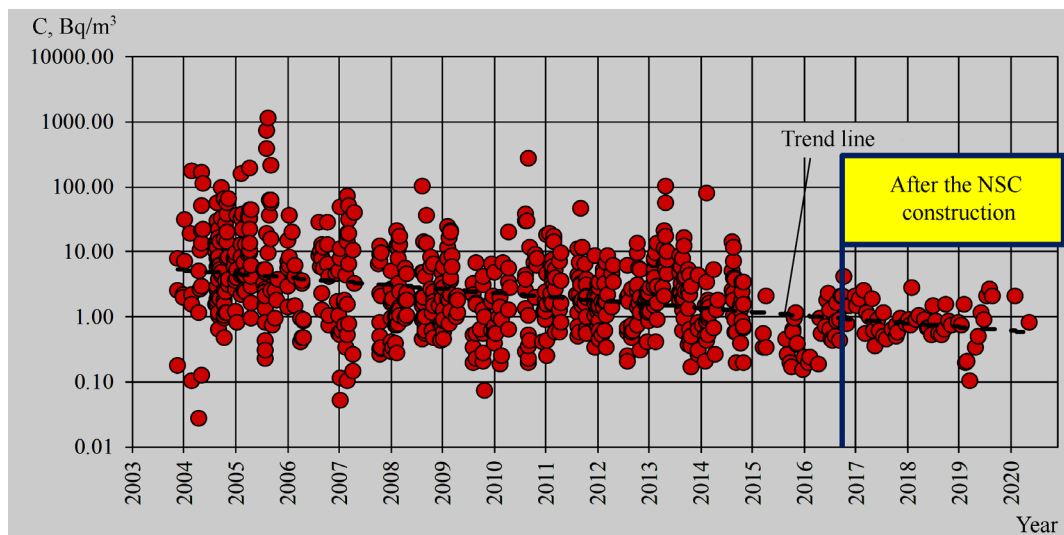


Fig. 3.28 — Dynamics of volumetric activity of $\Sigma\beta$ in the bypass system, 2003—2020

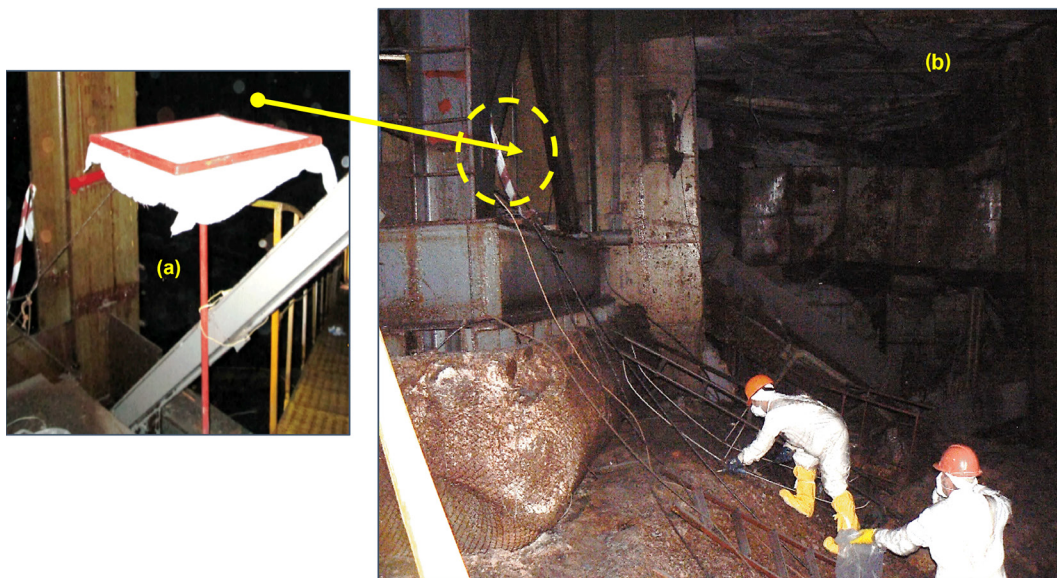


Fig. 3.29 — Deposition planchet for aerosol fallout sampling near the western support of the “Mammoth” beam:

a — General view of the deposition planchet; *b* — a place of installation

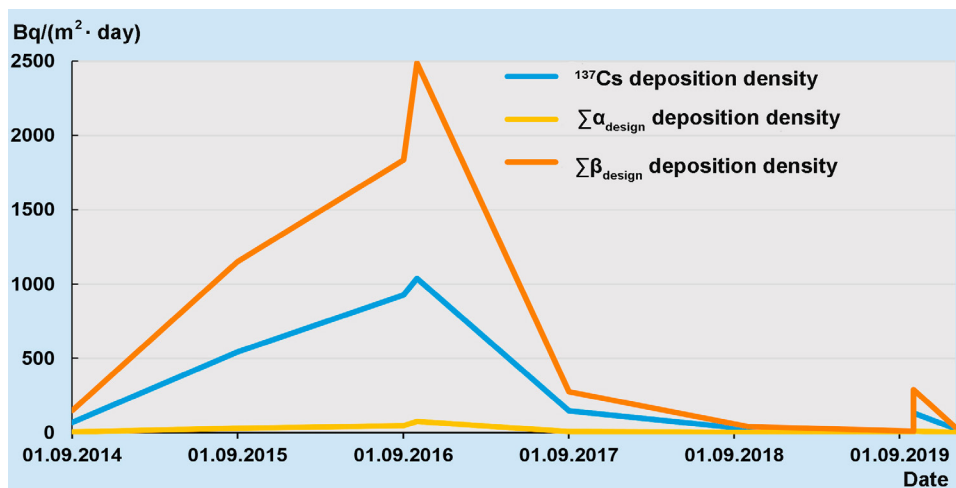


Fig. 3.30 — Deposition density of ^{137}Cs , $\Sigma\alpha_{\text{design}}$, $\Sigma\beta_{\text{design}}$ in the under-roof space of the Shelter object

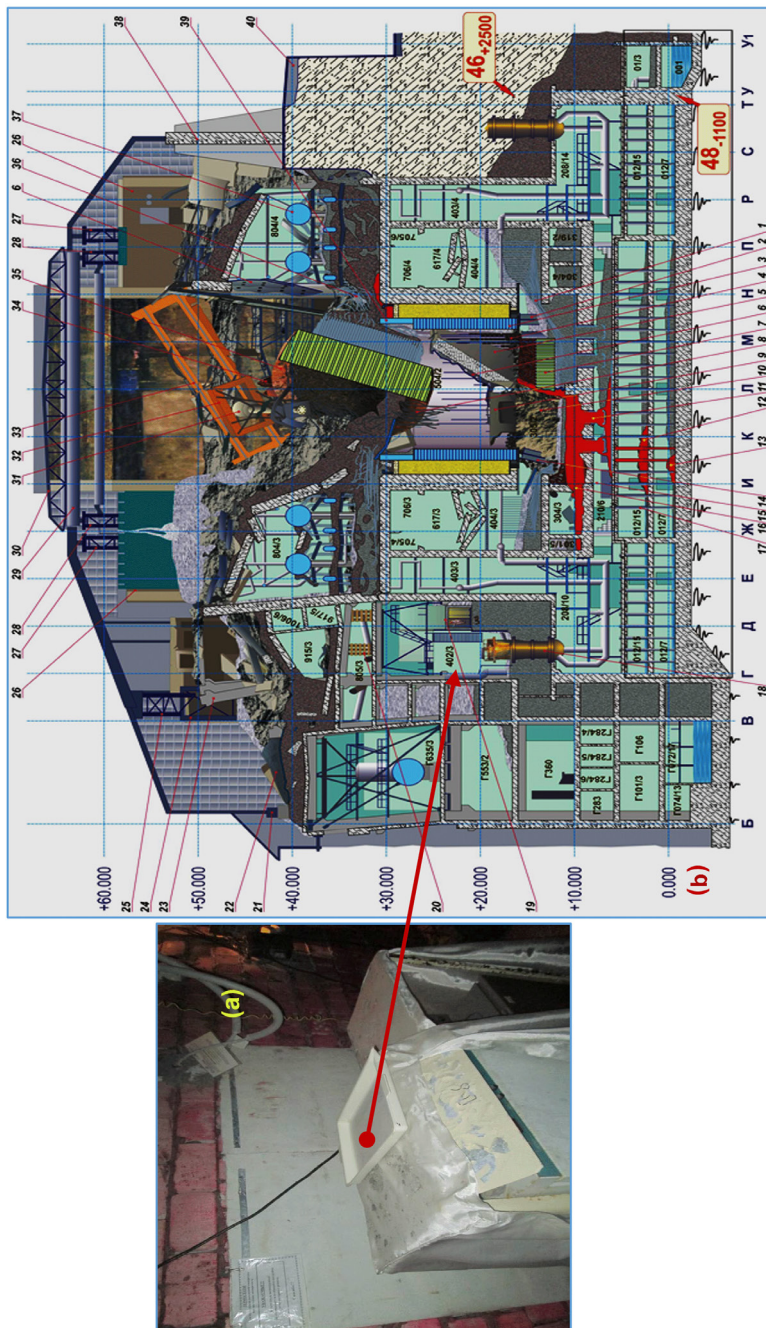


Fig. 3.31 — Control of radioactive depositions in room 402/3:
 a — cuvette with filter material; b — location of the deposition control point in room 402/3 on the scheme of the Shelter object

After the NSC was installed, the deposition density in the under-roof space of the Shelter object for the main nuclides (see Fig. 3.30) decreased by several orders of magnitude. The ratio of ^{137}Cs and ^{241}Am radionuclide concentrations in aerosol deposition samples significantly exceeds (73%) this value in the base fuel composition, which indicates the enrichment of ^{137}Cs due to its infusion from other RA sources. At an average annual $\Sigma\beta$ -emitters deposition density rate of $6.1 \cdot 10^{-4} \text{ Bq}/(\text{m}^2 \cdot \text{s})$, the surface contamination at the control point, without taking into account the natural decay of radionuclides, increases

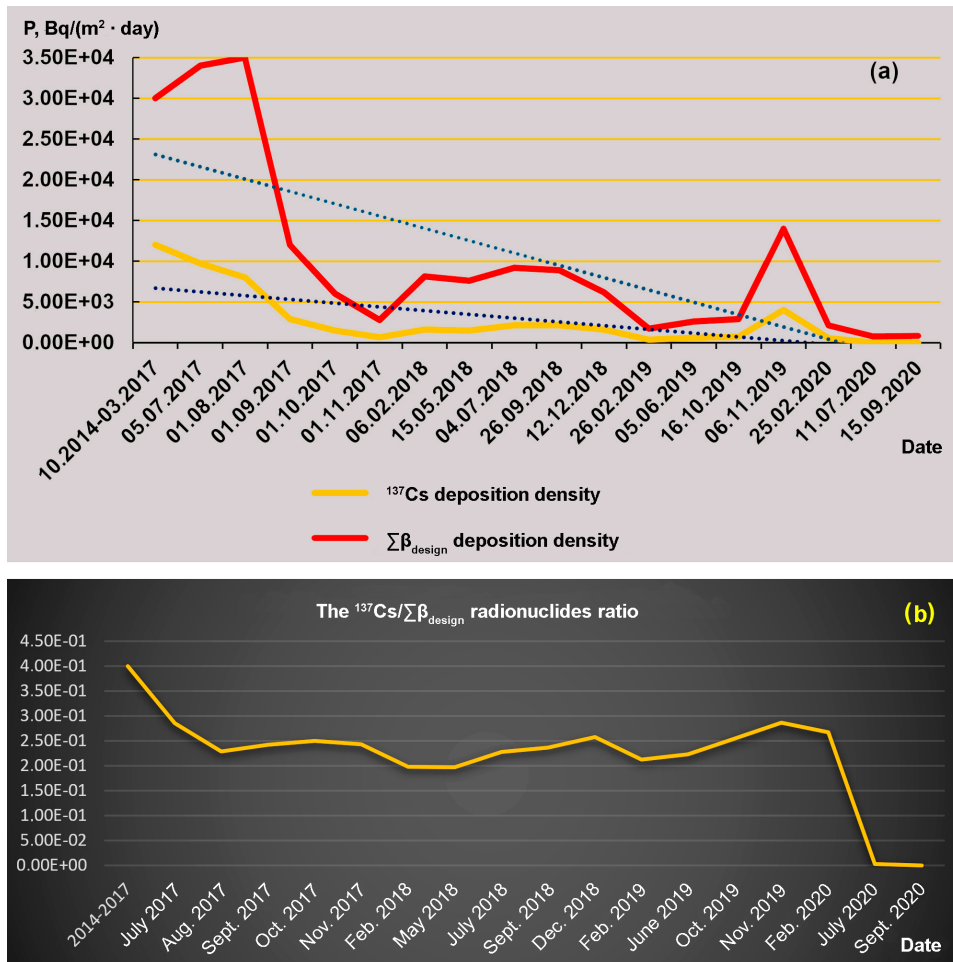


Fig. 3.32 — Characteristics of radioactive depositions in room 402/3:
 a — ^{137}Cs and $\Sigma\beta$; b — $^{137}\text{Cs}/\Sigma\beta$

by 58 particles ($\text{cm}^2 \cdot \text{min}$). The same nature of the deposition density (Fig. 3.32) is observed in room 402/3: a sharp decrease in the RA activity with significant enrichment of ^{137}Cs and ^{90}Sr . However, the ratio of radionuclide concentrations in depositions in room 402/3 is stable and close to fuel one. Some significant increases in the RA activity are caused by construction and installation works or the collapse of fragments of the Shelter object structures due to their destruction over time.

3.2.3 Radioactive aerosols in the air of a New Safe Confinement

Regular control of RA release through technological openings and gaps in the light roof from the Shelter object into the main volume of the NSC has been carried out since 1998 with the help of accumulating planchets installed above technological hatches (Fig. 3.33) [98].

Analyzing the dynamics of unorganized annual $\Sigma\beta$ -nuclides emissions through technological openings and gaps in the light roof of the Shelter object in 1998—2020 on the upper marks of the Shelter object (Fig. 3.34), we can distinguish four characteristic periods.

Period 1. 1998—2003: operation of the third power unit of the Chornobyl NPP, operation of the DSS only over the CH; the average emission of $\Sigma\beta$ is from 696 to 1,184 MBq/year.

Period 2. 2004—2008: construction and commissioning of a MDSS, sealing the Shelter object roof, intense work in its premises related to stabilization measures; the average emission of $\Sigma\beta$ is from 659 to 721 MBq/year.

Period 3. 2009—2016: concreting of the foundation under the NSC and construction of the NSC itself; construction of auxiliary premises of the NSC complex; construction of the NVS (2011) and dismantling of VT-2 (2013); dismantling of individual building structures of the Shelter object (2015); construction of the western and eastern walls of the NSC EP (2016), etc.; installation of the NSC arch into the design position; the average emission of $\Sigma\beta$ is from 152 to 378 MBq/year, which is more than three times less compared to period 1; the minimum emission is 128 MBq (recorded in 2015).

The dynamics of the average daily rate of unorganized emissions of $\Sigma\beta$ -nuclides through gaps at the upper marks of the Shelter object during 14 years of observations is shown in Fig. 3.35.

Period 4. 2017—2020: with the commissioning of the NSC, RA emissions into the main volume of the NSC decreased by more than ten times compared to period 1, although intensive construction work was carried out at this time to seal the NSC and put it into operation, which was accompanied by significant dust resuspension. According to the integrated emission estimate, the sum of α - and β -emitting nuclides in the release decreased almost three times (51 MBq). The rate of emissions into the main volume of the NSC, which tends to decrease gradually, has decreased by the same amount.

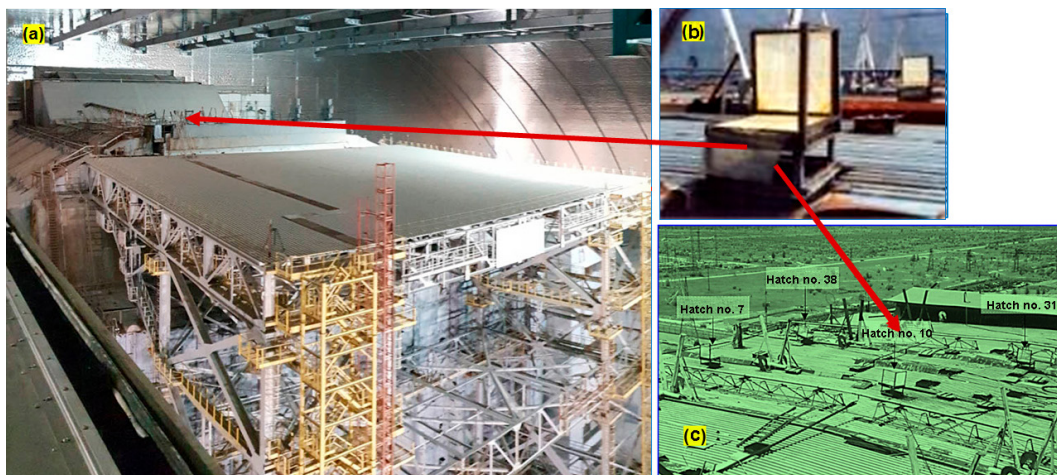


Fig. 3.33 — Characteristics of the place of the accumulating planchet installation:
a — appearance of the NSC main volume; *b* — the accumulating planchet installed
 on the light roof of the Shelter object; *c* — general view of the light roof of the Shelter object
 with the planchet installed

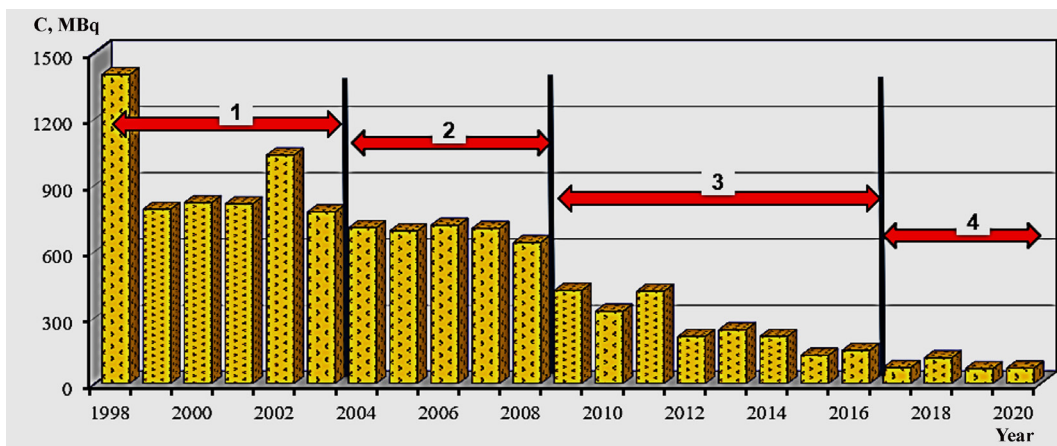


Fig. 3.34 — Dynamics of the $\Sigma\beta$ -active nuclides emission at the upper marks through gaps
 in the roof of the Shelter object, 1998—2020

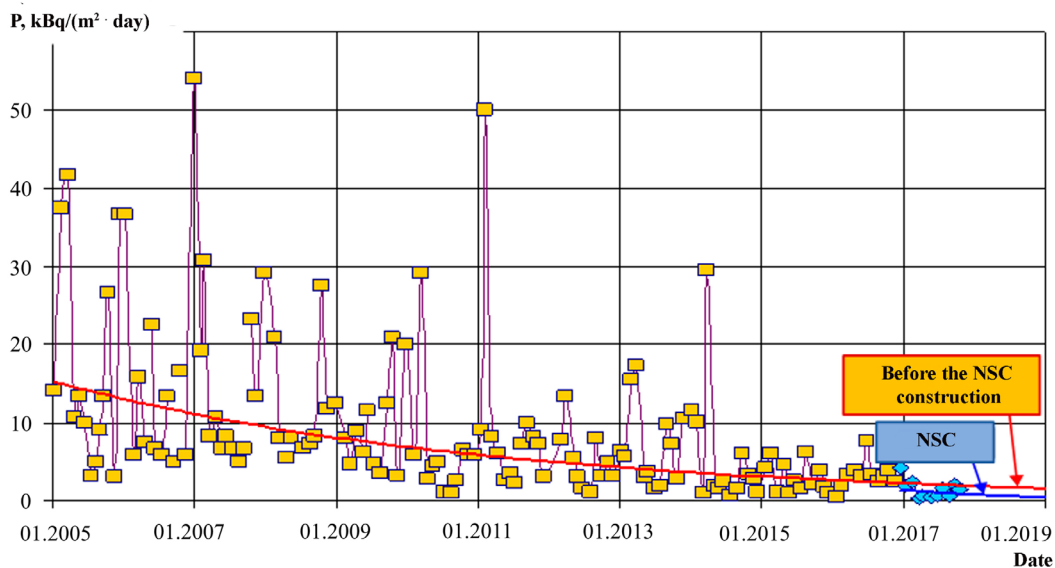


Fig. 3.35 — Dynamics of the average daily $\Sigma\beta$ emission rate through gaps at the upper marks of the Shelter object, 2005—2019

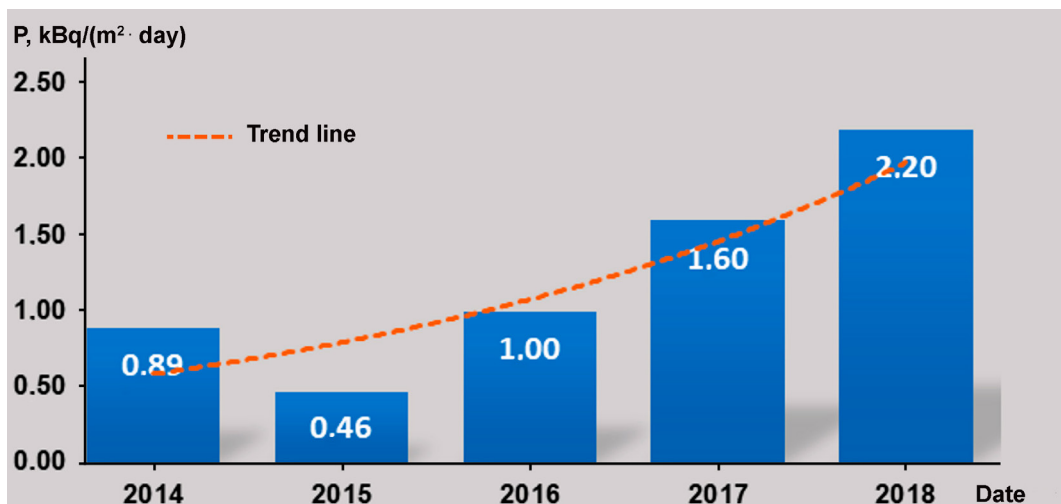


Fig. 3.36 — Dynamics of the $\Sigma\beta$ -emitting nuclides deposition rate on the roof of the Shelter object, 2016—2018

With the commissioning of the NSC, the RA dispersion space has changed. Now it is limited by the hermetic design of the arch. The depositions within the NSC main volume is formed by the RA particles carried through the light roof of the Shelter object, and by inert dust due to resuspension in the process of technological activity and dismantling of structures in several rooms of the Shelter object (for example, during the commissioning in August 2018 of the NSC ventilation system).

The average deposition density of $\Sigma\beta$ -emitting nuclides has almost doubled compared to 2014 (Fig. 3.36). In recent years, there has been a significant deposition of inert dust. It is already visible on the inner surfaces of the NSC with the naked eye.

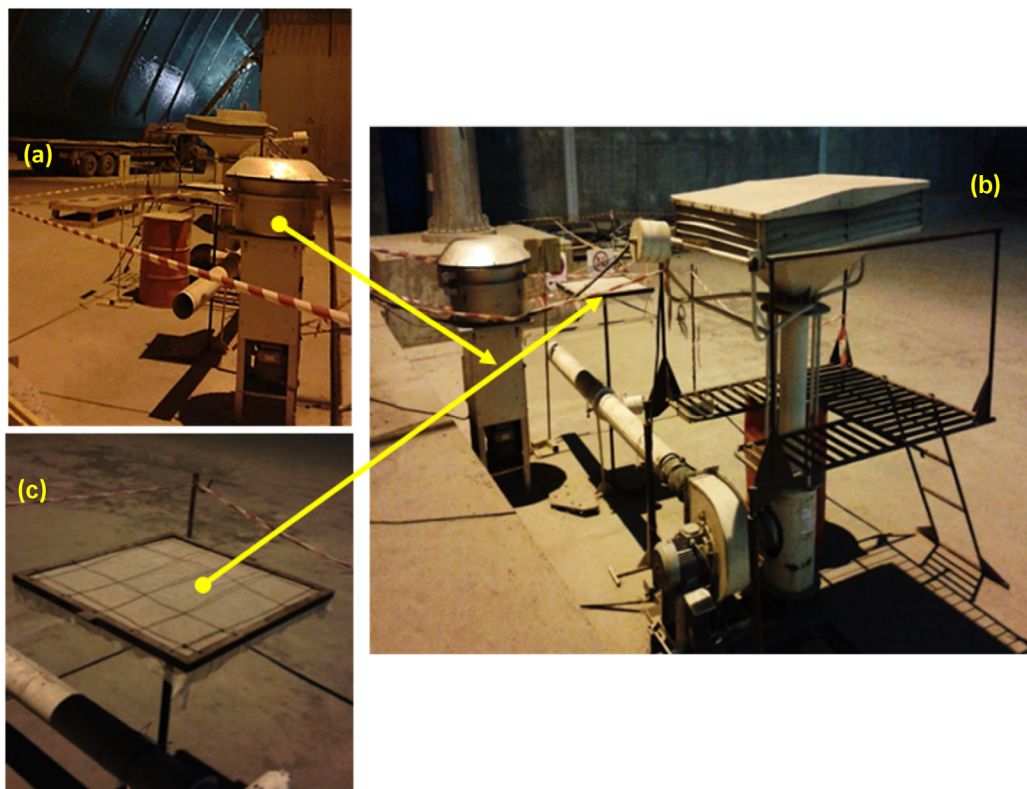


Fig. 3.37 — Equipment for monitoring the volumetric activity, radionuclide and particle size composition of the aerosol, and the radionuclide deposition density in the surface air in the main volume of the NSC:

a — appearance of FVU Grad-1.8 under the NSC; *b* — the appearance of the Andersen impactor; *c* — the deposition planchet

Radioactive aerosols in the surface air of the main volume of the NSC are formed by RA, emitted through the gaps of the Shelter object, and RA, formed in the main volume of the NSC during construction and installation work on sealing the arch of the NSC, and especially in the process of the EP creating.

Monitoring of the volumetric activity, radionuclide and particle size composition of the aerosol and the deposition density in the surface air in the main volume of the NSC (Fig. 3.37) is an important type of control that allows assessing the dose load on personnel performing work at the NSC.

The volumetric activity of the radionuclide and particle size composition of the aerosol in the air under the NSC is controlled by the filter-ventilation unit (FVU) Grad-1.8 (see Fig. 3.37, *a*). The particle size aerosol composition in the surface air under the NSC is controlled by the ANDERSEN impactor with the airflow rate of 1,650 m³/day (see Fig. 3.37, *b*) for five AMAD ranges: up to 0.8 µm; 0.8—1.4 µm; 1.4—2.3 µm; 2.3—4.9 µm; and 4.9—10.0 µm. The sampling frequency is twice a month.

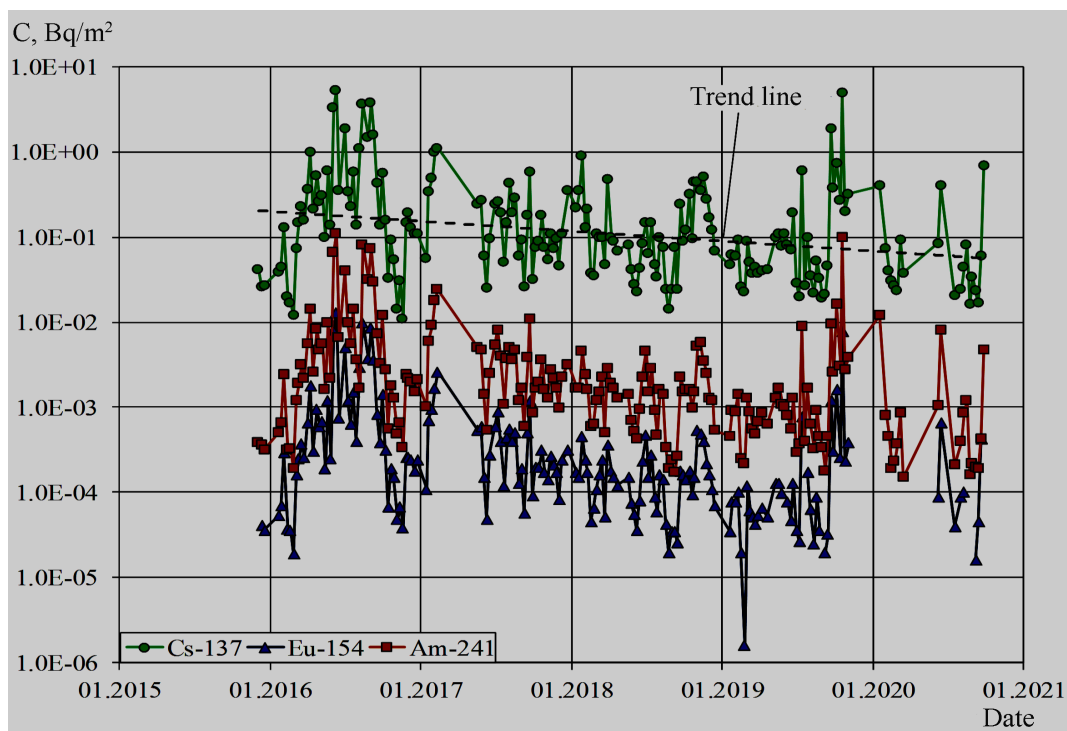


Fig. 3.38 — Dynamics of the ¹³⁷Cs, ¹⁵⁴Eu and ²⁴¹Am volumetric activity under the arch of the NSC (data of FVU Grad-1.8), December 2015 — September 2020

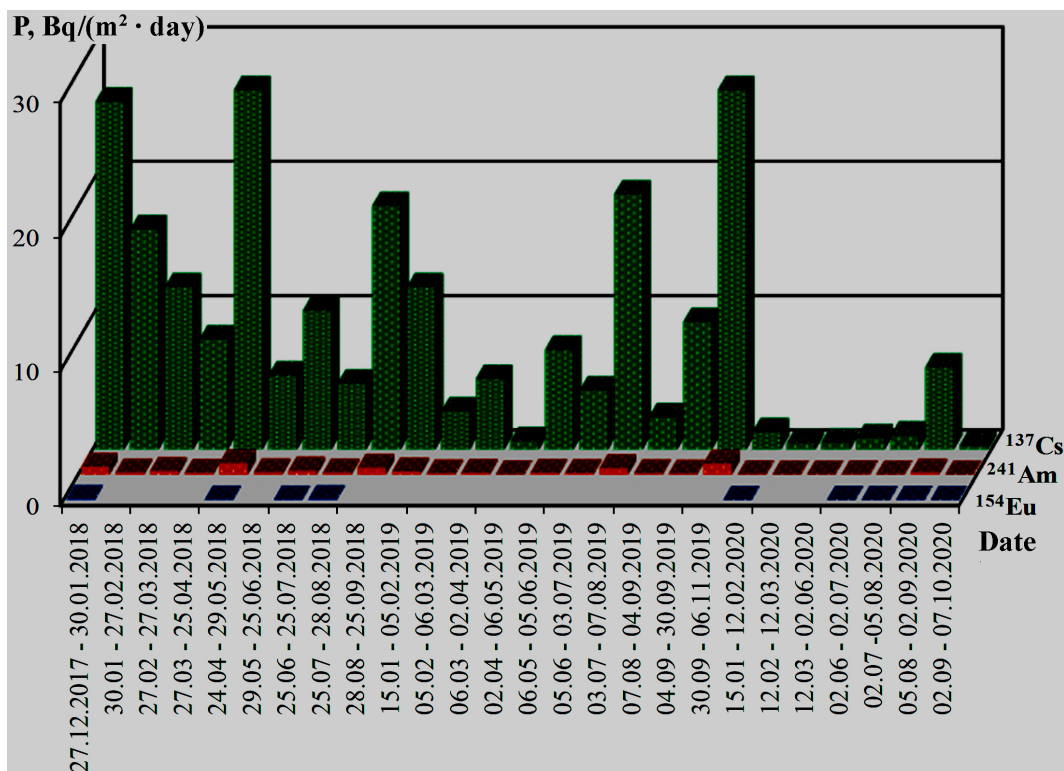


Fig. 3.39 — Dynamics of the radionuclide deposition density on the underlying surface near the southern wall of the turbine island of the fourth power unit of the Chornobyl NPP, December 2015 — October 2020

The fallout density on the underlying surface under the NSC is controlled using horizontal deposition planchets. The exposure period is one month.

The analysis of the obtained data showed (Fig. 3.38) that in 2016—2018 when intensive dust resuspension took place (work on sealing the NSC arch and the EP creating), the highest ^{137}Cs volumetric activity in the air under the NSC was recorded up to 3 Bq/m^3 in 2016 [99, 101, 102].

As of 2020, the trend of volumetric activity is steadily decreasing to 0.1 Bq/m^3 . In 2018—2020, the AMAD ranged from 1.2 to $4.3 \text{ }\mu\text{m}$ for ^{137}Cs carrier particles and from 1.3 to $5.0 \text{ }\mu\text{m}$ for ^{241}Am carrier particles [100].

The dynamics of the radionuclide deposition density on the underlying surface under the NSC are shown in Fig. 3.39. During the entire observation period, the ^{137}Cs deposition density ranged from 0.3 to $1.1 \cdot 10^3 \text{ Bq/(m}^2 \cdot \text{day)}$.

The high deposition density in the NSC main volume is most likely due to the sedimentation of construction dust, which was accumulating during the work on sealing the NSC, and especially the work on creating the NSC EP. The total annual activity of ^{137}Cs deposition under the NSC, due to the large area of the underlying surface in the main volume of the NSC, can be thousands of megabecquerels, so additional studies of this parameter are required.

3.2.4 Radioactive aerosols as a means of non-operational control of fuel containing materials state

The lack of data in various information sources on the physicochemical properties of FCM makes it impossible to fully assess the characteristics that determine the resistance of FCM to environmental conditions, as well as to predict their behavior in the future. But the control of parameters, which will indirectly contain information about their condition, can be implemented today. Given the available knowledge, we highlight the main processes of FCM degradation with the formation of radioactive dust:

- generation of fuel dust from the LFCM surface due to spontaneous dust formation;

- formation of small fractions due to the LFCM evolution as a result of physicochemical processes that take place in them after the accident, in particular, the crystallization processes;

- destruction of LFCM due to changes in environmental conditions (temperature, humidity).

Analysis of dust samples taken from the LFCM surface showed a direct relationship between the radionuclide composition (ratios of nuclides $^{137}\text{Cs}/^{241}\text{Am}$, $^{241}\text{Am}/^{238}\text{Pu}$, $^{241}\text{Am}/^{239+240}\text{Pu}$, $^{241}\text{Am}/^{154}\text{Eu}$, $^{90}\text{Sr}/^{241}\text{Am}$, $^{137}\text{Cs}/\Sigma\beta$) with the appropriate ratios in the LFCM accumulations [56]. This indicates the RA generation by just this accumulation, and the volume activity values indicate the degree of destruction. The dispersal analysis and the presence of particles with sizes from units to hundreds of microns indicate the LFCM destruction and the possibility of radioactive dust formation. The total annual dust generation in the Shelter object due to the LFCM destruction, under reasonable assumptions about their surface area, gives about $7 \cdot 10^{11}$ Bq and $4 \cdot 10^{13}$ Bq for α - and β -activity, respectively. The calculation of the LFCM specific activity shows that every year at least a few tens of kilograms of fuel are transformed into dust in the Shelter object [56].

Most LFCM are open accumulations, the surface of which is quite inhomogeneous, sometimes covered with cracks and consists of individual fragments (for example, in room 304/3). According to the simulation results taking into account the heterogeneity of the accumulation structure, the area of open surfaces of the LFCM accumulations is not less than $1,500 \text{ m}^2$ [56, 103].

Control of RA near LFCM has been carried out since 2010 in the premises of the Shelter object at different altitudes (Table 3.7) [100, 104—109]. Aerosols are selected using

a RadeCo H810 type sampler for one or two days at a rate that ensures the pumping of 100–250 m³ of air during exposure. To do this, packages consisting of the AFA RSP-20 and AFA RMP-20 filters with an area of 20 cm² are used. Aerosol particles are sampled and classified by size by a five-stage IBF-5K impactor. This device sorts aerosol particles in five AMAD ranges: up to 0.5 µm; 0.5–1.2 µm; 1.2–3.7 µm; 3.7–8.5 µm; 8.5–17.0 µm. A fine filter helps to capture submicron-sized aerosols (up to 0.5 µm) more fully.

Table 3.7 — Basic initial data and results of calculation of the open LFCM accumulations surface area in the rooms of the Shelter object [103]

Room no.	Surface structure	Open surface area, m ²
012-7	The average size of individual sintered “slag” fragments is 50 mm. The cavern’s size is 0.1...0.2 mm. There are large cavities up to 2–3 mm in diameter	12.2 ±1.4
012-15	The structure of the accumulation is a system of interconnected ridges with gaps between them 10–30 cm deep. The average size of individual sintered “slag” fragments is 50 mm. The structure of the LFCM cavities is the same as in room 012/7	92.7 ±16.2
210-7	Matte ceramics are permeated with large gas cavities, there are evenly distributed over the volume of lava metal globules of a very regular shape from 2.5 mm to 1 µm	82.3 ±17
304-3	The entire LFCM surface is a partially sintered fragments ranging in size from 1 to 20 cm. The average size of the pieces is 10 cm, the pieces are filled in half with a relatively dense layer of lava. The texture of the black LFCM sample is a cavity with a maximum size of up to 1.8 mm. It contains opaque graphite particles up to 2 mm in size	312 ±38

Room 012/7. Aerosol samples in room 012/7 were sampled onto two-layer packages of AFA filters in the immediate vicinity (about 0.5 m) from the accumulation of LFCM (Fig. 3.40, *a*). The sampling equipment was placed on a special remote device (Fig. 3.40, *b*). Additionally, to control the particle size distribution, the RA sampling was performed on the impactor (Fig. 3.40, *c*). The dynamics of ¹³⁷Cs and Σβ activity in room 012/7 in 2011–2020 are shown in Figs. 3.41 and 3.42.

The analysis of the obtained data showed that after the NSC construction the concentration of ¹³⁷Cs and Σβ-nuclides in the air of room 012/7 decreased tenfold (Fig. 3.41) and has a steady downward trend. Some increases in the values of these parameters in 2017–2019 are the result of construction and installation work on the NSC sealing and the EP construction, which was accompanied by a significant dust resuspension.

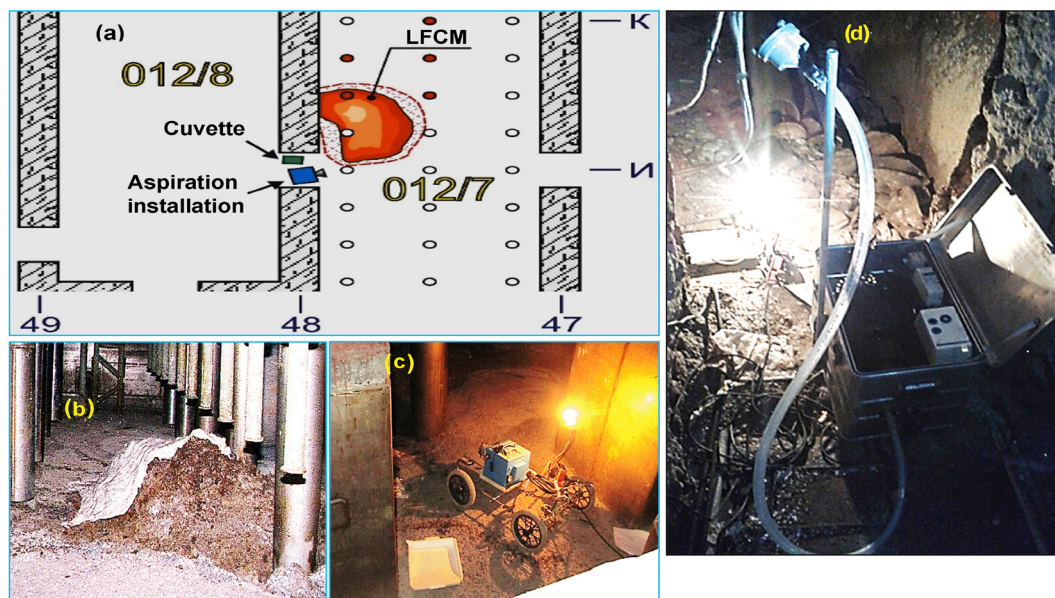


Fig. 3.40 — Room 012/7 of the Shelter object:

a — the spatial location of the LFCM accumulation; *b* — the appearance of LFCM accumulation; *c* — a sampling of RA onto a package of two-layer filters

As before the construction of the NSC, the ratios of radionuclide concentrations in aerosol samples and LFCM from this room are close. This indicates that the RA observed in room 012/7 are generated by LFCM accumulations located here due to its degradation [65, 110]. We should also note a large increase in the enrichment of RA by condensation ^{137}Cs and ^{90}Sr (Fig. 3.42). This is due to the dust generation by the surfaces of bottom sediments, opened due to the drying of radioactively contaminated water accumulations, for which the average ratio of ^{90}Sr and ^{241}Am activities in water is about 170.

The results of the RA particle size distribution measurements for 2010–2020 showed that before the NSC construction, in 2010–2011, $\Sigma\beta$ carriers were most often particles with AMAD from 2 to 8 μm [100, 104, 107]. After the commissioning of the NSC, the aerosol particle size composition did not undergo significant changes. Observation data for 2014–2020 are given in Table 3.8 and Fig. 3.43.

With the construction of the NSC, the volumetric activity and the deposition density of RA decreased by almost two orders of magnitude, which is probably due to a decrease in the velocity of airflows that lead to dust resuspension. The ratios of radionuclide concentrations in RA samples and depositions correspond to similar ratios for LFCM in the accumulation of room 012/7 [100, 104, 107]; therefore, their source is the generation from the LFCM in room 012/7.

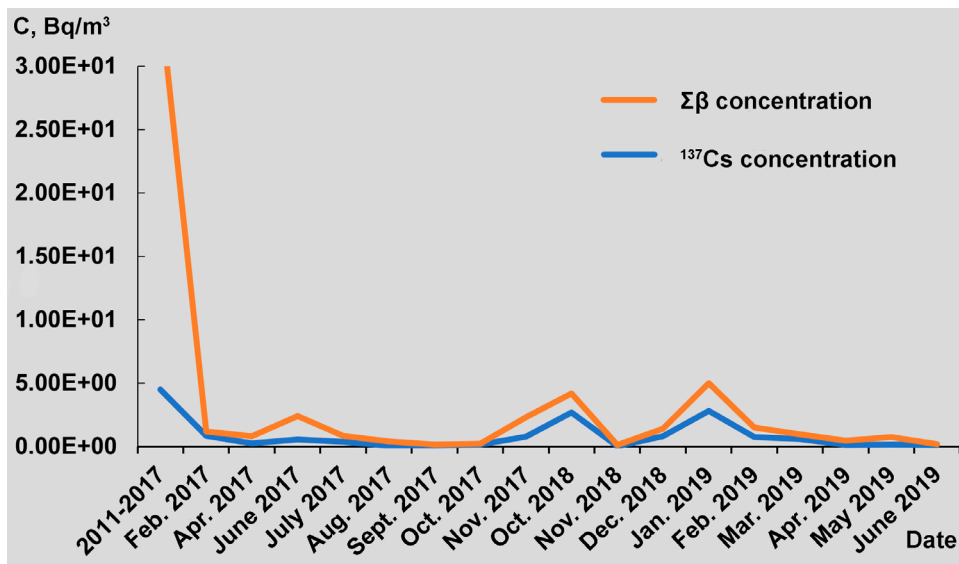


Fig. 3.41 — Dynamics of the ^{137}Cs , $\Sigma\beta$ volumetric activity in room 012/7 of the Shelter object, 2010—2020

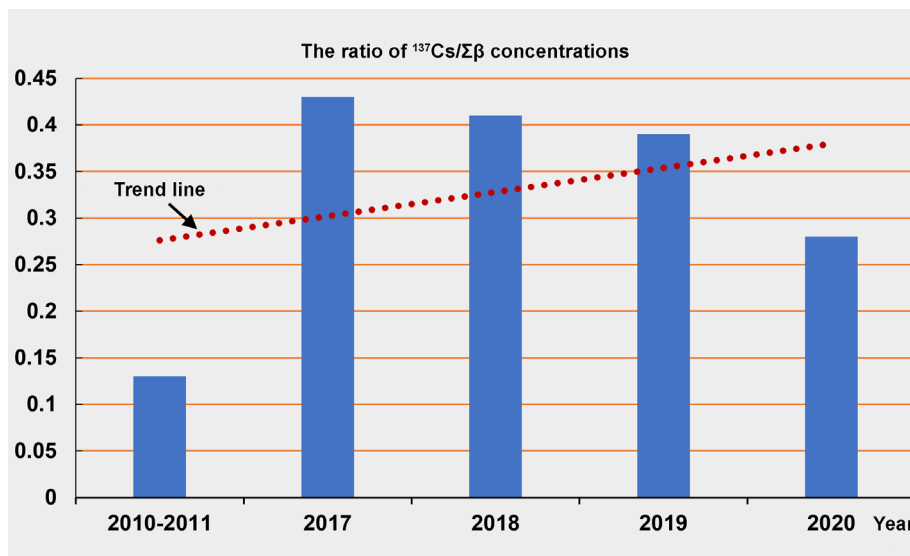


Fig. 3.42 — Dynamics of the $^{137}\text{Cs}/\Sigma\beta$ volumetric activity ratio in room 012/7 of the Shelter object, 2010—2020

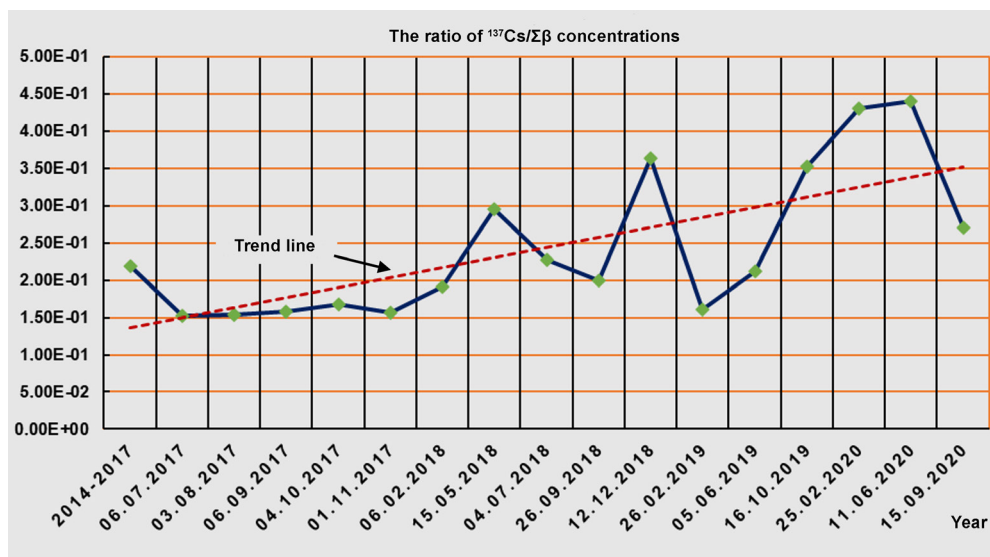


Fig. 3.43 — Dynamics of the $^{137}\text{Cs}/\Sigma\beta$ activities ratio in the deposition density in room 012/7

Table 3.8 — Deposition density of ^{137}Cs , ^{154}Eu and ^{241}Am in room 012/7, 2014—2020

Year	The average deposition density of radionuclides over the years, Bq/(m ² · day)			
	^{137}Cs	^{154}Eu	^{241}Am	$\Sigma\beta$
2014—2017	6.58E+02	7.81E+00	6.73E+01	4.19E+03
2018	9.05E+01	7.70E-01	7.10E+00	4.58E+02
2019	9.20E+00	1.20E-01	5.10E-01	3.37E+01
2020	9.95E+00	6.20E-02	3.90E-01	2.90E+01

Room 012/15. After the commissioning of the NSC, since 2017, the RA enrichment with ^{137}Cs and ^{90}Sr becomes noticeable due to the activity infusion from other sources. The particle size composition did not undergo significant changes; it is still determined by the presence of particles 2—8 μm in size. Aerosol sampling in room 012/15 is carried out on two-layer packages of AFA filters or the impactor close to the LFCM accumulations (Fig. 3.44). The sampling equipment was placed in room 012/16. The dynamics of the ^{137}Cs and $\Sigma\beta$ volumetric activities and their $^{137}\text{Cs}/\Sigma\beta$ ratio in the depositions of room 012/7 in 2017—2020 is shown in Fig. 3.45 [100, 105, 108].

After the construction of the NSC, the ^{137}Cs concentration in the air of room 012/15 has not changed significantly and averages 0.4 Bq/m³. Parameters such as $\Sigma\beta$ and $^{137}\text{Cs}/\Sigma\beta$ remain stable, except for a sharp increase in 2018 due to man-made activities that do not affect

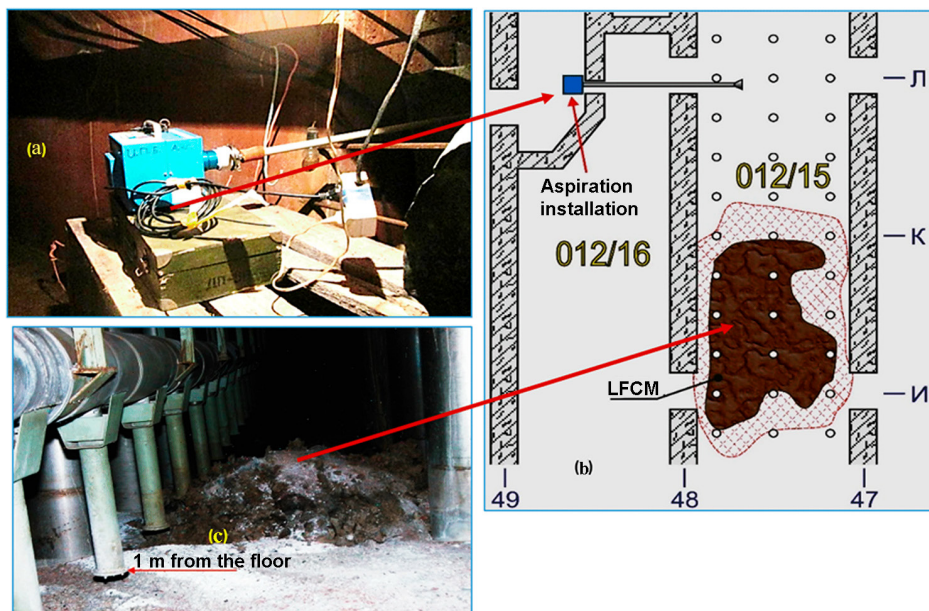


Fig. 3.44 — Location of the RA sampling equipment in room 012/16 and the LFCM in room 012/5:
a — location of the RA sampling equipment in room 012/16; *b* — the LFCM accumulation
in room 012/15 on the spatial layout diagram; *c* — a photo of the LFCM accumulation
in room 012/15

the overall trend. The particle size composition is still determined by $\Sigma\beta$ carriers with AMAD from 0.8 to 4 μm . The ratios of radionuclide concentrations in RA correspond to the material composition of the LFCM accumulation in this room and are the result of their destruction.

Room 210/7. Aerosol samples in room 210/7 were selected on two-layer filter packages AFA and an impactor near the LFCM accumulation (Fig. 3.46, *a*, *b*) [100, 106, 109]. The sampling equipment was placed in room 208/12 (Fig. 3.46, *c*).

Dynamics of the deposition density of ^{137}Cs , $\Sigma\beta$ radionuclides and their ratio ($^{137}\text{Cs}/\Sigma\beta$) in room 210/7 in 2017–2020 is shown in Fig. 3.47, the average annual density of radionuclide deposition and their main ratios are shown in Table 3.9.

Based on the obtained data, it can be stated that the concentration of ^{137}Cs and $\Sigma\beta$ -emitting nuclides in the air in room 210/7 decreased by almost an order of magnitude at a constant $^{137}\text{Cs}/\Sigma\beta$ concentration ratio. Significant emissions in 2018 and 2019, as noted earlier, are related to man-made activities and do not affect the overall downward trend. The particle size composition is determined, as in 2013, by $\Sigma\beta$ carriers with AMAD from 0.8 to 4 μm . The ratio of radionuclides concentrations in aerosols correspond to the material

composition of LFCM in this room and is the product of their destruction. In RA samples, the activity of ^{90}Sr and ^{137}Cs almost doubled, which is the result of the destruction of surfaces on which particles of condensation origin were previously deposited [100].

Table 3.9 — The annual average density of radionuclide depositions and their main ratios in room 210/7, 2014—2020

Year	Average annual radionuclide deposition density, Bq/(m ² · year)				The ratio of radionuclides in the depositions		
	^{137}Cs	^{90}Sr	^{241}Am	$\Sigma\beta$	$^{137}\text{Cs}/^{241}\text{Am}$	$^{90}\text{Sr}/^{241}\text{Am}$	$^{137}\text{Cs}/\Sigma\beta$
2014—2017	2.10E+02	6.50E+01	2.80E+00	3.60E+02	7.50E+01	2.32E+01	5.83E-01
2017	2.70E+02	1.40E+02	6.16E+00	5.97E+02	4.38E+01	2.27E+01	4.52E-01
2018	1.61E+02	1.25E+02	4.22E+00	3.78E+02	3.82E+01	2.96E+01	4.26E-01
2019	2.90E+01	—	8.20E-01	7.00E+01	3.54E+01	—	4.14E-01
2020	3.00E+01	—	8.15E-01	6.90E+01	3.68E+01	—	4.35E-01

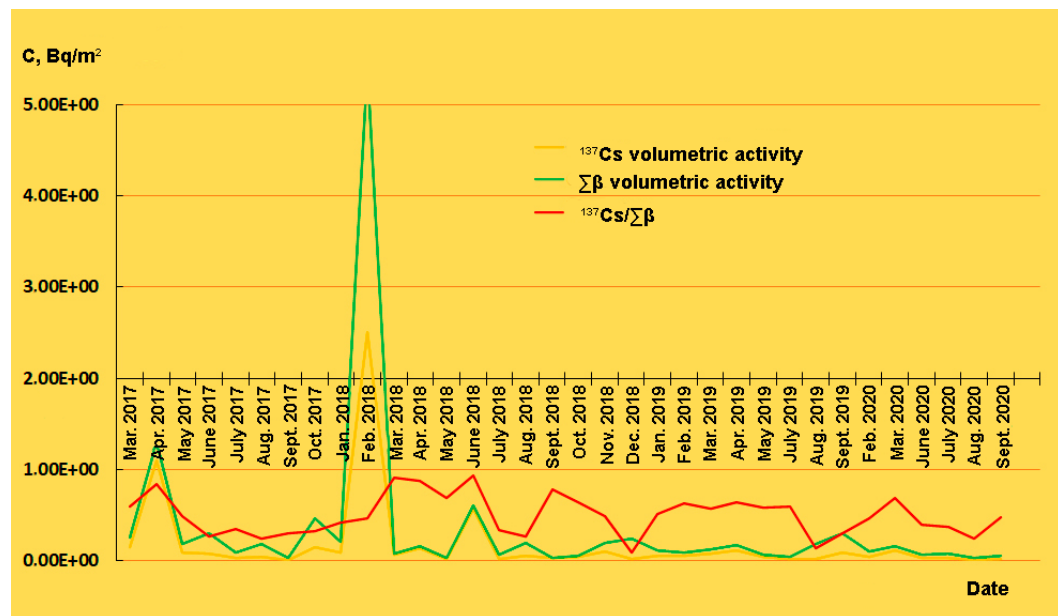


Fig. 3.45 — Dynamics of the ^{137}Cs , $\Sigma\beta$ volumetric activities and their ratio ($^{137}\text{Cs}/\Sigma\beta$) in the depositions in room 012/7, 2017—2020

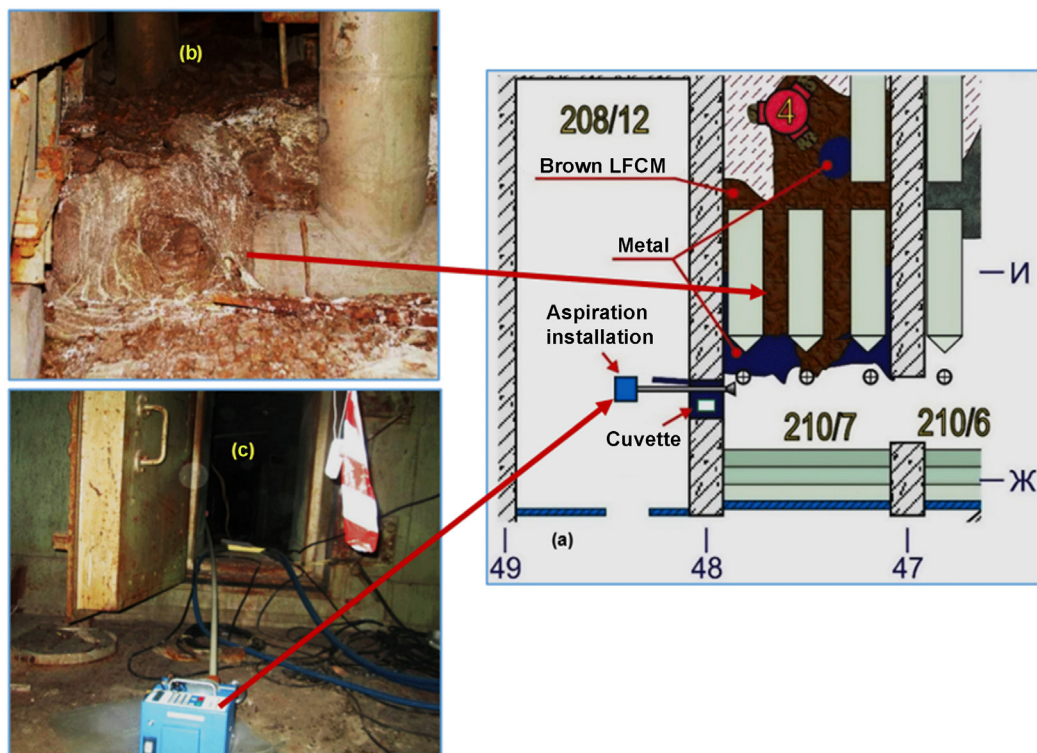


Fig. 3.46 — Location of the LFCM accumulations and radioactive aerosols sampling equipment in room 210/7:

a — a photo of the LFCM accumulation in room 210/7; *b* — scheme of rooms 208/12 and 210/7 with LFCM; *c* — placement of sampling equipment in room 208/12

Room 304/3. Aerosol samples from room 304/3 were selected through a well in room 308/2 [100] (Fig. 3.48).

According to the results of radiometric and γ -spectrometric measurements of ^{137}Cs , $\Sigma\beta$ concentrations and their ratios in aerosol samples in 2017—2020 (Fig. 3.49), analysis of particle size distribution and ratios of concentrations of basic radionuclides (Table 3.10), we can state that with the construction of the NSC the concentration ^{137}Cs and $\Sigma\beta$ in the air of room 304/3 decreased almost fivefold at a constant $^{137}\text{Cs}/\Sigma\beta$ concentration ratio. Significant emissions in 2017 are related to man-made activities and do not affect the overall downward trend. The ratio of concentrations of basic radionuclides in aerosol samples has not changed. This means that the main and only source of RA in room 304/3 is the destruction of the LFCM located in it.

Table 3.10 — The ratio of radionuclide concentrations in aerosol samples from room 304/3

Date	$^{137}\text{Cs}/^{241}\text{Am}$	$^{241}\text{Am}/^{238}\text{Pu}$	$^{241}\text{Am}/^{239+240}\text{Pu}$	$^{90}\text{Sr}/^{241}\text{Am}$
01.03.2017	58	3.6	1.7	20
08.02.2018	44	3.5	1.5	21
17.04.2018	37	4.7	1.7	22

The general conclusions from the results of RA behavior monitoring near the LFCM accumulations are as follows:

the process of the LFCM destruction, as well as the spontaneous transition of destruction products to an aerosol state, are observed;

after the NSC moving over the Shelter object, the humidity temperature regime changes; the average annual volumetric activity of RA in the air of premises with LFCM accumulations, decreased sharply;

the radionuclide composition of the aerosol changes; as before, the processes of degradation of LFCM and the generation of RA with a fuel component take place. At the same time,

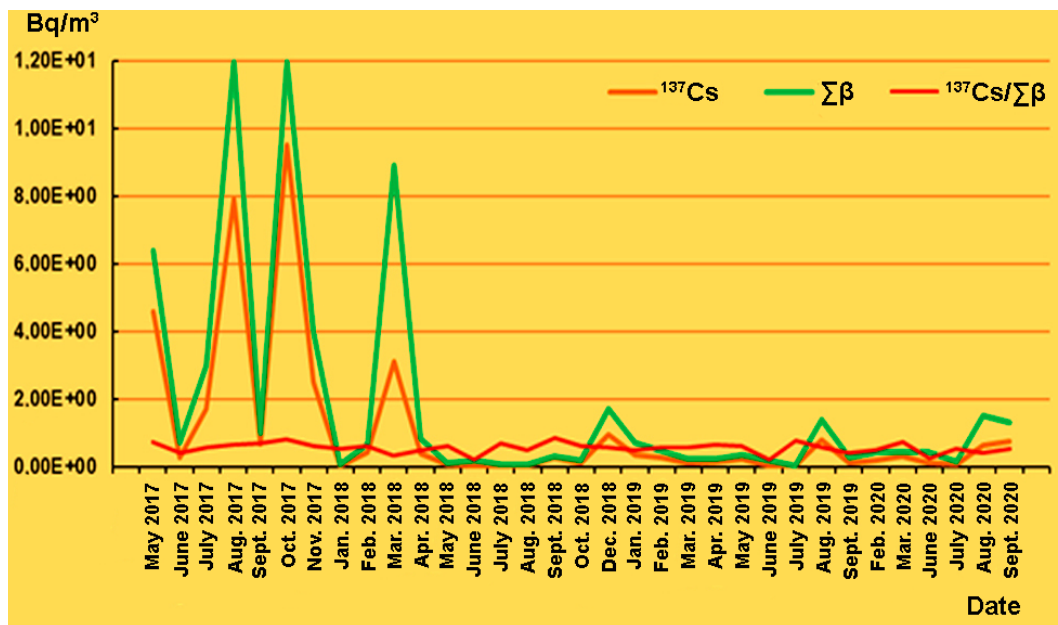


Fig. 3.47 — Dynamics of the ^{137}Cs and $\Sigma\beta$ radionuclides deposition density and their ratio ($^{137}\text{Cs}/\Sigma\beta$) in room 210/7, 2017—2020

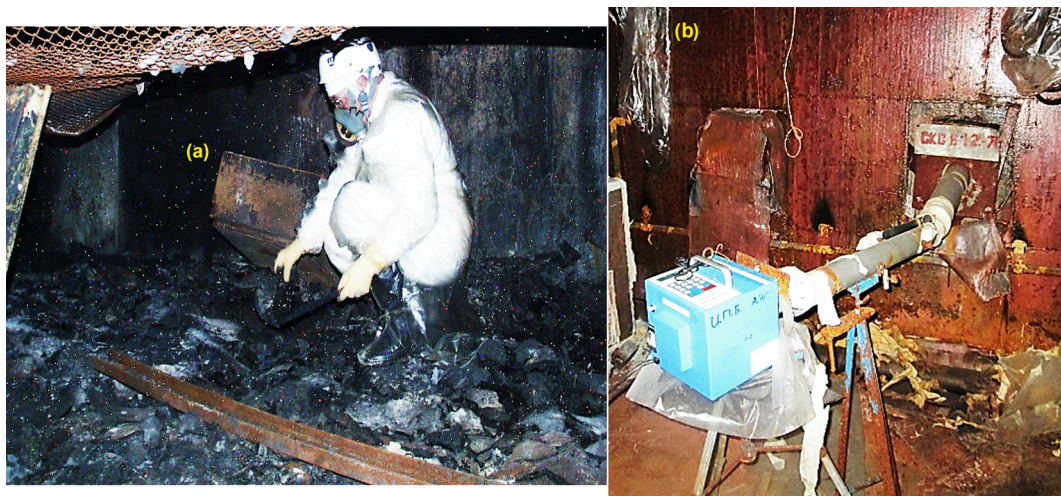


Fig. 3.48 — Sampling of radioactive aerosol in room 304/3:
a — black LFCM in room 304/3 (photo by O. Kupnyi);
b — placement of sampling equipment in room 318/2

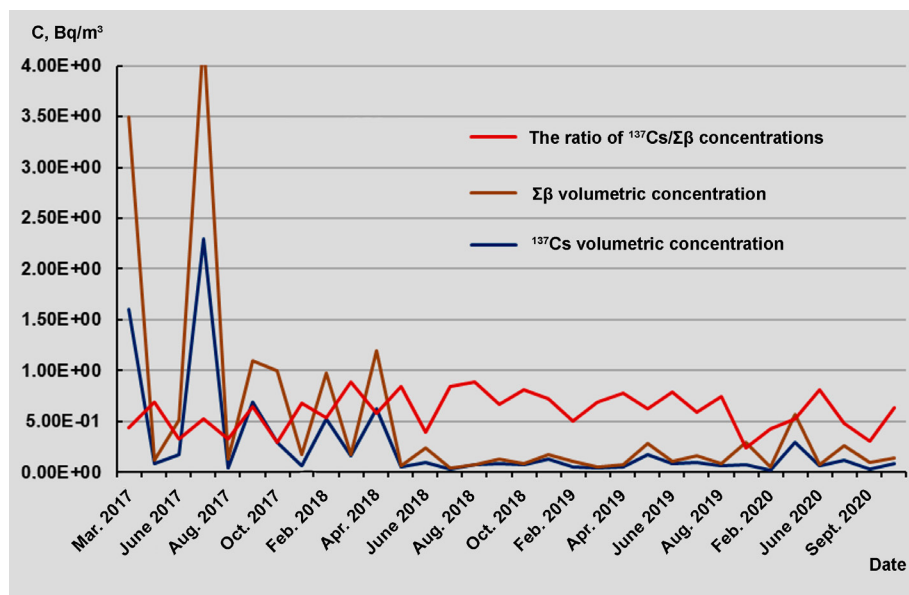


Fig. 3.49 — Dynamics of volumetric activity of ^{137}Cs , $\Sigma\beta$ and the ratio of their concentrations in room 304/3, 2017–2020

the process of RA enrichment with ^{137}Cs and ^{90}Sr through the generation from the surfaces of dried bottom sediments of water accumulations, which were previously in the mentioned or adjacent premises, becomes noticeable. The formation of aerosol depositions has a similar character;

it remains unclear how the products of LFCM destruction get into the air in the absence of mechanical impact and wind transport (the LFCM are exactly in such conditions). We can only assume that the generation of aerosols from the LFCM surfaces is affected by electrostatic charges that may occur during radioactive decay.

3.3 Radioactively contaminated water in the premises of the Shelter object

The study of RW began immediately after the construction of the Shelter object: initially, it was occasionally, and since 1991 and still, the study became with a certain frequency.

Before the construction of the NSC, the main sources of water inside the Shelter object (in the first 10—15 years, according to various estimates, up to $3,000 \text{ m}^3/\text{year}$) were precipitation and a large number of man-made solutions.

Radioactively contaminated water could cause several types of hazards [111]: increase in the effective multiplication factor of neutrons in case of contact with the LFCM accumulations; destruction of LFCM with the subsequent uncontrolled movement of radioactivity indoors and removal of radionuclides outside the Shelter object; increasing the potential nuclear hazard of the facility due to the transfer of dissolved salts of enriched uranium.

Three sources of water influx into the room have been identified on the lower marks of the Shelter object [112]. One of them is man-made — a standard DSS: the volume of solutions that are sprayed into the space under the CH roof during its operation was approximately $200 \text{ m}^3/\text{year}$. The other two sources were natural — precipitation (on average $1,800\text{—}2,000 \text{ m}^3/\text{year}$) and condensate (almost $1,600 \text{ m}^3/\text{year}$).

At that time, water was spreading through partially destroyed pipelines, pipe and cable penetrations, hatches, stairs, doors, cracks and crevices in the floors and walls. At such volumes, it was possible to allocate even separate branches of water streams (Fig. 3.50).

Most of the RW accumulations observed now are contained in room 001/3 (see Fig. 3.50) of the northern part of the Shelter object (lower marks). According to 1995—1997 data, high-level water flows from the PSP ($80\text{—}90 \text{ m}^3/\text{year}$) and low-level flows from the cascade wall ($600\text{—}700 \text{ m}^3/\text{year}$) came here. As a result, the RW of the north stream from under the cascade wall entered the premises of the third power unit (Fig. 3.51). It was pumped out from there (up to $700 \text{ m}^3/\text{year}$) and went to treatment systems.

All water accumulations detected within the Shelter object can be classified as medium-active LRW (from $3.7 \cdot 10^8$ to $3.7 \cdot 10^{13} \text{ Bq/m}^3$), except for the water flow from the well in the cascade wall. The RW in it belongs to the category of low-level LRW.

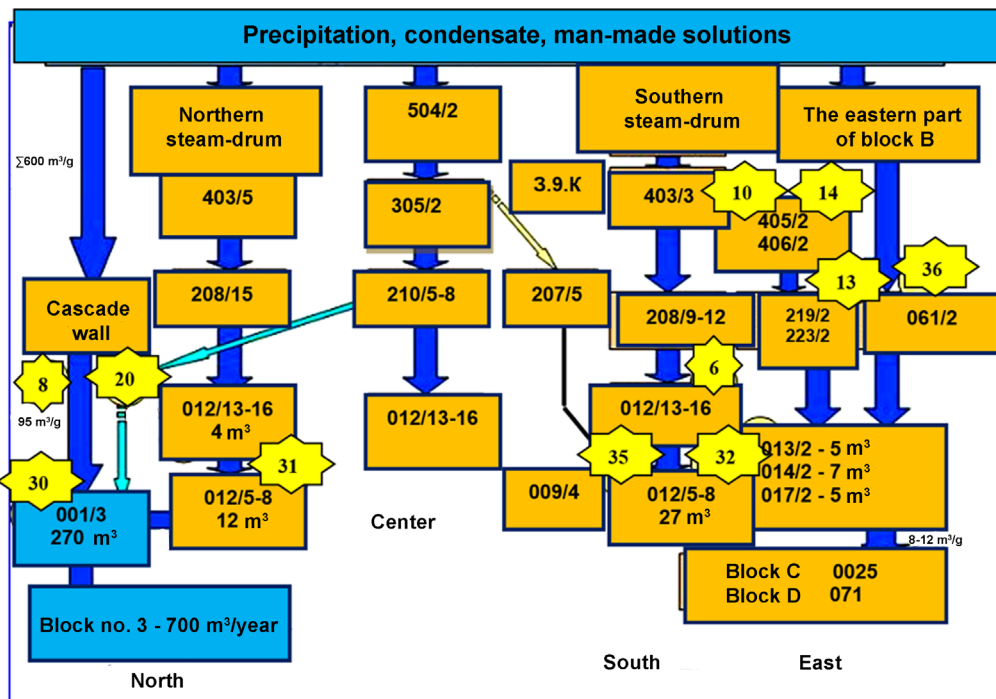


Fig. 3.50 — Generalized scheme of radioactive water streams and flows in the Shelter object, 1990—2000

Different FCM modifications located on the waterways in the Shelter object have different effects on its radionuclide contamination. Studies from 1995 to 1997 showed that oxidized fuel particles (U_3O_8) are the main source of pollution of “block” waters by fission products and transuranic elements. The rate of their dissolution is much higher than the same rate of weakly oxidized fuel particles (UO_2) and LFCM.

Based on the data obtained at that time, the integrated rate of the destruction of FCM lying in the watercourse of the Shelter object was determined. Given that the average concentration of uranium in room 001/3 was approximately 3 mg/l, and the intensity of the northern and south-eastern flows was 740 and 370 m³/year, respectively, annually from the reactor compartment of the fourth power unit about 4 kg of fuel (U) was dissolved and taken out of it. In years when the precipitation intensity is much higher than the average, this number may increase to 10.

The radiation hazard is because the water destroys the FCM, contributing to the uncontrolled movement of radioactivity indoors and the removal of radionuclides outside the Shelter object.



Fig. 3.51 — Radioactive water flowing into the premises of the third power unit of the Chornobyl NPP [113]

Sources of inflow and migration routes of water (watercourses) within the Shelter object, the dynamics of levels and volumes of water accumulations were studied in 1996—2001. The laboratory studies of RW samples and bottom sediments were conducted [114—120]; 132 water samples were taken in all known water accumulations of the fourth power unit (at 22 points); laboratory analyzes determined the radionuclide and macrocomponent composition of RW, in particular the volumetric activities of fission products (^{90}Sr , ^{137}Cs) and transuranic elements (^{238}Pu , $^{239+240}\text{Pu}$, ^{241}Am , ^{244}Cm), uranium, components HPO_4^{2-} , HCO_3^- , CO_3^{2-} , hydrogen value (pH).

It has been established that soluble and colloidal forms of radionuclides are transported by watercourses to the lower marks of the Shelter object, coagulate, settle and form highly active bottom sediments in water accumulations. The volume of bottom sediments, for example in room 001/3, is approximately 65 m^3 . The number of colloidal forms of radionuclides and uranium that have accumulated at the lower marks of the Shelter object was estimated in [111]: ^{137}Cs — $0.9 \cdot 10^{12} \text{ Bq/year}$; ^{90}Sr — $0.2 \cdot 10^{12} \text{ Bq/year}$; plutonium (all isotopes) — $2.4 \cdot 10^8 \text{ Bq/year}$; uranium — 270 g/year . The data obtained gave confidence that there was no nuclear danger, but constant monitoring of large accumulations remained.

The bottom sediments contain fuel particles, which are washed off and mechanically transported by the water flow. Therefore, the water itself has not yet posed a nuclear threat, but it could not be argued that in the event of its entry into the FCM accumulation under certain conditions will not be a significant increase in K_{er} .

Another important question at the time was: does RW move beyond the Shelter object? During the described period, many studies were conducted to balance the inflow and evaporation of water. It turns out that every year the Shelter object receives about 1,000 m³ of water more than it evaporates. Excess moisture could flow from room 001/3 to the premises of the third power unit. The fact of overflow is confirmed by direct observations and research using a tracer. However, the magnitude of errors in the balance sheet, as well as measurements and estimates of water flow, is large. It allowed other, as yet uncontrolled water outflows in the hundreds of cubic meters per year, outside the reactor unit, in particular, the ingress of RW into groundwater.

For many years, it was important for the safety of the Shelter object to reduce the RW volume entering the facility, to organize constant monitoring of its location, radionuclide composition, the presence of dissolved fissile materials and, if necessary, the use of active countermeasures, in particular sealing of a roof (Fig. 3.52). Closing many openings in the roof of the turbine island, deaerator shelf, filling long cracks in the sloping parts of the roof, lying to the north and south of the pipe rolling, prevented water from entering through them, but at the same time led to poor natural ventilation.

To combat condensation, in 1996 a program was developed (air heating in some rooms, restoration of natural ventilation, etc.) and its implementation began immediately. As a result, the amount of condensation moisture in the interior of the Shelter object decreased between 1996 and 2000. Among the measures taken there was the organization of pumping



Fig. 3.52 — Replacement of the light roof covering of the Shelter object

RW from the lower marks of the turbine island of the third power unit of the Chornobyl NPP, “paving” around the walls of the Shelter object to reduce the ingress of rainwater.

Radioactive water has become a kind of marker for diagnosing the condition of FCM. Flowing through the premises of the Shelter object, water flows are accumulated in the lower rooms, where samples are taken. On their way, they wash different FCM accumulations (in particular, not accessible for many reasons) with different ratios of radionuclides, inherent only in a certain FCM accumulation and, thus, carry important information about the state of these accumulations.

After the NSC was put into operation, there were fundamental changes in the behavior of RW, which are primarily determined by the lack of atmospheric moisture, a significant decrease in the amount of dust-suppressing solutions, an increase in average temperature in the Shelter object and the main volume of NSC, changing the mode of ventilation of the premises (Fig. 3.53). During 2016—2020, a monthly visual inspection, sampling, depth measurement and assessment of the area of RW accumulations in the premises at the lower marks of the Shelter object were conducted. As a result of changes in evaporation conditions (condensation of moisture and cessation of precipitation), the volume of unorganized RW accumulations began to decrease sharply, and some of them completely dried up.

Radioactive water comes to room 009/4 (Fig. 3.54) from the above rooms 207/4-5, and in the spring and summer is replenished by condensate. The color of the water (Fig. 3.54, *a*) in room 009/4 indicates direct flows of dust suppression solutions. In 1998, the water depth here was about 25 cm. During 1999, the volume of water decreased significantly, and by mid-2000, only small puddles remained from the water accumulation. However, after heavy rainfall in July 2000, the water level recovered. Over time, the volume of water ranged from complete drying to a small puddle. In 2009 and 2010, the amount of water in room 009/4 increased significantly, and in 2011—2013 the level of water accumulation reached 10—15 cm. In the case of a further increase in the level, excess water flowed through the threshold to room 012/7. The depth of the water accumulation varied in 2016 from 6 cm in January to 16 cm in November. Starting from January 2017, the amount of RW in room 009/4 began to decrease and in February 2019 completely dried up (Fig. 3.54, *b*).

The RW accumulation in the northern part of rooms 012/5-8 of the PSP was formed by the leakages from the above rooms located on the second floor of the pressure-suppression pool and steam distribution corridor as well as moisture condensation in the summer. The water color was defined by the presence of dust suppression solution (Fig. 3.55, *a*). The RW amount in the rooms has varied significantly in recent years. Water leaks in the direction of room 007/3 through the wall penetration.

The RW accumulation in the southern part of rooms 012/5-8 of the PSP was formed in the same way as in the northern part: by the leakages from above rooms located on the second floor of the PSP and room 208/11 of the SDC as well as moisture condensation in the summer but, in addition, organized leakages penetrated here from wells in rooms 207/4-5.

The water color was defined by the presence of a dust suppression solution. The RW accumulations in these rooms are slightly flowing. The total amount of accumulations is defined by the evaporation and condensation processes. Since March 2018 there is no water in the southern part of rooms 012/5-8 (Fig. 3.55, b).

There were permanent RW accumulations in rooms 013/2, 014/2 and the southern part of the corridor 017/2, 018/2 due to the water entrance from the upper marks. The RW level in the southern part of room 017/2 was determined by the doorstep height in room 018/2 — excess water flowed here with level increase. Until 2017 constant volume of RW in room 017/2 was about 5.4 m³. Part of water from room 018/2 came through drains to the trunk pipeline of room 001/3 and from there to room 001/3. The color of water in rooms 013/2, 014/2, 017/2 and 018/2 was defined by direct leakages of the dust suppression solution.

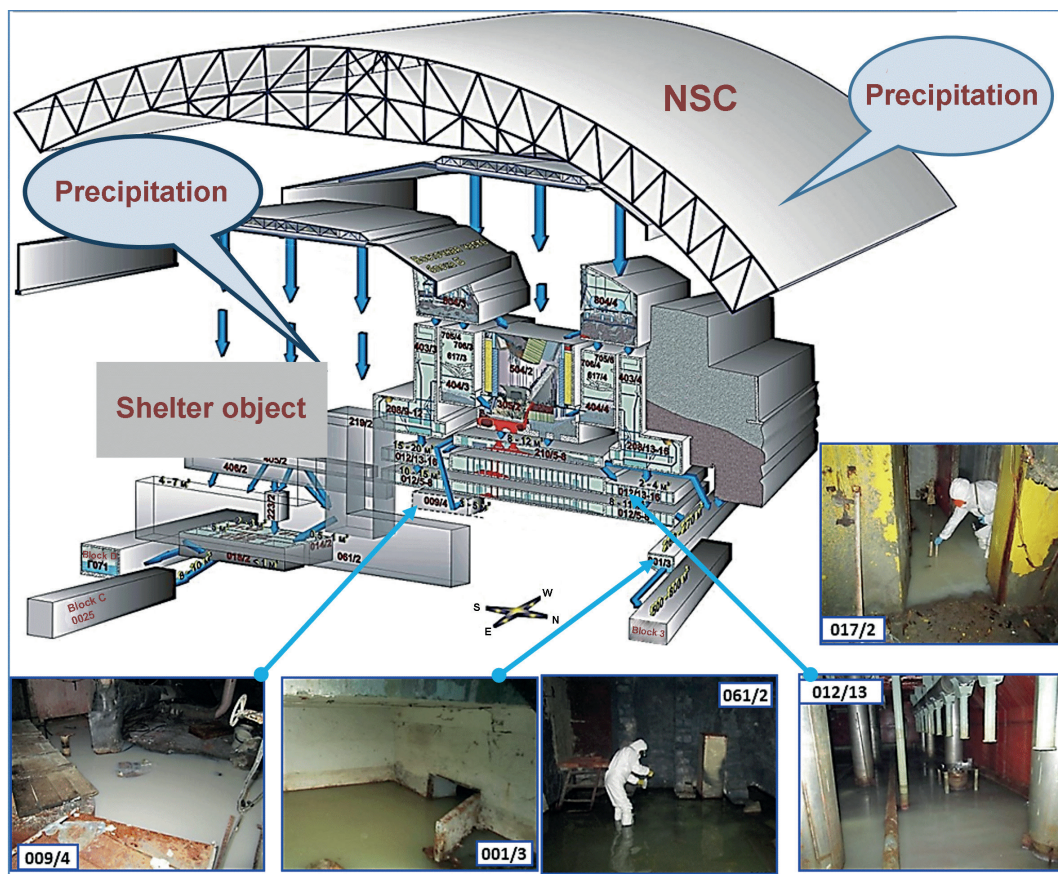


Fig. 3.53 — Scheme of the location of radioactive water accumulations in the NSC

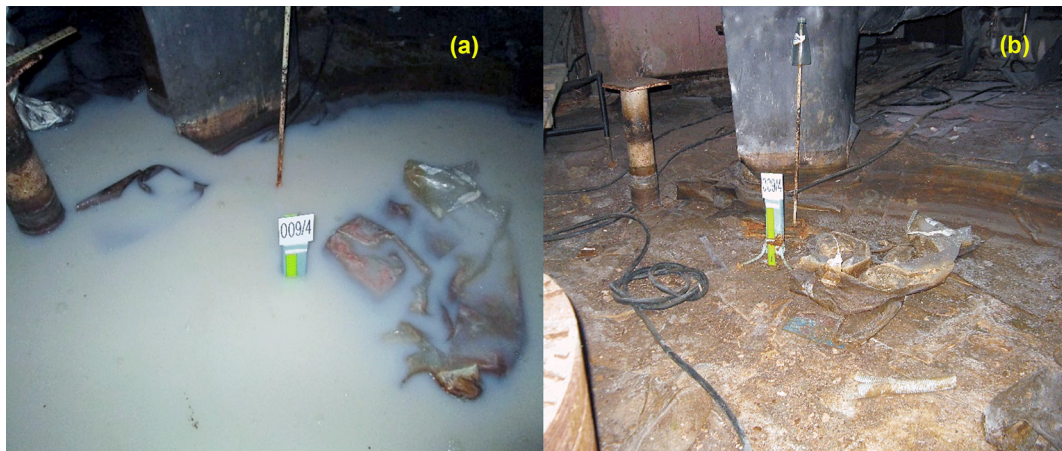


Fig. 3.54 — Drying out of radioactive water accumulation in room 009/4



Fig. 3.55 — Radioactive water accumulations in room 012/16:
a — September 2016; *b* — February 2020

Currently, there is no water in rooms 013/2 (Fig. 3.56, *a*), 014/2 and 018/2. It should be noted that due to the drying up of RW accumulations, sediments, which in time are transformed into additional sources of radioactive dust, are exposed (Fig. 3.56, *b*).

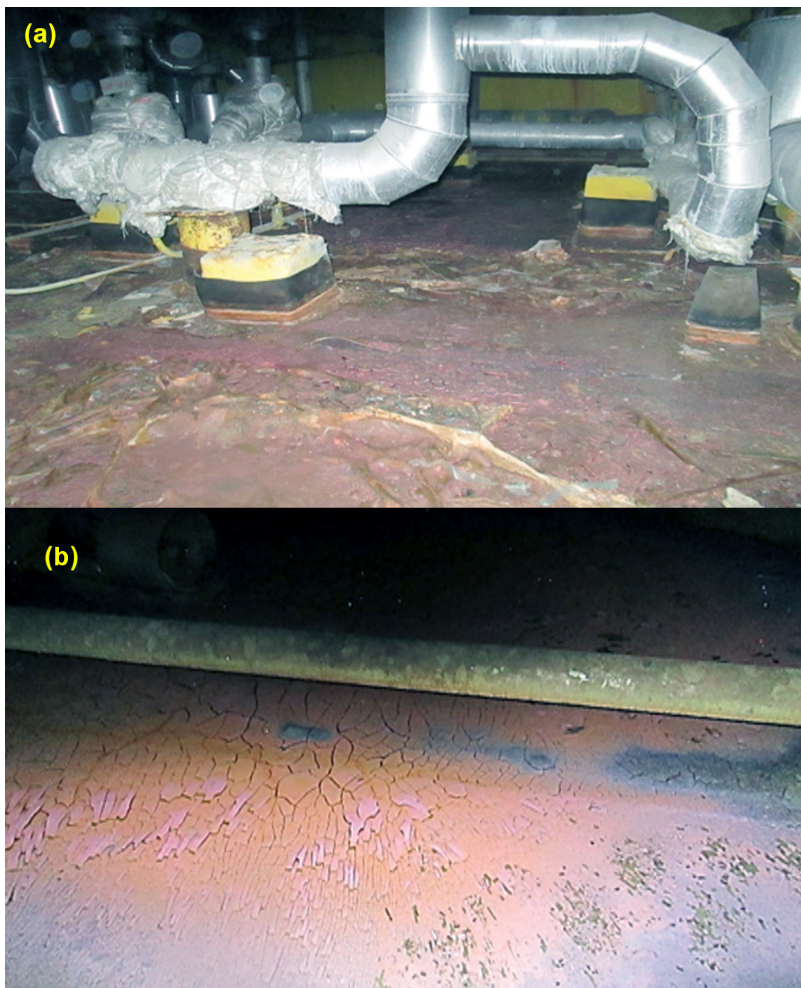


Fig. 3.56 — Sediments after drying of radioactive water accumulations, 2020:
a — in room 013/2; *b* — in room 012/8

Radioactive water accumulations in the northern part of rooms 012/13-16 of the PSP (Fig. 3.57) were formed by the leakages from SDC rooms located above as well as moisture condensation in the summer. And, besides, leakages from the central part of the PSP get here. During the period when evaporations become the primary process, water accumulations are reduced to the size of puddles. Water leakage is formed in the direction of the first floor rooms of the PSP.

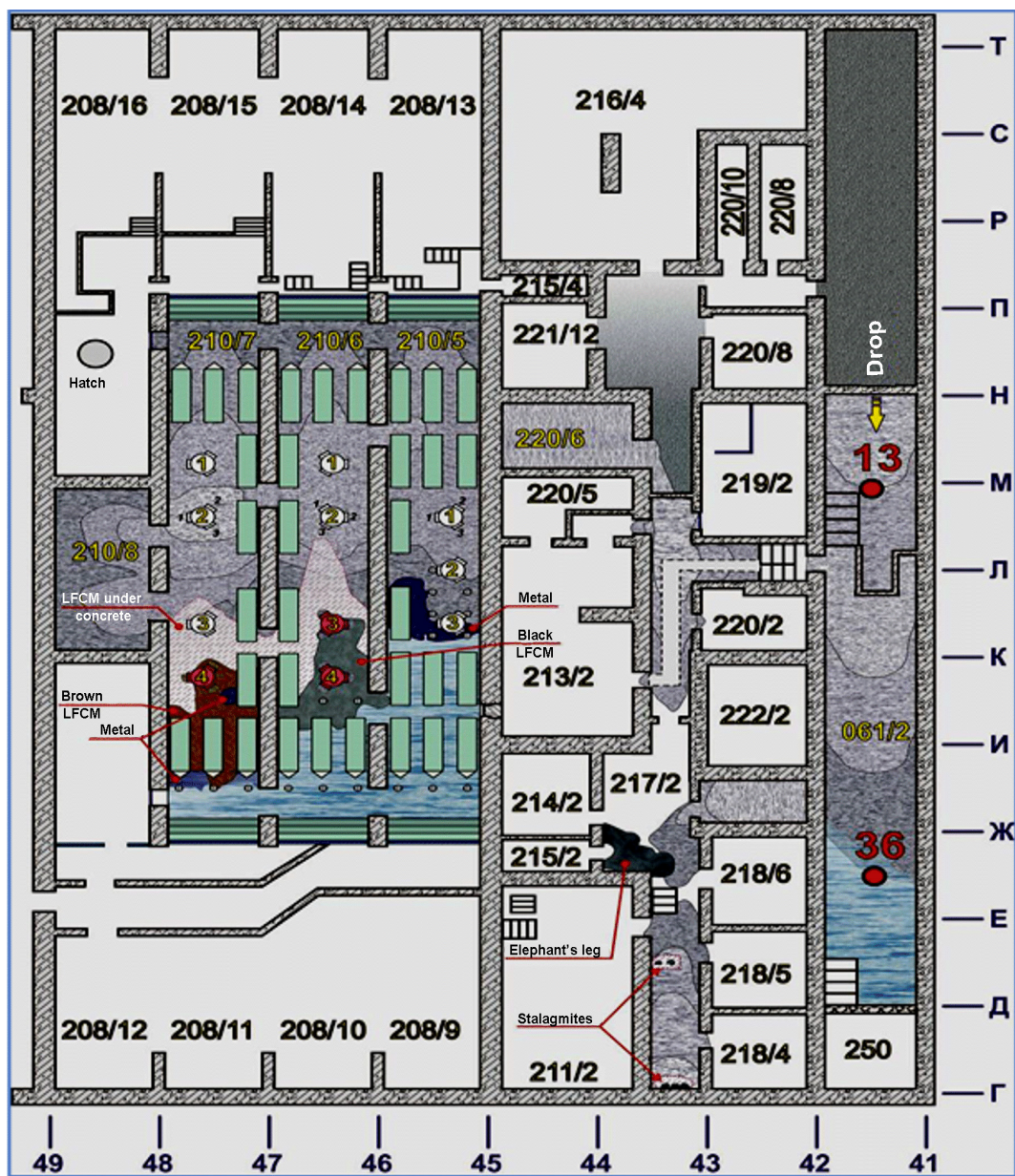


Fig. 3.58 — Location plan of radioactive water accumulations and sampling points in rooms of the Shelter object at the mark +6.000

Radioactive water accumulation with a volume of about 5 m^3 (Fig. 3.58) in the southern part of room 061/2 was formed by the RW leakage (in particular dust suppression solution) from the upper marks through the pit of the refueling machine to the northern part of the room and then by the slope of the concrete deck in the southern direction. In the cold period of the year, the accumulation freezes completely. Ice melting ends in May. Due to seasonal crystallization, RW in the accumulation remains colorless and clear until the dust suppression solution leakages flow. The height of the water layer near the southern wall of the room was 40 cm but from September to October 2016 the RW level in room 061/2 was about 20 cm. During 2017–2018, the RW accumulation dried up completely.

There is also the RW accumulation in the southern part of rooms 210/5-7 of the SDC. The total volume of RW can reach 10 m^3 . Control of accumulations in these rooms is complicated by the high level of γ -radiation from LLFCM. There is a possibility of leakage to the PSP rooms located below.

Volumes of RW accumulations in controlled rooms and dynamics of water flow during the year are specified by the seasonal trend (Fig. 3.59). The periods of water evaporation from the RW accumulations and periods of condensation moisture entry are well seen in the diagram.

We will pay special attention to the RW accumulation in room 001/3 because it is the biggest accumulation of RW (the volume is about 265 m^3) and sediments (up to 65 m^3).

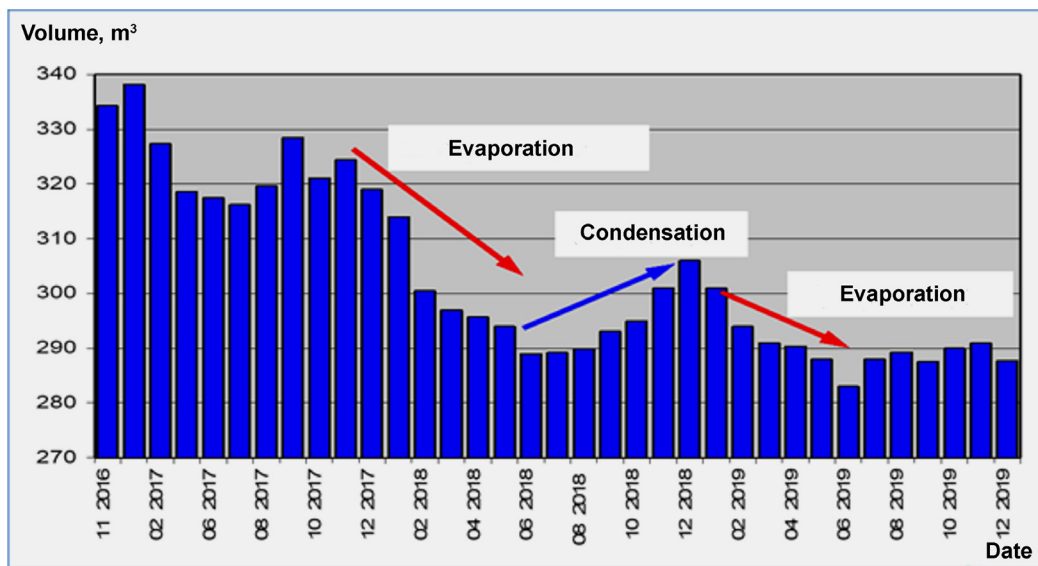


Fig. 3.59 — Dynamics of seasonal changes of radioactive water volumes in the NSC, 2016–2019

Data on the inflow of RW into room 001/3 from the visually controlled sources — from wells and a pipe of the SDC — is given in Table 3.11. In 2020 water inflow from the side of the cascade wall from the well was not observed (Figs. 3.60 and 3.61). It is due to the groundwater level decrease in the local zone of the Shelter object as a result of the Chornobyl NPP CP draining. The inflow of RW from the SDC pipe is very small — 0.001...0.0015 m³ monthly. Most probably, it is the leakage of process water from the water supply lines of the fourth power unit.

Survey results of RW accumulations in different rooms of the Shelter object are given in Table 3.12 as of 2020, and dynamics of the RW accumulations depth change in 2016—2020 is shown in Fig. 3.62.

Table 3.11 — Inflow of radioactive water into room 001/3 from visually controlled sources, January — March 2020

Month	RW inflow, m ³ /month			Weather data	
	point 8	point 20	total	precipitation, mm	t, °C
January	0.0	0.0011	0.0011	27.4	0.6
February	0.0	0.0015	0.0015	26.1	1.9
March	0.0	0.0008	0.0008	19.8	5.0
Total	0	0.0034	0.0034	73.3	

Table 3.12 — Volumes of the main radioactive water accumulations in the Shelter object, 2020

Room number	Mark, m	Axis	Row	Depth, cm	Area, m ²	RW volume, m ³
012/6, 7, 8	−0.95	46÷49	C÷T	24	27	6.4
012/6	−0.65	46÷47	Π÷T	0.1	10	0.01
012/7	−0.65	47÷48	Π÷T	0.5	10	0.05
012/8	−0.65	48÷49	Π÷T	0.2	10	0.02
012/13	+2.20	45÷46	Π÷T	2.6	40	1.1
012/13	+2.20	45÷46	Γ÷Ж	1.0	20	0.2
012/14	+2.20	46÷47	Γ÷Ж	1.5	20	0.3
012/15	+2.20	47÷48	Γ÷Ж	2.0	15	0.3
012/16	+2.20	48÷49	Γ÷Ж	2.2	30	0.66
017/2	+0.00	43÷44	Γ÷E	4.6	5.0	0.23
001/3	−2.60	41÷51	Y÷Y1	110	250	273

Table 3.13 — Concentration of uranium, g/m³, and radionuclides, Bq/m³, in radioactive water, 2020

Room number (sampling point)	Uranium	⁹⁰ Sr	¹³⁷ Cs	¹⁵⁴ Eu
012/16 (6)	140 ± 20	$(3.8 \pm 0.5) \cdot 10^9$	$(1.4 \pm 0.2) \cdot 10^{11}$	$(1.1 \pm 0.2) \cdot 10^7$
017/2 (18)	11 ± 2	$(3.8 \pm 0.7) \cdot 10^7$	$(6.7 \pm 0.8) \cdot 10^9$	$(1.9 \pm 0.3) \cdot 10^5$
01/3 (20)	29 ± 4	$(3.4 \pm 0.6) \cdot 10^9$	$(1.3 \pm 0.2) \cdot 10^{11}$	$(1.3 \pm 0.2) \cdot 10^6$
012/13 (21)	2.6 ± 0.4	$(1.3 \pm 0.2) \cdot 10^7$	$(4.8 \pm 0.6) \cdot 10^9$	$(1.9 \pm 0.7) \cdot 10^5$
001/3 (30)	7.4 ± 1.1	$(1.3 \pm 0.2) \cdot 10^9$	$(8.1 \pm 1.2) \cdot 10^9$	$(7.5 \pm 1.9) \cdot 10^5$
012/6 (31)	32 ± 4	$(2.5 \pm 0.5) \cdot 10^9$	$(2.7 \pm 0.3) \cdot 10^{10}$	$(1.2 \pm 0.3) \cdot 10^6$
Room number (sampling point)	²³⁸ Pu	²³⁹⁺²⁴⁰ Pu	²⁴¹ Am	²⁴⁴ Cm
012/16 (6)	$(7.2 \pm 0.8) \cdot 10^6$	$(1.5 \pm 0.2) \cdot 10^7$	$(9.2 \pm 1.1) \cdot 10^7$	$(2.8 \pm 0.4) \cdot 10^6$
017/2 (18)	$(1.6 \pm 0.2) \cdot 10^5$	$(4.2 \pm 0.6) \cdot 10^5$	$(1.8 \pm 0.3) \cdot 10^6$	$(3.9 \pm 0.7) \cdot 10^4$
01/3 (20)	$(2.7 \pm 0.4) \cdot 10^6$	$(5.9 \pm 0.8) \cdot 10^6$	$(1.4 \pm 0.2) \cdot 10^7$	$(4.2 \pm 0.8) \cdot 10^5$
012/13 (21)	$(9.4 \pm 1.7) \cdot 10^4$	$(1.9 \pm 0.2) \cdot 10^5$	$(1.8 \pm 0.3) \cdot 10^6$	$(4.5 \pm 0.8) \cdot 10^4$
001/3 (30)	$(2.5 \pm 0.3) \cdot 10^5$	$(4.9 \pm 0.7) \cdot 10^5$	$(6.3 \pm 0.9) \cdot 10^6$	$(1.9 \pm 0.4) \cdot 10^5$
012/6 (31)	$(3.2 \pm 0.5) \cdot 10^5$	$(7.5 \pm 1.1) \cdot 10^5$	$(8.2 \pm 1.3) \cdot 10^6$	$(2.7 \pm 0.6) \cdot 10^5$

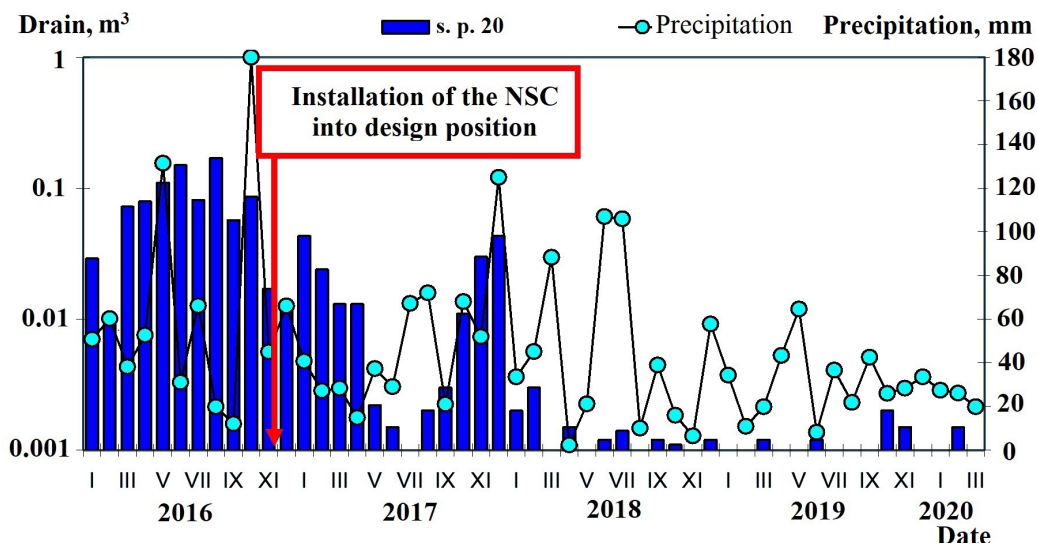


Fig. 3.60 — Average monthly inflow of radioactive water from the SDC pipe



Fig. 3.61 — Radioactive water drying in a container for radioactive water collection from the SDC pipe in room 001/3 of the Shelter object

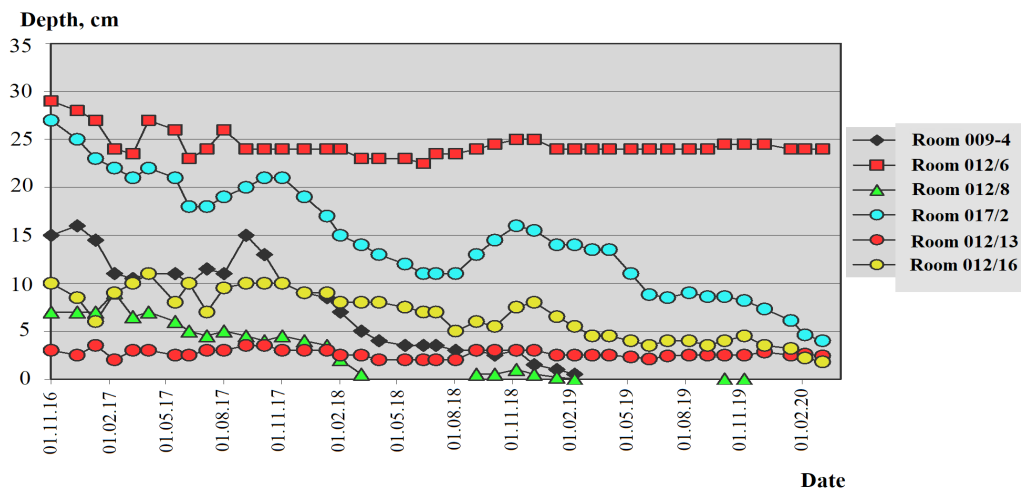


Fig. 3.62 — Dynamics of depth change of radioactive water accumulations in rooms of the Shelter object, 2016—2020

As of 2020, there is no RW in rooms 012/5, 012/5, 012/6, 012/7, 012/8, 012/14, 012/15, 012/16, 009/4, 013/2, 014/2, 018/2, 210/7. It should be noted that during the period of water evaporation (January—March) RW inflow into rooms 012/13, 012/6-8 and 001/3 is possible only from damaged water supply pipes of the Shelter object. It is a problem that needs to be solved in the nearest time. The nuclide composition of the main RW accumulations remains the same as before the NSC installation and is defined by radionuclides of Chornobyl genesis (radioactive debris of ^{90}Sr , ^{137}Cs and transuranium elements ^{238}Pu , $^{239+240}\text{Pu}$, ^{241}Am and ^{244}Cm).

Data of γ -spectrometer measurements and radiochemical analysis of RW samplings collected at the bottom marks of the Shelter object in 2020 are given in Table 3.13. The concentration of uranium varies from 2.6 to 140 g/m³. The maximum specific activity of ^{137}Cs in RW of the southern part of room 012/16 is $1.4 \cdot 10^{11}$ Bq/m³. The specific activity of transuranium elements ^{238}Pu , $^{239+240}\text{Pu}$, ^{241}Am and ^{244}Cm is largest in the same in room 012/16 and amounts to $1.5 \cdot 10^7$ Bq/m³ for $^{239+240}\text{Pu}$, and $9.2 \cdot 10^7$ Bq/m³ for ^{241}Am . The minimum spread in annual average values of uranium concentration and volumetric activity of radionuclides is in low-flow RW accumulations located in room 009/4, the northern part of rooms 012/5-8, and in rooms 012/13-16. During the year, the largest changes of the uranium concentration and the volumetric activity of ^{90}Sr and transuranium elements take place in leakages from the SDC pipe and collector at the mark +9.000 m, into room 017/2, through which the main water flow in the south-east part of the block B exists. The concentration of uranium in RW of the NSC after the arch installation ranged from 0.6 to 60 g/m³ (only in July it was 80 g/m³).

The volumetric activity of ^{90}Sr in RW depending on a sampling place ranges from $1.3 \cdot 10^7$ to $3.18 \cdot 10^{10}$ Bq/m³. In 2020 activity concentration of ^{90}Sr in permanent accumulations and leakages of RW was about $1 \cdot 10^{11}$ Bq/m³. The highest volumetric activity of ^{137}Cs in RW of the Shelter object was registered in 2002 in the southern part of room 012/7 — $1,2 \cdot 10^{12}$ Bq/m³.

The volumetric activity concentration of ^{154}Eu and ^{155}Eu isotopes in RW ranges from $8.7 \cdot 10^3$ to $1.1 \cdot 10^6$ Bq/m³. The maximum activity of transuranium elements ($^{238}\text{Pu} + ^{239+240}\text{Pu} + ^{241}\text{Am} + ^{244}\text{Cm} + ^{242}\text{Cm}$) can amount to $1 \cdot 10^8$ Bq/m³. We should mention that there is ^{242}Cm radionuclide in RW, which is due to the decay of parent radionuclide ^{242}Am . As before, ^{241}Am makes the biggest contribution to the total α -activity — up to 80%.

Concentrations of radionuclides ^{90}Sr , ^{137}Cs , $^{239+240}\text{Pu}$, ^{241}Am , uranium (almost 3 times) increase in rooms of the first and the second floors of the NSC pressure-suppression pool due to the water evaporation from these accumulations (Fig. 3.63). Stabilization of the average concentrations of ^{90}Sr in RW at this moment may be caused by the following reasons: co-deposition of the excess of strontium and CaCO_3 with increasing concentration of carbonate ions when the evaporation prevails over the condensation; dissolution of deposited forms of strontium with a decrease of carbonate ions concentration, for example in case of intensive water inflow.

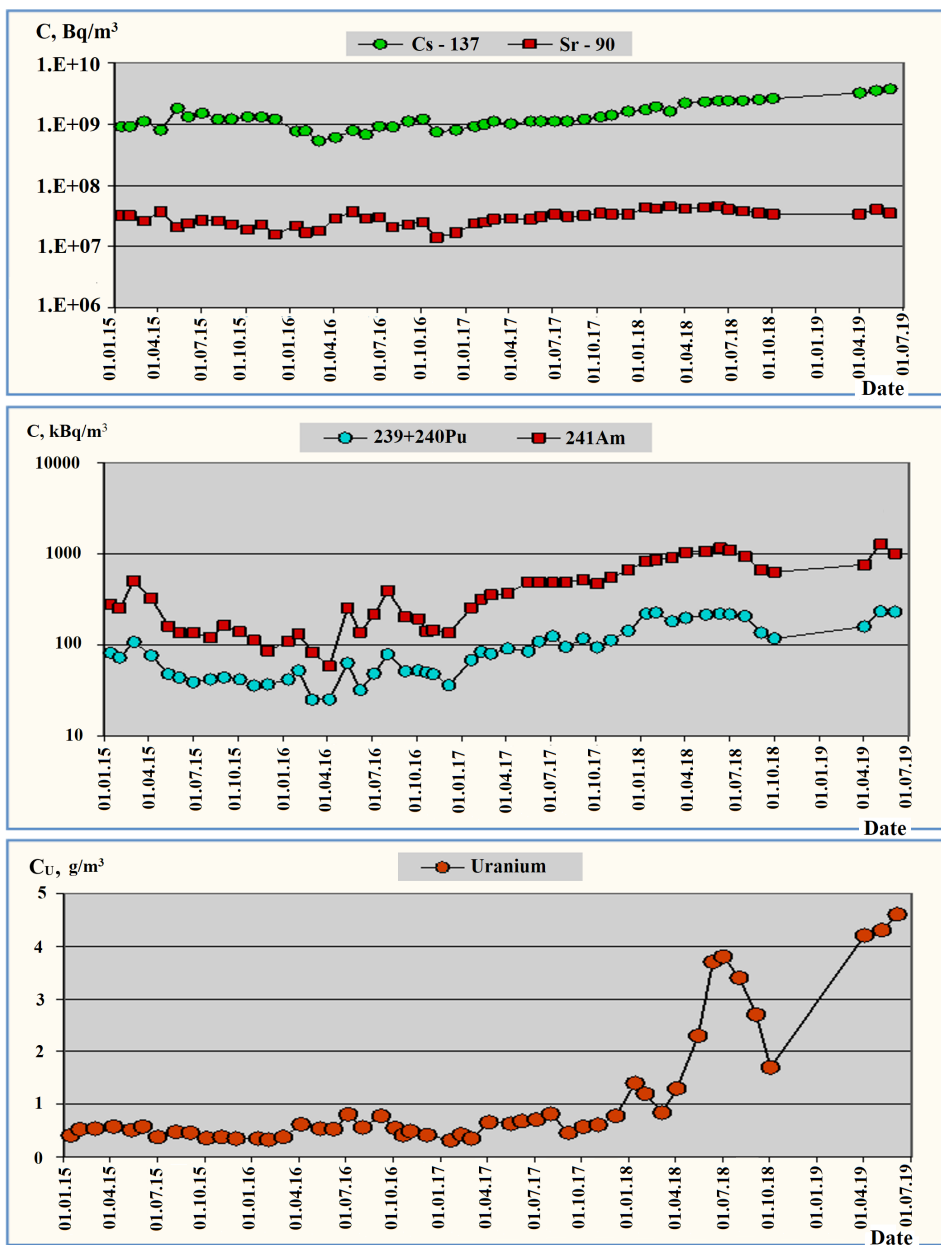


Fig. 3.63 — Dynamics of concentration increase of radionuclides ^{90}Sr , ^{137}Cs , $^{239+240}\text{Pu}$, ^{241}Am , uranium in room 017/2 of the Shelter object (sampling point 18), 2015—2019

The chemical composition of RW in the Shelter object is defined mainly by the leaching of macrocomponents (sodium, potassium, calcium, magnesium, carbonates, chlorides, sulfates, etc.) from concrete building structures and organic components of cleansing solutions and MDSS solutions [118, 119]. Therefore, as before the NSC installation, RW macrocomponents composition practically has not changed. As of today, the only exception is a decrease in the concentration of organic compounds, which are part of dust suppression solutions, due to an abrupt decrease in the amount of dust suppression sessions.

The value of pH in RW accumulations changes from 9.2 to 9.7. It confirms their alkaline medium. The concentration of phosphates (HPO_4^{2-}) varies from 0.11 to 4.9 mg/dm³. The content of carbonates and hydrocarbonates is 160—910 and 460—2140 mg/dm³, respectively. The concentration of hydrocarbonates has increased significantly in RW of rooms 01/3, 017/2, 012/13, 014/2, 012/16 and exceeds 1,000 mg/dm³. An increase of macrocomponents concentration is logical and caused by a decrease of RW volumes due to evaporation and, accordingly, the concentration of cations and anions.

The dynamics of the carbonates and hydrocarbonates concentration and the pH value in RW of room 017/2 after the NSC construction are shown in Fig. 3.64.

Sediments in water accumulations are formed due to coagulation and deposition of colloids and suspended particles of the solid phase (in the form of suspension). Therefore, the research methodology contained a sampling of sediments as well as unit water with suspended particles of solid phase without sediment detachment. The total volume of sediments is 70 m³; besides, most of them, about 65 m³, are grouped in room 001/3. An assessment of the amount of sediment in the Shelter object rooms is given in Table 3.14.

Table 3.14 — Average volumes of sediments in the main water accumulations of the Shelter object

Mark	Room number	Coordinates, axis/row	The volume of sediments, m ³
–2.600	001/3	Y÷Y1/42÷51	65
–0.650	009/4	И÷E/49÷50	0.1
–0.650	013/2	Г÷E/44÷45	2.0
–0.650	014/2	И÷Ж/44÷45	1.0
–0.650	017/2	Г÷Д/43÷44	0.1
–0.650	018/2	Г÷И/42÷43	0.1
–0.650	012/5-8	Г÷Т/45÷49	1.0
+2.200	012/13-16	Г÷Т/45÷49	0.5
+6.000	219/2	М÷Н/42÷43	0.3
+6.000	223/2	И÷Ж/42÷43	0.3

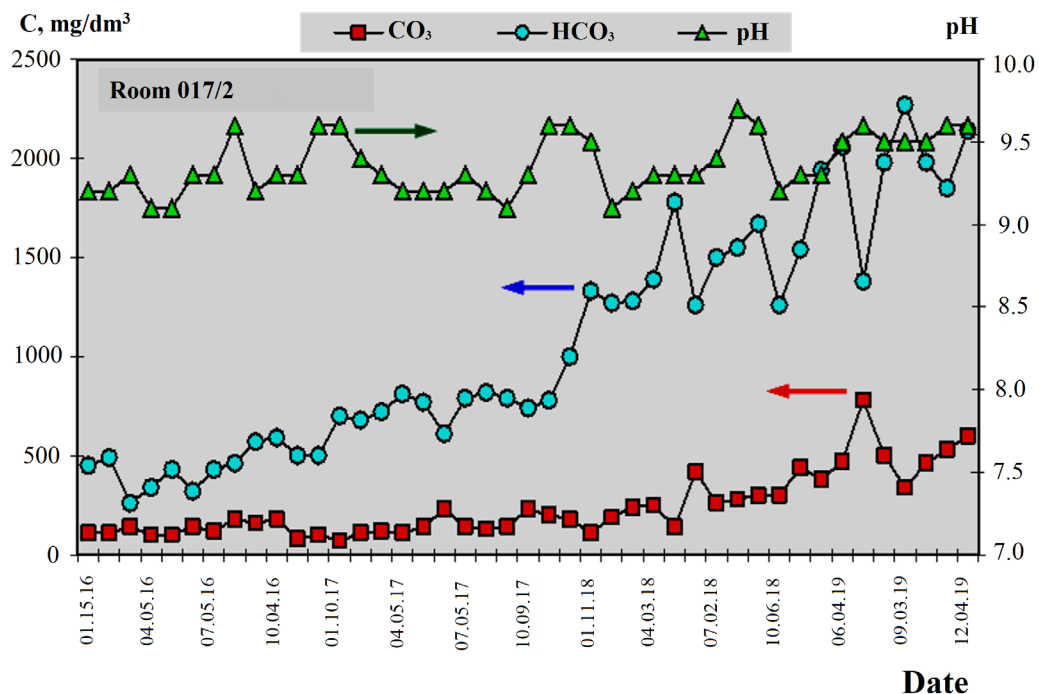


Fig. 3.64 — Dynamics of the carbonates and hydrocarbonates concentration and the pH value in radioactive water of the NSC room 017/2

Sediments are a heterogeneous mix of coarsely dispersed particles and black mud with a specific scent of decaying organic matter. The bottom layer of sediments mainly consists of standard sand (SiO_2), which probably was formed by the destruction of plasticized concrete. The top layer consists of lighter and more radioactive clay fraction. It contains calcium and silicon compounds, most likely in form of CaCO_3 , CaSiO_3 (more than 60% in terms of solid residual), iron, magnesium, uranium as well as some amount of organic compounds. The average density of dried sludge is 1.54 g/cm^3 . The moisture of the sediment clay fraction is about 85%.

According to information available at this moment, the composition of sediments usually is formed due to the destruction of plasticized and constructional concrete, corrosion of metal structures, coagulation and deposition of colloid forms and soluble products of destruction and corrosion, organic compounds deposition. Thus, during the time passed after the accident, a large amount of highly active sediments (up to $1,010 \text{ Bq/kg}$) have accumulated at the bottom marks of the fourth power unit. Their drying up will lead to the increase of contamination level, and isotopes ^{241}Am and $^{238, 239, 240}\text{Pu}$ are the most hazardous while inhalation intake.

Sediments in room 001/3 (Fig. 3.65) appeared as a result of dispersed phase deposition, formation of poorly soluble salts of calcium and magnesium carbonates, coagulation and deposition of poorly soluble heavy metals hydroxide up to 33 cm thick. Samplings of sediments were collected in 2016—2017 using a metal bailer through the well (s. p. 30) drilled in the floor of room 001/3.

The moisture of the sediments sample is 54%; loss during the calcination is 19% (mainly determined by the amount of organic phase in sediments). The sludge density is from 1.2 to 1.4 g/cm³.

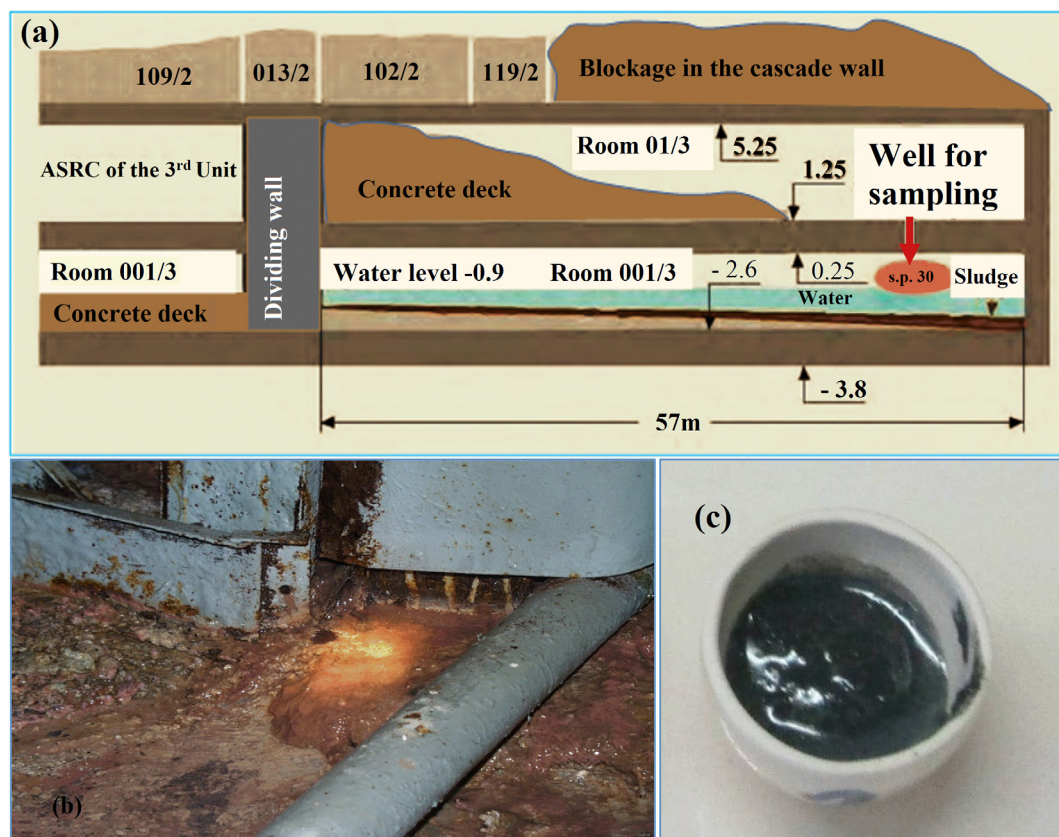


Figure 3.65 — Room 001/3:

- a* — plan of room at the mark -2.60 m with the biggest radioactive water accumulation in the Shelter object;
- b* — sediments;
- c* — view of sludge sample

The specific activity of radionuclides in sediments samples of room 001/3 in 2016 by the sum of α -, β -emission nuclides was $3 \cdot 10^9$ Bq/kg (in terms of air-dry state) and corresponded to values obtained in 2006—2015 within the order of magnitude. It verifies the conclusion about the stability of radionuclides content in room 001/3 during the last decade (Table 3.15).

Table 3.15 — Specific activity of sediments in room 001/3 of the Shelter object, Bq/kg

Date of sampling	^{90}Sr	^{137}Cs	^{154}Eu	^{238}Pu	$^{239+240}\text{Pu}$	^{241}Am	^{244}Cm
02.07.2015	$5.7 \cdot 10^8$	$8.5 \cdot 10^8$	$1.1 \cdot 10^6$	$3.3 \cdot 10^5$	$7.1 \cdot 10^5$	$7.5 \cdot 10^6$	$2.7 \cdot 10^5$
07.06.2016	$6.9 \cdot 10^8$	$9.1 \cdot 10^8$	$7.1 \cdot 10^5$	$2.8 \cdot 10^5$	$6.5 \cdot 10^5$	$5.1 \cdot 10^5$	$1.7 \cdot 10^5$
05.07.2017	$7.4 \cdot 10^8$	$8.1 \cdot 10^8$	$9.8 \cdot 10^5$	$5.1 \cdot 10^5$	$1.1 \cdot 10^6$	$7.3 \cdot 10^6$	$2.4 \cdot 10^5$

Content and isotope composition in sediments of room 001/3 are given in Table 3.16. The concentration of uranium in analyzed samples of sediments is from 2 to 3 g/kg that corresponds to the values of 2006 and 2015 within the uncertainty of measurements. The content of ^{235}U is from 0.026 to 0.033 g/kg. Isotope composition of uranium in sediments as a whole corresponds to the isotope composition of irradiated fuel of the Chornobyl NPP fourth power unit with an average burnup.

Table 3.16 — Uranium content in sediments of room 001/3 of the Shelter object, 2015—2017

Date of sampling	Uranium, g/kg	Isotope composition of uranium, %			
		^{234}U	^{235}U	^{236}U	^{238}U
02.07.2015	$3.1 \pm 0,5$	0.016	1.06	0.19	98.7
07.06.2016	$2.4 \pm 0,4$	0.015	1.03	0.19	98.8
05.07.2017	$2.2 \pm 0,4$	0.015	0.98	0.17	98.85

To forecast the radiation state of sediments and their further treatment, it is necessary to know the chemical form of radionuclides and uranium in them. ^{137}Cs enrichment of sediments, possibly, is because ion forms of cesium were sorbed on fine particles of natural inorganic ionites, formed by the destruction of structural materials and covering components (sand, clay), thrown from the helicopters onto the destroyed fourth power unit during the active phase of accident consequences elimination.

Radioactive water entering room 001/3 from the upper level of the Shelter object is brackish and sufficiently dissolves ^{90}Sr and ^{137}Cs . During the water movement from the upper to bottom marks, it interacts with concrete, therefore, carbonates concentration in RW increases and solubility of alkaline-earth elements (Mg, Ca and Sr) decreases. When concentrations of carbonate-ions are high that is typical for RW at the bottom marks, strontium forms poorly soluble strontium carbonate — SrCO_3 , which co-deposits with CaCO_3 .

It has been found experimentally that the average concentration of calcium in RW at the bottom marks of the Shelter object is approximately 30 mg/l. This value is a limit of calcium solubility in alkali carbonate solutions, therefore, calcium carbonate excess precipitates. An exploration of the chemical composition of sediments confirmed that the most enriched ^{90}Sr fine particles of the solid phase (from 0.01 to 0.03 μm) mostly consist of CaCO_3 . During the destruction of fuel containing materials due to the impact of moisture, transuranium elements form under the condition of the Shelter object (alkali-carbonate medium) insoluble compounds, a bigger part of which remains in the FCM localization area.

Approximately 25% of ^{241}Am and less than 5% of plutonium isotope are transferred to the bottom marks of the Shelter object, and solely in colloid forms. The distribution of radionuclides ^{154}Eu , ^{238}Pu , $^{239+240}\text{Pu}$, ^{241}Am and ^{244}Cm intake forms in sediments of room 001/3 is shown in Fig. 3.66. The majority of water-soluble and exchangeable forms belong to ^{137}Cs , which is 3.5 and 45.0%, respectively. More than 65% of ^{90}Sr is contained in carbonate compounds, its exchange forms are 17%. Mobile fractions of ^{90}Sr and ^{137}Cs , which usually include the sum of water-soluble, exchangeable, carbonate and acid-soluble forms (in 1 mol/l HCl), are 97 and 89%, respectively.

Transuranium elements ^{238}Pu , $^{239+240}\text{Pu}$, ^{241}Am and ^{244}Cm according to their chemical properties are predominantly contained in hydroxide compounds and transformed into the soluble state if pH is ≥ 4.8 . Part of exchangeable forms of plutonium, americium and curium does not exceed 4%. More than half of ^{238}Pu and $^{239+240}\text{Pu}$ have acid-soluble forms.

According to the data on the state and behavior of RW, we can conclude that installation of the NSC into design position made moisture ingress into the Shelter object rooms impossible, and optimization of the DSS operation minimized ingress of technogenic solutions. Results of the recent researches have shown that there is no RW in rooms of the first floor of the PSP 012/5-8 except for areaways of rooms 012/6-7. In room 017/2 of the south-eastern part of block B, there is less than 0.5 m^3 of RW. In rooms of the second floor of the PSP 012/13-16, there are no RW accumulations except for room 012/13. In the northern part of room 012/13, there is consistently from 1.2 to 1.8 m^3 of RW regardless of the season.

Water evaporation consistently is compensated by its ingress. Today the source of water ingress into the northern part of room 012/13 is not found. Probably, water enters from the damaged technological feedwater manifold of the Shelter object. This fact is worth paying attention to.

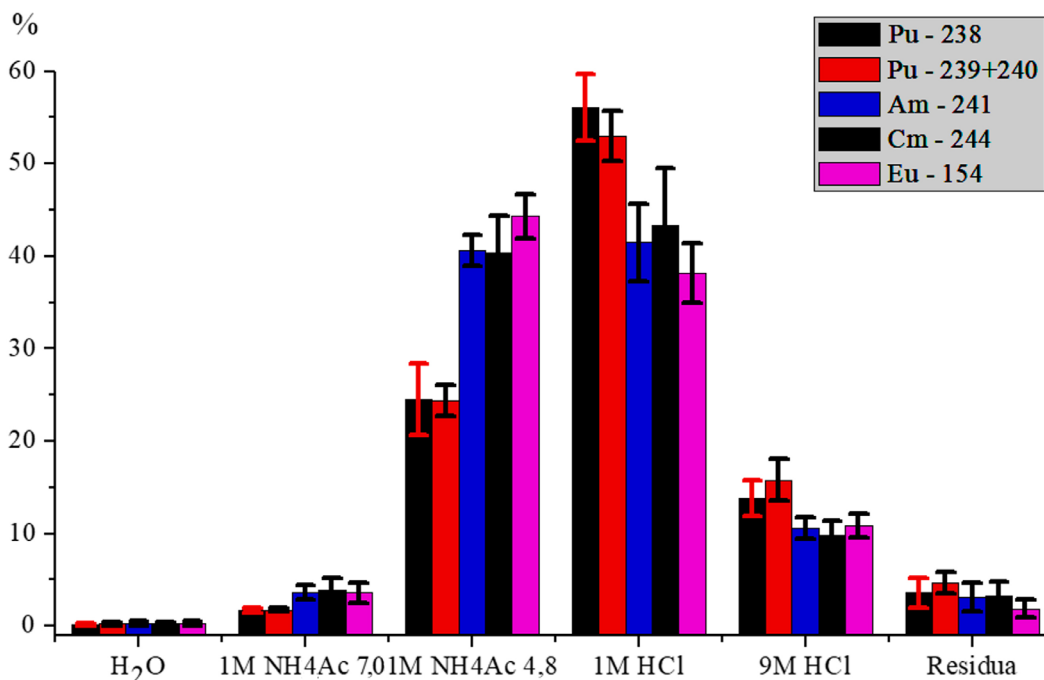


Fig. 3.66 — Distribution of radionuclide forms in sediments of room 001/3

Radioactive water accumulations with practically unchanged volumes are accumulations in room 001/3, the largest in the Shelter object. Here not only a big amount of leakages from the northern part of block B are accumulated, but also leakages from the southern watercourse. There are most of the sediments of the Shelter object here in room 001/3. The top layer of sediments is flowing black sludge with the characteristic smell of decaying organic matter. The thickness of the layer in the sampling point is approximately 0.2 m. The layer of packed sediments with high content of sand lies below. The volume of sediments is approximately 65 m³. Water flows from the controlled room leaks through the dividing wall to room 001/3 of the third power unit and requires periodical removal.

During the drying out of RW accumulations sediments with an elevated abundance ratio of ²⁴⁴Cm are formed, which is the main source of spontaneous fission neutrons.

Radioactive water volumes in the Shelter object room decrease due to the water evaporation, at the same time uranium concentration and volumetric activity of radionuclides in the RW increase several times. Intensive drying out of RW accumulations and denudation of highly active fine-dispersed sediments can lead to the formation of new sources of RA.

To prevent their hazardous impact on the NSC radiation safety, analysis of sediments and the development of preventive measures for their localization should become a priority.

Before the NSC installation, RW was a kind of marker since it contained information on the FCM state, and RW monitoring is one of the methods of their nonoperational control. Now, this kind of control should be replaced by more effective ones, for instance, video monitoring of FCM accumulations and sediment study.

Chapter 4. IMPACT OF THE NEW SAFE CONFINEMENT ON THE ENVIRONMENT

The impact of the Shelter object on the environment is under control during the whole period of its existence [120—123]. In the first years, monitoring of radioactive contamination was sporadic, and only in 1987 holistic system was formed for providing scheduling monitoring of the atmospheric surface layer at the territory, which is immediately adjacent to the Shelter object (hereafter referred to as the Shelter object local zone), and adjacent areas. It is important to monitor the air pollution because there are natural factors of RA intake, for example, atmospheric transport of radioactive dust from open areas of adjacent territories; forest fires at territories of the Chornobyl NPP near zone [124]; excavation at the Chornobyl NPP site; road traffic; construction works in the Shelter object local zone. Until recently, the Shelter object was an important source of RA intake. Today the monitoring system of the surface air radioactive contamination is a key system, which controls the NSC safe operation.

Due to the significant amount of destroyed reactor radioactive materials that are contained in the ground of the Shelter object local zone after 1986, there is intensive contamination of the hydrogeological area by radionuclides. The contamination value is determined by constant groundwater movement as well as changes in their level and velocity. The Chornobyl NPP is located in the floodplain of the Prypiyat river, in the direction in which the groundwater moves. Thus it is extremely important to monitor the level of radioactive contamination and conditions, which determine the ability of radionuclide transfer by groundwater [125—127]. To this end, there is a system of radiohydrogeological monitoring, which for decades controls the state of groundwater and assesses the impact of different factors on radionuclides contamination.

4.1 Radioactive aerosols in the surface air of the Chornobyl NPP local zone

Monitoring of RA in the surface air is due to the necessity of radiation impact control on the personnel working on the site, effective decision-making in case of emergencies, as well as assessment of the Shelter object impact on the environment.

Before the NSC construction, contamination of the surface air in the Shelter object local zone and adjacent territory of the Chornobyl NPP industrial site was determined by

non-organized aerosols emission through the holes and cracks of the light roof and walls of the Shelter object and the turbine island. It was confirmed that there is a direct correlation between RA emission and the aerosols volumetric activity in the surface air of the local zone. The RA of the Shelter object were emitted at a height of about 50 m from the ground through the holes and cracks in the roof with a total area of about 120 m². In 1998—2003, the average emission of $\Sigma\beta$ -activity was from 696 to 1,184 MBq/year. At the same time, the highest RA concentration in the surface air in the amount of 0.02 Bq/m³ was observed on the site at a distance of 40—50 m from the Shelter object walls in the air shadow zone. The RA contribution, emitted from the Shelter object, into the total level of air pollution in the local zone could reach 70% [128].

The second most important RA source in the surface air is the ground contaminated by radionuclides. The contribution of the dust resuspension from the surface of the Shelter object site and surrounding territories to the surface air contamination was up to 30% depending on meteorological conditions. Some measurements of the aerosols activity in the air in this regard began in the first days after the accident, and regular measurements started in 1998. According to the scheduling monitoring in 2006, at the territory of the Shelter object local zone α -active aerosols volumetric activity in the air was, from $5.7 \cdot 10^{-4}$ to $1.1 \cdot 10^{-2}$ Bq/m³, and β -active ones — from $1.9 \cdot 10^{-3}$ to $2.1 \cdot 10^{-1}$ Bq/m³ [128].

The contribution of the main radionuclides to the volumetric activity in the air of the site was (in %): ⁹⁰Sr — 19.05; ¹³⁷Cs (condensed) — 33.6; ¹³⁷Cs (fuel) — 33.6; ²³⁸, ²³⁹, ²⁴⁰Pu — 0.43; ²⁴¹Pu — 13.03; ²⁴¹Am — 0.29. The distribution over α -emitting nuclides was approximately following (in %): ²³⁸ + ²³⁹ + ²⁴⁰Pu — 50, ²⁴⁴Cm — 3; by β - and γ -emitting nuclides, %: ⁹⁰Sr + ⁹⁰Y — 52, ¹³⁷Cs — 31%, ²⁴¹Pu — 14.

At all sites of the stabilization works (2002—2007), the size distribution of the ¹³⁷Cs carrying aerosol shifted towards a coarsely dispersed fraction with an aerodynamic diameter of 3.5 μ m and more [128].

The third factor, which has the biggest impact on the RA behavior, is anthropogenic one related to installation and construction works in the Shelter object local zone in different periods under the program of the Shelter object transformation into an ecologically safe system, such as: strengthening the ventilation stack VT-2 (1998), reinforcement of beams B1-B2 (1999), installation of the updated DSS (2004), removal of the pioneer wall berm (2007), stabilization measures (2008), a buildup of the NSC site (2009), dismantling of VT-2, construction of a NVS (2013), etc. These works were accompanied by intensive road traffic, excavation, installation, welding works, which significantly worsened the radiation situation in the NPP local zone.

It should be noted that the rate of RA emission from the Shelter object, and consequently levels of air pollution near the object considerably depend on seasonal factors and meteorological conditions. During the autumn and winter, the aerosol emission and their volumetric activity in the local zone usually were higher than in the summer. The reason is

the airflow rate from the Shelter object in autumn and winter is higher than in the summer and determined by the temperature difference inside and outside. In the summer, values of the aerosol volumetric activity in the surface air match the values of the aerosols volumetric activity at the upper marks (+36.000). It is explained by the effect of aerosol resuspension and transport from the underlying surface of surrounding territories.

In recent years, there has been a trend of stabilization of the achieved air pollution level in the local zone and at the Shelter object site. According to the reports on the safety state of the Shelter object, long-term control of the radionuclides volumetric activity in the air during various operation and construction works shows that a temporary increase in the radioactive contamination level of the air in rooms has no impact on the total release from the Shelter object, and change of the radiation situation during the excavation works has short-term character. In so doing the values of the radionuclides volumetric activity in the air of the local zone do not exceed reference levels.

The location of the monitoring system of the RA state (volumetric activity in the air and depositions) is shown in Fig. 4.1.

The aerosol samples are collected on the FPP-15-1.5 filters. The air sampling rate is 8...12 thousand cubic meters per day. The period of filter exposure is 13...20 days, and during radiatively hazardous works, which are accompanied by deterioration of radiation situation in the surface air (radioactive dust resuspension), is 4...7 days.

The activity of the ^{137}Cs , ^{154}Eu , ^{241}Am radionuclides was identified and determined according to the data of γ -spectrometer measurements. The activity of α -emitting ($\Sigma\alpha$ ^{238}Pu , ^{239}Pu , ^{240}Pu) and β -emitting ($\Sigma\beta$ ^{137}Cs , ^{90}Sr + ^{90}Y i ^{241}Pu) nuclides was calculated by their ratios with the ^{241}Am activity in the basic composition of the fourth power unit fuel at the moment of measurements [129—132]. Dynamics of the RA annual average volumetric activity in the surface air of the NSC site according to the measurement results in 1998—2020 at the control points AU-1, AU-2, AU-3 is shown in Fig. 4.2.

An analysis of the sum RA volumetric activity dynamics in the surface air of the NSC site shows that several periods can be conditionally distinguished that are characterized by the impact on the radiation situation in the surface air from different RA sources and related to the anthropogenic activity and installation and construction works.

During the first period (until December 2000) (Fig. 4.2, 1) the third power unit of the Chornobyl NPP worked, as well as works on reinforcement of the ventilation stack VT-2 (1998) and beams B1-B2 (1999) were conducted.

During the second period (Fig. 4.2, 2), an updated DSS was installed and commissioned (2003—2007), reinforcement measures of the unstable structures were taken (2005—2007).

The third period (Fig. 4.2, 3) is the NSC construction, including removal of the berm of the pioneering wall (2008), a buildup of the site for the NSC installation (2010), construction of the NVS (2010), dismantling of VT-2, partial collapse of the turbine island roof of the Shelter object (2013), dismantling of some building structures of the Shelter object, and

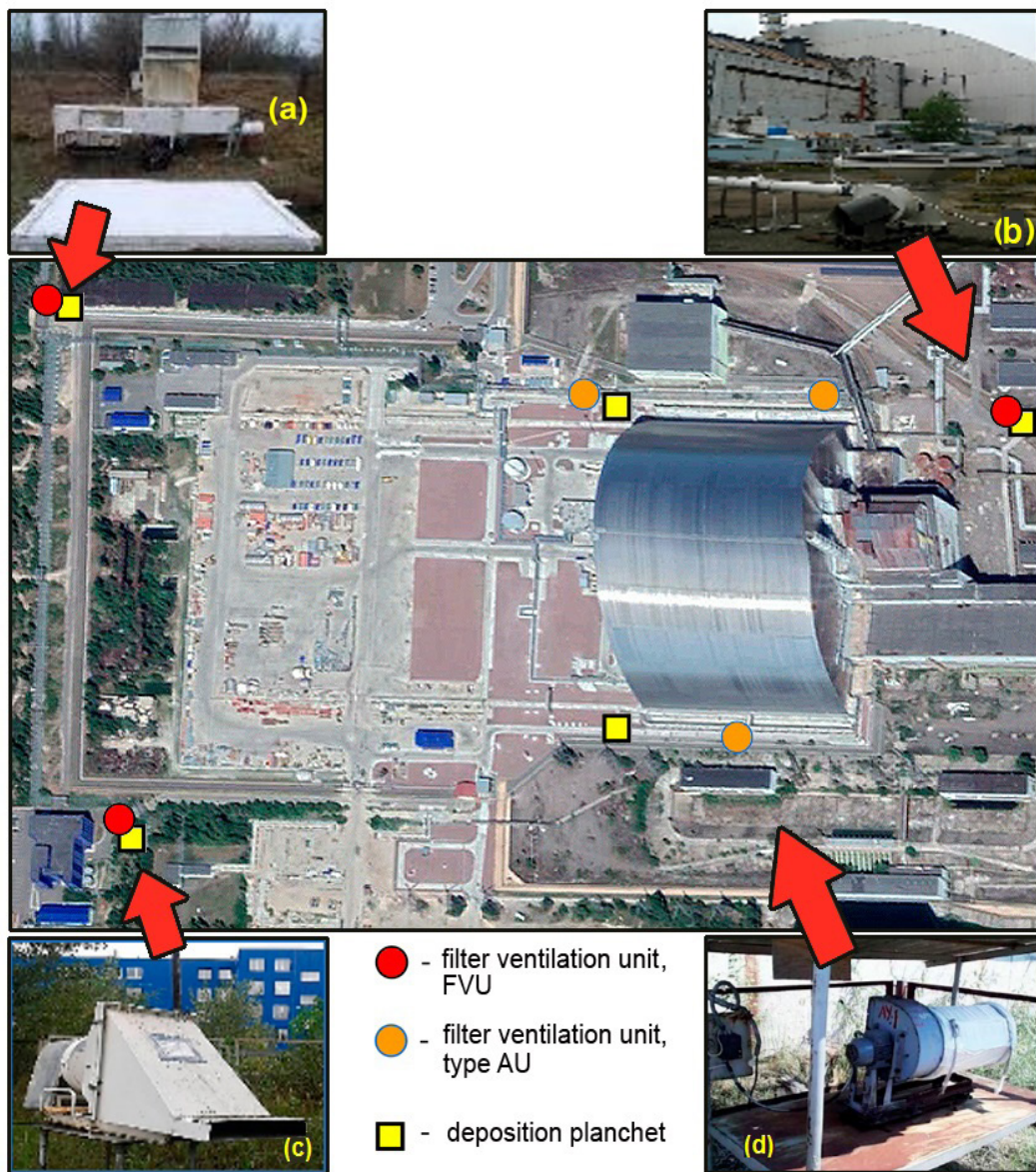


Fig. 4.1 — Location plan of radioactive aerosols control points in the surface air of the Chernobyl NPP local zone:

a — FVU “Typhoon”; *b* — FVU GRAD-1.0; *c* — FVU “Wentmecca”; *d* — AU-3 South

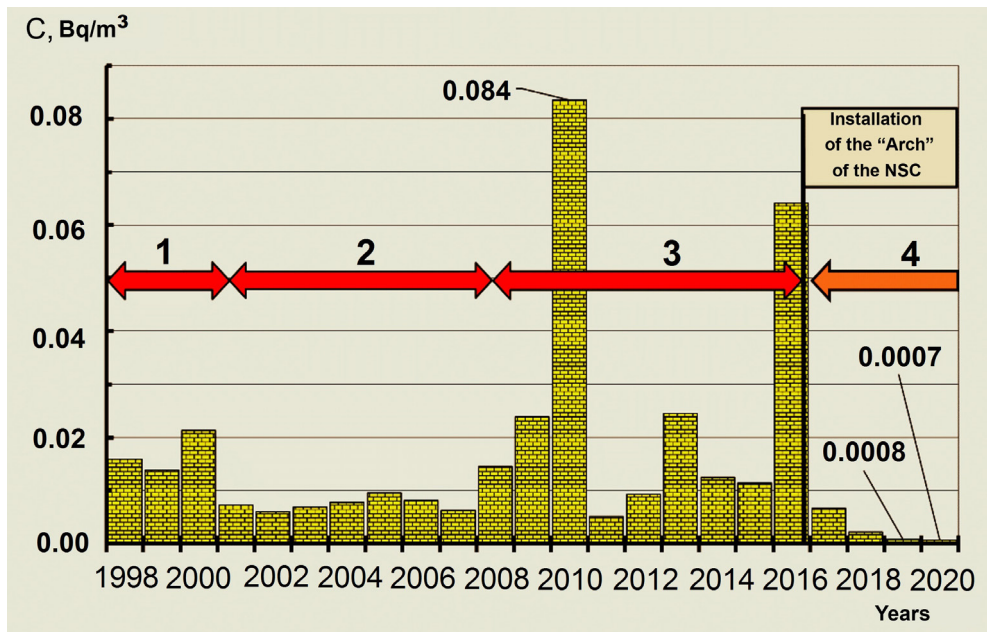


Fig. 4.2 — Change of the total RA volumetric activity in the surface air of the site at the different stages of the Shelter object transformation into an ecologically safe system

construction walls of the NSC EP (2016). It should be noted that in 2010 during excavation works including soil extraction for foundation strips of the NSC, the annual average RA volumetric activity in the air of the local zone reached a maximum value for the entire period of observation — 0.08 Bq/m^3 [133].

The fourth period (Fig. 4.2, 4) is the completion of works on the NSC commissioning and the start of operation.

According to the data in Fig. 4.3, before the NSC construction in 2016, the average annual values of the $\Sigma\alpha$ and $\Sigma\beta$ volumetric activity in the surface air of the site were $9.4 \cdot 10^{-4}$ and $6.2 \cdot 10^{-2} \text{ Bq/m}^3$, respectively [98]. After the NSC commissioning and putting in order an adjacent territory they decreased almost by one order of magnitude and in 2020 reached $1.3 \cdot 10^{-5}$ and $7.0 \cdot 10^{-4} \text{ Bq/m}^3$, respectively. Maximum values of $\Sigma\alpha$ - and $\Sigma\beta$ -emitting nuclides activity in 2016 were registered in the south of the local zone (AU-3) from August 29 to September 5 and were amounted to $1.8 \cdot 10^{-2}$ and 1.4 Bq/m^3 , respectively.

To take into account the impact of dust resuspension during the work on the NSC site, the dust mass concentration in the surface air was assessed. According to the data in Fig. 4.4, in 2016, during intensive construction and dismantling works the average dust concentration, at the observation points AU-1, AU-2 and AU-3 amounted to 0.021, 0.033, 0.047 mg/m^3 ,

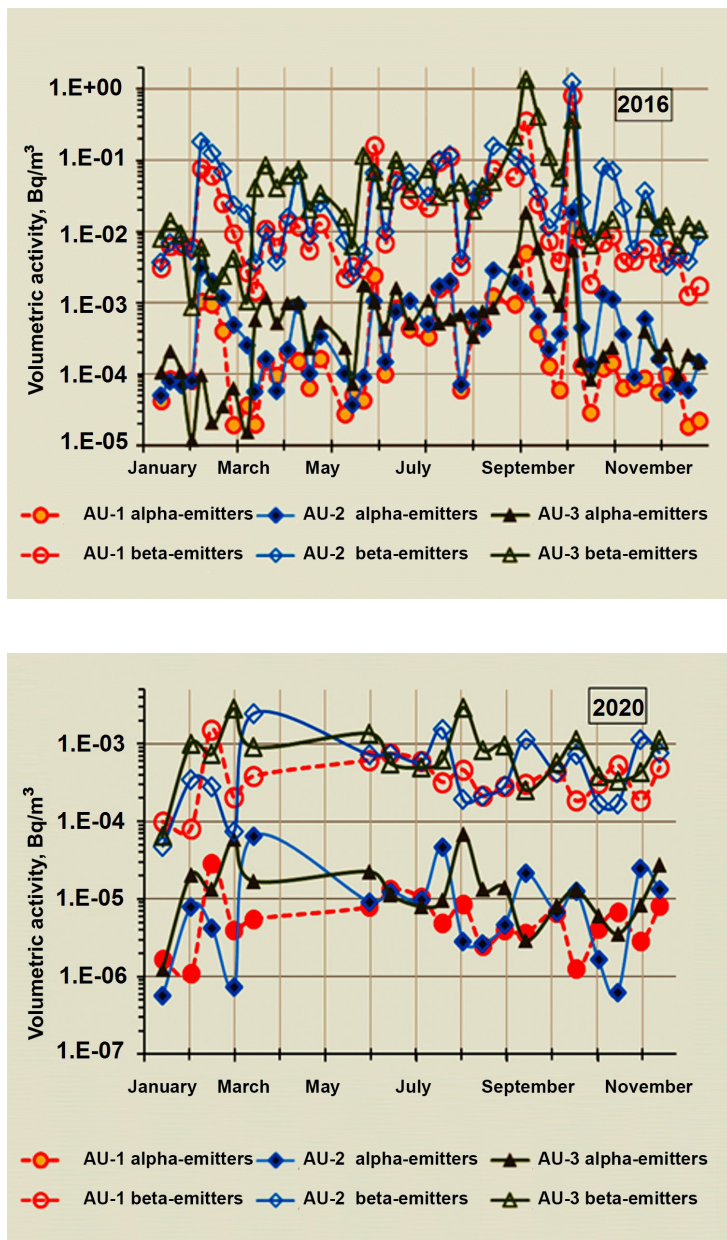


Fig. 4.3 — Volumetric activity of $\Sigma\alpha$ - and $\Sigma\beta$ -emitting aerosols in the surface air of the Shelter object local zone in 2016 and 2020

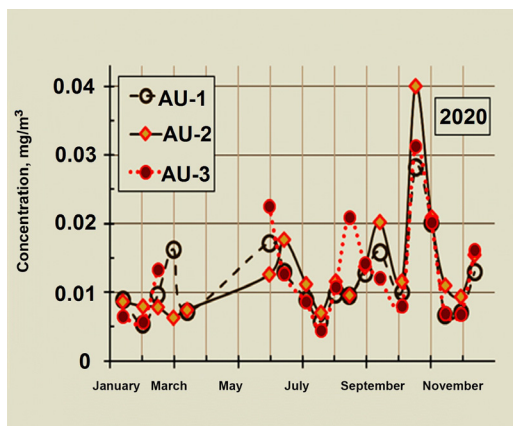
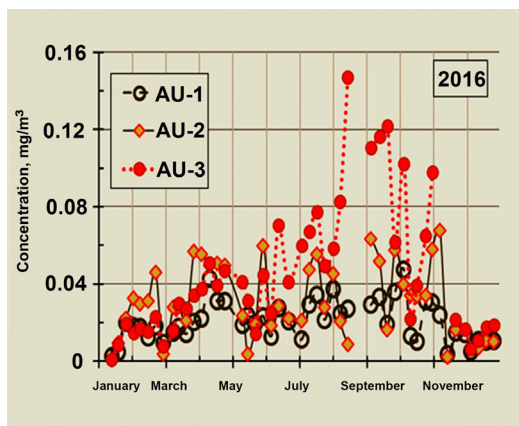


Fig. 4.4 — Dust concentration in the surface air of the Shelter object local zone in 2016 and 2020

respectively, and average dust concentration in the local zone was 0.033 mg/m^3 . A maximum dust concentration of 0.15 mg/m^3 was observed from August 8 to 15 at the AU-3 [98].

In 2020, the dust concentration decreased 4.5 times. The average dust concentration at AU-1, AU-2 and AU-3 was 0.012 , 0.013 , 0.013 mg/m^3 , respectively, and the average concentration in the local zone was 0.012 mg/m^3 . These data indicate the absence of intensive works that would cause an increase in dust resuspension.

The absence of emission from the NSC is also confirmed by the ratio of radionuclides that indicates the possible source of the aerosols, as well as the degree of the fuel particles transformation and nature of work resulting in the aerosol generation. After 2010, the ratio of ^{137}Cs and ^{241}Am , as well as ^{137}Cs and ^{154}Eu activities in the RA of the local zone surface air, increases as compared to activities ratios of these nuclides in the basic fuel composition of the fourth power unit [134].

Therefore, the surface air of the local zone was enriched with ^{137}Cs non-connected to the fuel particles.

After 2016, the contribution of ^{137}Cs , non-connected to the fuel particles, into the total ^{137}Cs activity is stable and exceeds 50% (Fig. 4.5). This indicates that there are no considerable emissions from the NSC, and the radiation situation in the surface air on the site is defined by the resuspension during the anthropogenic activity in the surrounding territories.

Radioactive aerosols in the surface air are controlled at the distance 600—1,000 m in three points by the FVU: Grad-1.0 — at the territory adjacent to the BK-2 building (Fig. 4.6, a); “WENTMECA” — at the territory of sanitary inspection building SP-1430 (Fig. 4.6, b); “Typhoon” — at the territory of the administration building (Fig. 4.6, c).

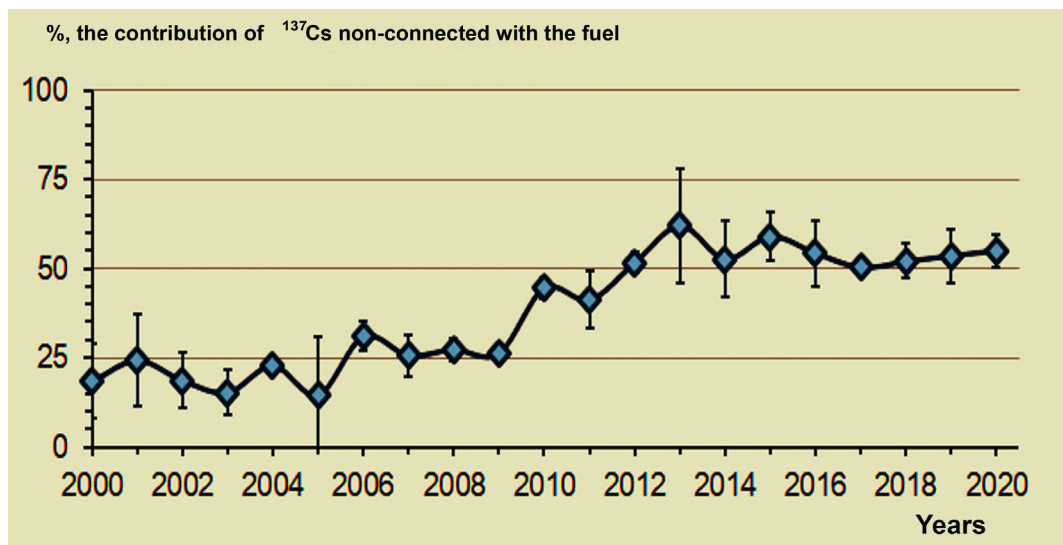


Fig. 4.5 — Relative contribution of ^{137}Cs , non-connected with the fuel, into the total ^{137}Cs activity in the surface air of the local zone in 2000—2020

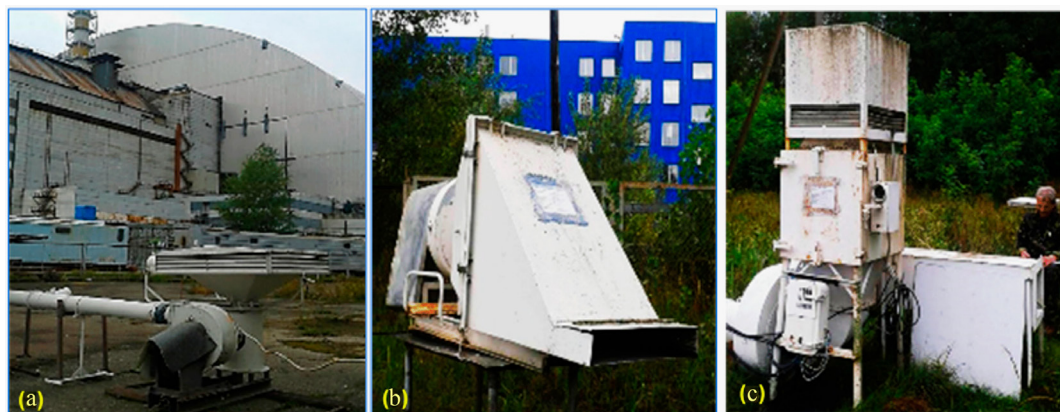


Fig. 4.6 — Location of the filter ventilation units

There is a significant decrease of the nuclides volumetric activity in aerosols of the surface air over time (Fig. 4.7). For example, before the NSC construction the ^{137}Cs volumetric activity in the air samples ranged from $5.0 \cdot 10^{-2}$ to 360 mBq/m^3 ; ^{154}Eu — from $5.3 \cdot 10^{-4}$ to 0.7 mBq/m^3 ; and ^{241}Am — from $1.1 \cdot 10^{-3}$ to 6.2 mBq/m^3 . After the NSC commissioning in

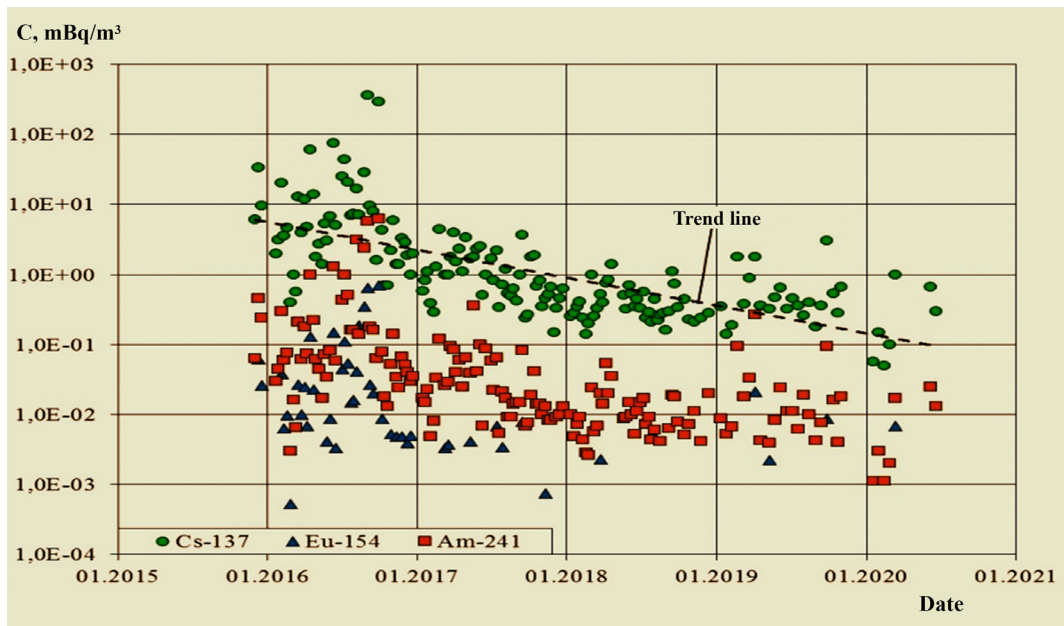


Fig. 4.7 — Volumetric activity of ^{137}Cs , ^{154}Eu and ^{241}Am in the surface air at the territory adjacent to the BK-2 building, 2015—2020

2020 it decreased by two orders of magnitude (^{137}Cs — from $5.0 \cdot 10^{-2}$ to 1.0 mBq/m^3 ; ^{241}Am — from $1.1 \cdot 10^{-3}$ to $2.5 \cdot 10^{-2} \text{ mBq/m}^3$). Similar trends on decrease the volumetric activity of aerosols in the surface air are observed in the other control points: near the sanitary inspection room SP-1430 and administration building of the Shelter object. Hereafter, the aerosols activity in the surface air of the local zone also will be determined by anthropogenic factors.

To expand the control of the NSC impact on the radiation state of the territory adjacent to the NSC for the periods before and during the NSC installing into design position, additional deposition planchets were installed to collect aerosol depositions. They were placed near the north-western, south-western corners and in the east (close to the south-eastern corner) of the NSC (Fig. 4.8).

Analysis of the density of ^{137}Cs and ^{241}Am fallout on the underlying surface of the local zone showed its abrupt decrease in several orders of magnitude after the NSC construction (Fig. 4.9): ^{137}Cs — from $17 \text{ Bq}/(\text{m}^2 \cdot \text{day})$ in 2016 to $9.5 \cdot 10^{-3} \text{ Bq}/(\text{m}^2 \cdot \text{day})$ in 2020; ^{241}Am — from $0.62 \text{ Bq}/(\text{m}^2 \cdot \text{day})$ in 2017 to $2.9 \cdot 10^{-4} \text{ Bq}/(\text{m}^2 \cdot \text{day})$ in 2020 in the north-western part of the local zone.

The results of researches of the NSC impact on the state of radioactive contamination of the surface air of the Chornobyl NPP local zone showed that before the NSC construction



Fig. 4.8 — Deposition planchets in the Chernobyl NPP local zone:
a — the north-western corner; *b* — the south-western corner; *c* — in the east

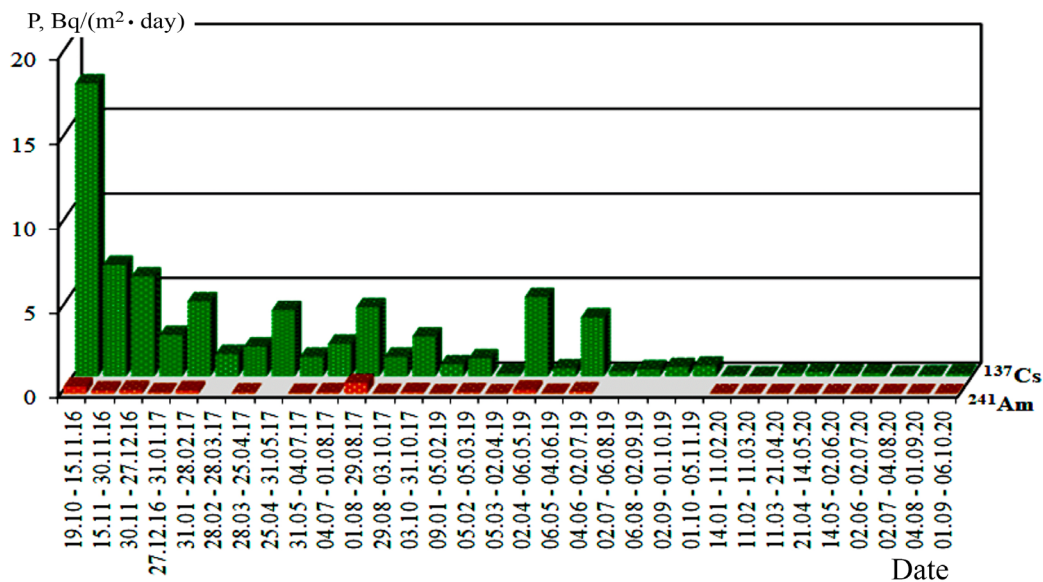


Fig. 4.9 — Density of the radionuclides fallout on the underlying surface
in the north-western area of the local zone in 2016—2020

average annual values of the volumetric activity of the $\Sigma\alpha$ and $\Sigma\beta$ aerosols in the local zone surface air were determined by the RA emissions from the Shelter object and anthropogenic activity on the site, and they varied in the range from 0.01 to 0.084 Bq/m³. After putting in order the site territory and the NSC commissioning, their concentration decreased in 2020 to $1.3 \cdot 10^{-5}$ and $7.0 \cdot 10^{-4}$ Bq/m³ respectively, i.e. by almost two orders of magnitude;

similar trends on the decrease (up to two orders of magnitude) of the aerosol volumetric activity are also observed in control points at the BK-2 building, the sanitary inspection building and the administration building;

before the NSC construction, the maximum dust concentration on the site in 2016 was 0.15 mg/m³, and in 2020 it decreased 4.5 times to 0.033 mg/m³. This indicates that there are no emissions from the Shelter object and intensive works that could cause a local increase of the dust resuspension;

the decrease of the aerosol volumetric activity is due to the NSC installation into design position, which completely prevented radioactive dust release from the Shelter object into the environment. The concentration of fuel origin radionuclides from the object decreased, aerosol was enriched in ¹³⁷Cs, and the deposition density reduced;

in the future, the aerosol activity both at the site and in the local zone will be determined by anthropogenic factors: dust resuspension from the surrounding radioactively contaminated territories, meteorological effects (wind gusts, temperature difference, precipitation) and forest fires.

4.2 Results of radiohydroecological monitoring

Radiohydroecological monitoring includes:

observation of the groundwater level regime, direction and speed of their movement;

control of the radioactive contamination, conditions of radionuclides intake and migration with groundwater;

control of chemical pollution;

forecasts of radiation conditions change using mathematical radiohydroecological models;

substantiation of change of monitoring system taking into account changes of radiohydroecological conditions of the territory.

Studies are conducted at more than 50 observation wells (Fig. 4.10). The part of them turned out to be under the NSC after its installation into a design position.

A free aquifer has been developed at the NSC site, confined to the alluvial soil of the first floodplain terrace. Aqueous soils are represented by medium-grained sands, sometimes coarse and fine ones with layers of clay sand and loam of shallow depth. Aquifer thickness is from 28 to 30 m [135, 125].

After installation of the NSC into design position and, as a consequence, termination of high-activity water inflow from the Shelter object into the environment, the main

source of radionuclides intake into groundwater was an infiltration of precipitation through contaminated soils of the aeration zone into groundwater and water loss from the water supply systems.

Decommissioning of the Chornobyl NPP CP was another factor that affected significantly the radiohydroecological state of the Shelter object site. Due to that, the direction of the groundwater motion nearby the Shelter object changed from the north to northeast toward the flood-plain of the Prypiat river and residual lakes at the place of the former cooling pond (Fig. 4.11). As a result, groundwater velocity increased to 40 m/year. Correspondingly, the rate of radionuclides migration with groundwater, which is discharged into the Prypiat river and residual lakes of the cooling pond, also increased [135].

The groundwater level near the NSC, depending on hypsometry of day surface, varies from 5 to 13 m [100]. According to the radiohydroecological monitoring, in 2019-2020 groundwater level was the lowest for the period of observation since 1994. This is due to the impact of both a decrease of water level in the Chornobyl NPP CP and abnormally dry recent years.



Fig. 4.10 — Location of radiohydroecological monitoring wells at the NSC area [138]

After the NSC was installed into design position, hydrochemical conditions in groundwater changed due to a decrease of the unit water intake into the environment. In wells located under the first bench of the cascade wall (see Fig. 4.10), the concentration of basic ions and mineralization in the upper part of the aquifer decreased by 1.5—4 times [136]. Therefore, the NSC installation over the Shelter object facilitated a decrease in chemical contamination of groundwater.

To determine the content of ^{90}Sr , ^{137}Cs , ^3H , U , ^{238}Pu , $^{239} + ^{240}\text{Pu}$ and ^{241}Am in water samples, radiochemical researches of groundwater were conducted. In recent years, there has been a significant increase of ^{90}Sr volumetric activity in groundwater samples in some areas near the Shelter object [100]. High concentrations of ^{90}Sr in groundwater samples (50 Bq/l and more) are localized at six sites (Fig. 4.12), located: 1) to the north of the Shelter object, where groundwater filtrates under the first bench of the cascade wall; 2) to the west of the Shelter object near buttress wall; 3) in the north of the Shelter object local zone, where there is groundwater on the site of spreading dome; 4) to the south of the NSC; 5) to the west of the NSC; 6) near the eastern walls of the third power unit of Chornobyl NPP.

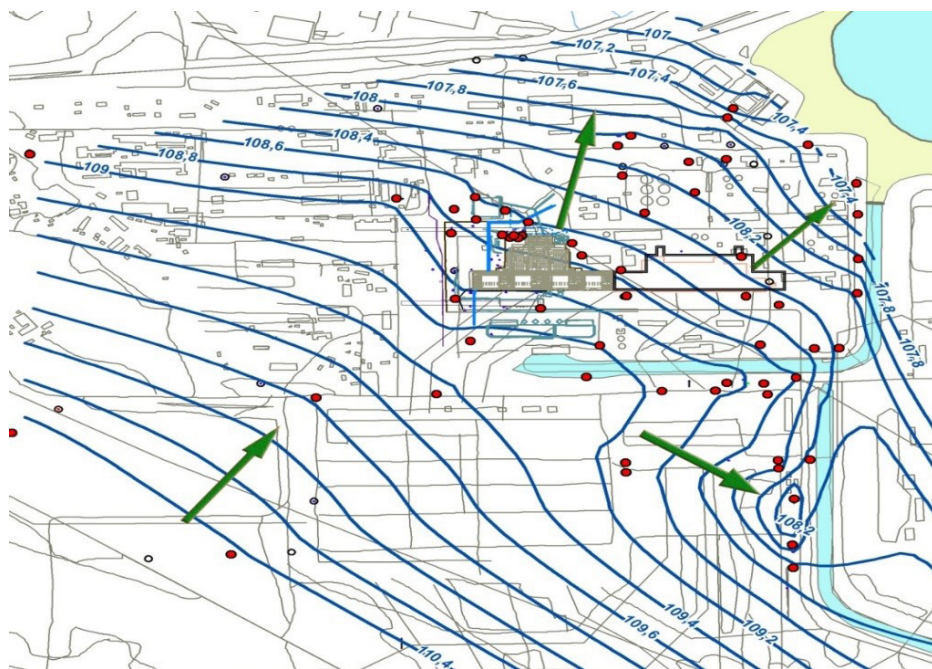


Fig. 4.11 — Map of groundwater hydroisohypses near the Chornobyl NPP as of 02.10.2017 (arrows show the direction of groundwater movement)

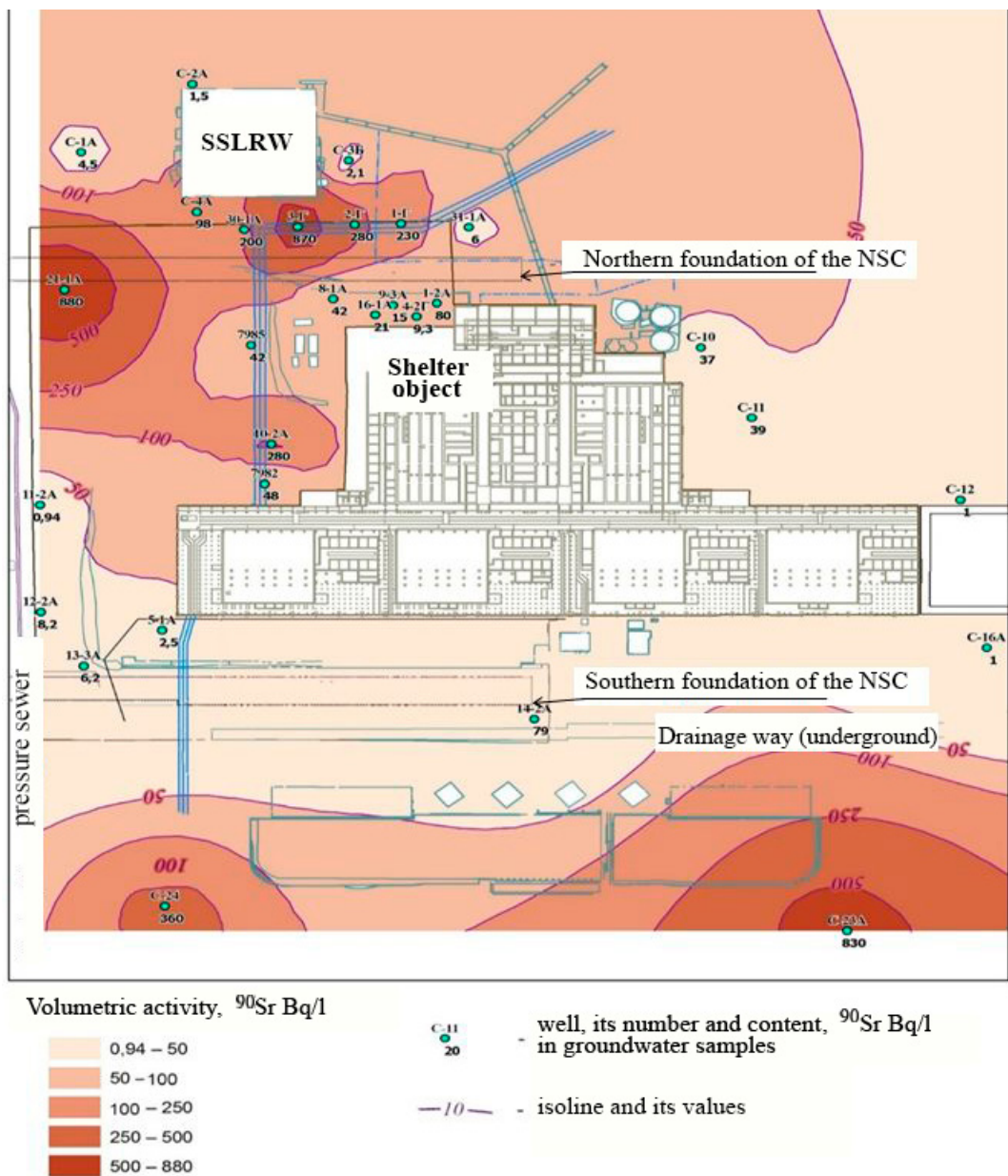


Fig. 4.12 — Map of ^{90}Sr volumetric activity distribution in groundwater during the second quarter of 2017 [144]

The values of ^{90}Sr volumetric activity and potential of hydrogen pH in groundwater samples from the well 2-G, located at the first site (Fig. 4.13), confirm that from 2009 to 2017, the ^{90}Sr volumetric activity increased from 1.0...3.0 Bq/l to 260...340 Bq/l [135]. It is assumed that one of the reasons for a significant increase of ^{90}Sr in soil samples is the formation of an alkaline medium in groundwater, in which migration capacity of ^{90}Sr increases abruptly due to a decrease in sorption properties of the soil skeleton.

Similar regularities were observed also in other wells, such as the well located under the NSC (Fig. 4.14).

Values of ^{90}Sr volumetric activity in the groundwater samples from wells, located downstream of the Shelter object (the first site), are closely related to pH value and correlate with Ca^{2+} , K^+ , Na^+ , HCO_3^{2-} concentrations in the water. This site is characterized by an increase in the ^{90}Sr volumetric activity with increasing pH over 9.5 and the conditions indicated in Figs. 4.13 and 4.14 as period III. High pH values are formed directly in case of contact of groundwater and concrete of structures foundations or due to intake of water masses, which had contact with concrete, into the aquifer.

At the fourth and fifth sites, high values of ^{90}Sr volumetric activity in groundwater samples are also caused by the inflow of radioactively contaminated water masses to the free aquifer due to concentrated infiltration of precipitation or losses from water-supply systems, and the formation of high calcium ion concentrations in groundwater, which increases migration capacity of ^{90}Sr , enhanced by the desorption from the soil skeleton surface.

It is known that calcium ions most strongly reduce the absorption of radiostrontium by the solid phase of the soil, and so cause an increase of the ^{90}Sr volumetric activity in the aquifer water, in particular, due to increased desorption of particles of previously deposited ^{90}Sr from the soil skeleton surface. This is confirmed by the results of groundwater samplings from well 21-1A, where a significant increase of the ^{90}Sr volumetric activity was observed from 15 Bq/l in 2013 to 880 Bq/l in 2017 (Fig. 4.15).

Simultaneously with an increase in radionuclides volumetric activity in samples from well 21-1A, chemical contamination of groundwater takes place at this site. As compared to 2014, in 2017 concentrations of sodium ions increased significantly from 40 to 70 mg/l; calcium ions — from 16 to 87.8 mg/l (Fig. 4.16); hydrocarbon ions — from 52 to 70 mg/l; sulphate ions — from 76.8 to 63.4 mg/l. The mineralization index also increased from 216 to 683.8 mg/l.

Analysis of given data shows that there are additional sources of radioactive and chemical contamination of groundwater at the site, where wells are located. Most likely that these sources are the loss of wastewater from the pressure sewer with their further inflow in groundwater.

^{137}Cs concentration in groundwater samples from observation wells was registered in the range from 0.3 to 42 Bq/l in 2017 and from 0.34 to 19 Bq/l in 2018. Maximum concentrations of ^{137}Cs are observed at three sites near the NSC (Fig. 4.17). At the site, located near the building of SSLRW, rainwater inflow from the roof of this building and its infiltration

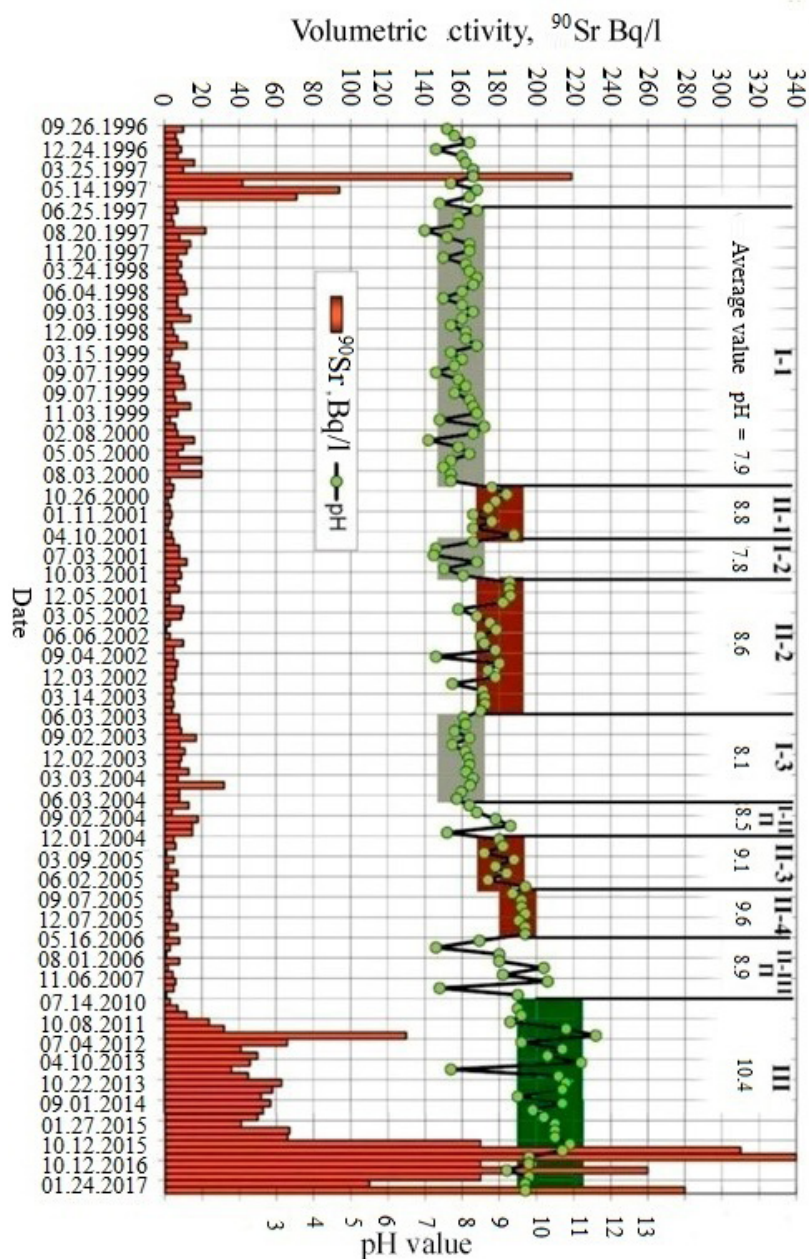


Fig. 4.13 — ^{90}Sr volumetric activity and pH value in groundwater samples from well 2-G [145]

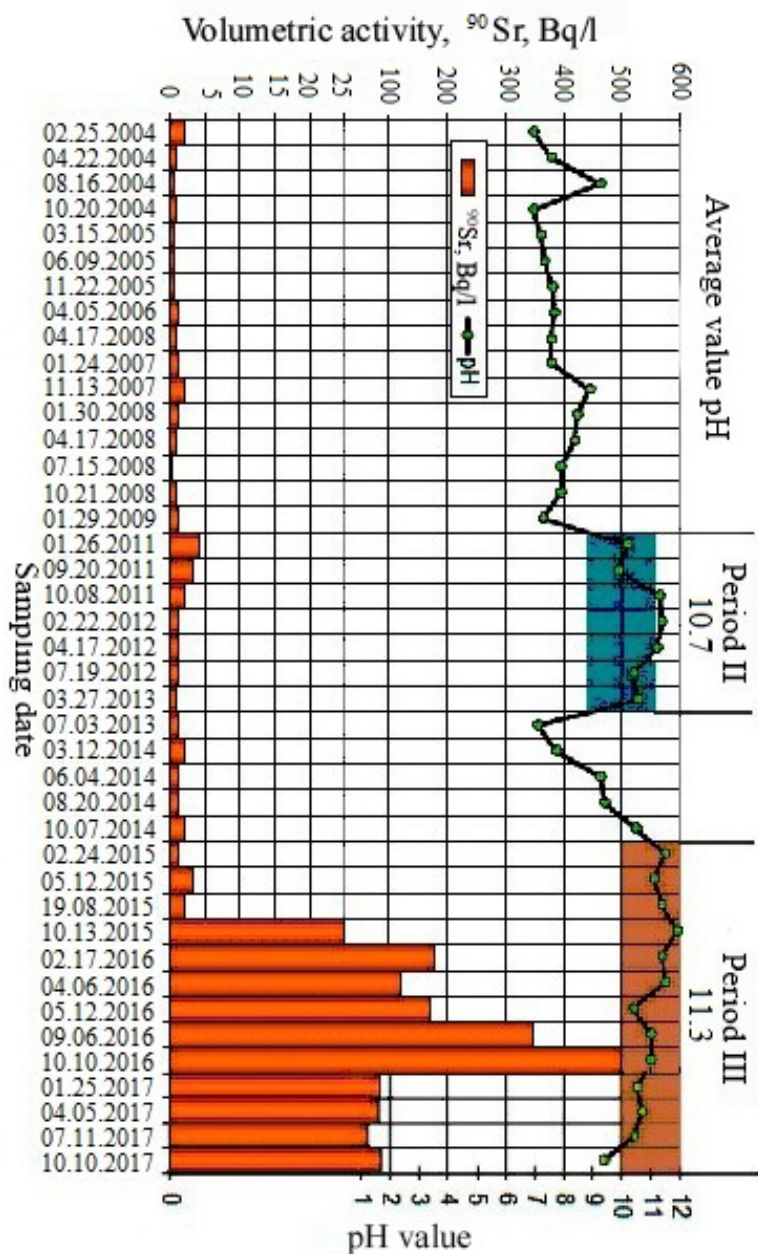


Fig. 4.14 — ^{90}Sr volumetric activity and pH value in groundwater samples from well 1-2A [145]

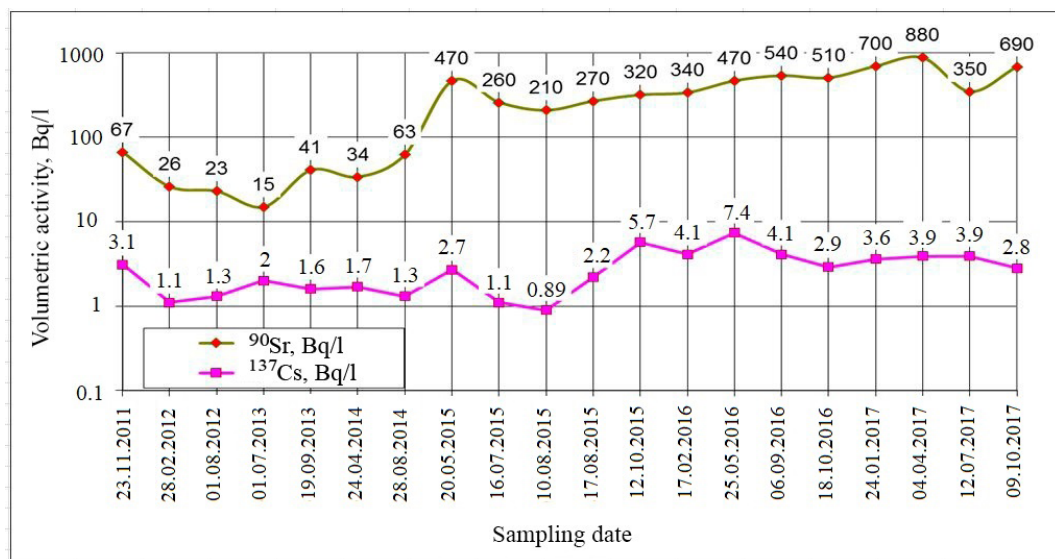


Fig. 4.15 — Volumetric activity of ^{90}Sr and ^{137}Cs in groundwater samples from the well 21-1A [100]

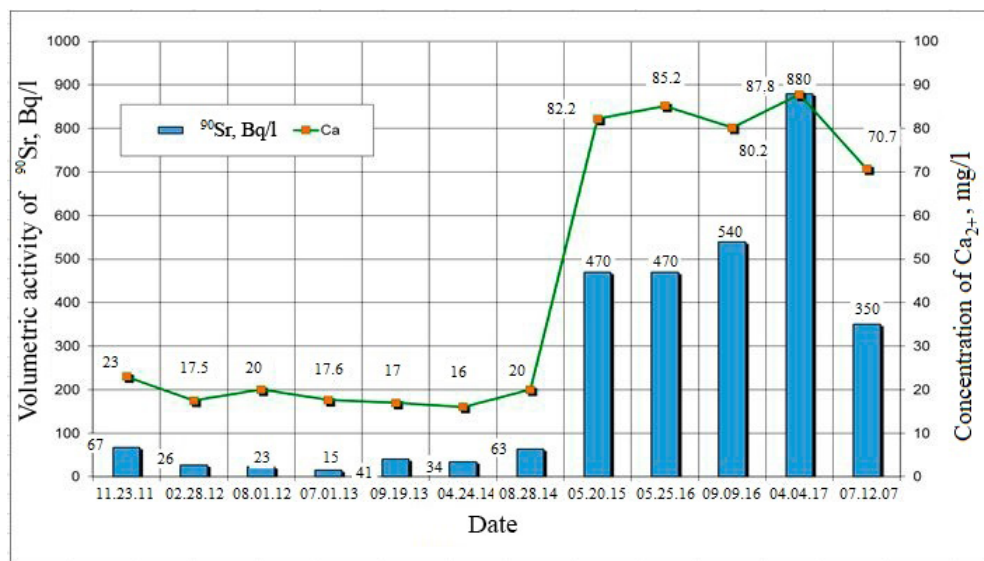


Fig. 4.16 — Content of calcium ions and the ^{90}Sr volumetric activity in water samples from the well 21-1A [100]

through radioactively contaminated soils of aeration zone is one of the sources of groundwater contamination. The unit water is the source of the groundwater contamination in wells, located in the southern part of the Shelter object near the first bench of the cascade wall. It is confirmed by high concentrations of chemical elements and species in samples from these wells, which are typical for the Shelter object unit water. High ^{137}Cs concentrations in wells, which are located near the western end face of the turbine island, can be the result of both concentrated infiltration of precipitation and losses from water supply systems.

Earlier, tritium was used as a “natural” indicator for assessment of conditions of radioactively contaminated water inflow from the rooms of the destroyed unit to the groundwater. Among sources of groundwater contamination, tritium is detected in essential amounts only in the unit water. High tritium concentration, downstream of groundwater from the Shelter object (the first bench of cascade wall), indicated places of radioactive contamination of aquifer due to the unit water inflow and leakage of the Shelter object (Fig. 4.18).

After the NSC installation into the design position, maximum tritium concentration decreased from 1,070 to 53.2 Bq/l (Fig. 4.19) due to a decrease of the unit water inflow into the environment as a result of precipitation access termination inside the Shelter object.

However, in the second half of 2018 due to decommissioning of the Chornobyl NPP cooling pond the direction of groundwater movement changed from the north to the north-east. Due to it, a new area of tritium spreading was recorded, according to measurement data in the well located in the northeast of the Shelter object (Fig. 4.19).

As compared to the data of 2016, after the installation of the NSC into design position, the tritium volumetric activity decreased from two to four times in wells located on the first bench of the cascade wall under the NSC (Figs. 4.20, 4.21). A decrease in tritium concentration occurred before the arch installation also. But in some wells, the rate of decrease accelerated sharply after the NSC was installed into a design position.

The uranium concentration in groundwater near the NSC in 2017 and 2018 changed in the range from 0.02 to 26.3 $\mu\text{g/l}$ (Fig. 4.22). The highest values of the uranium concentration were found in samples from wells, located at the northern side (on the first bench of the cascade wall) of the Shelter object and at the western one. It is possible to assess the presence of uranium fuel in groundwater by the ratio of ^{234}U and ^{238}U activities [137]. For natural uranium, this value predominately amounts to 1.0.

For the most contaminated groundwater samples, the ratio of ^{234}U and ^{238}U activities ranged from 2.1 to 2.6, indicating the presence of uranium fuel (which is characterized by a ratio of ^{234}U and ^{238}U ranging from 1.69 to 3.06) [137]. Moreover, samples contain ^{236}U , which are present in uranium fuel solely. This indicates that groundwater contamination by uranium occurred due to the unit water outflow from the Shelter object before the installation of the NSC.

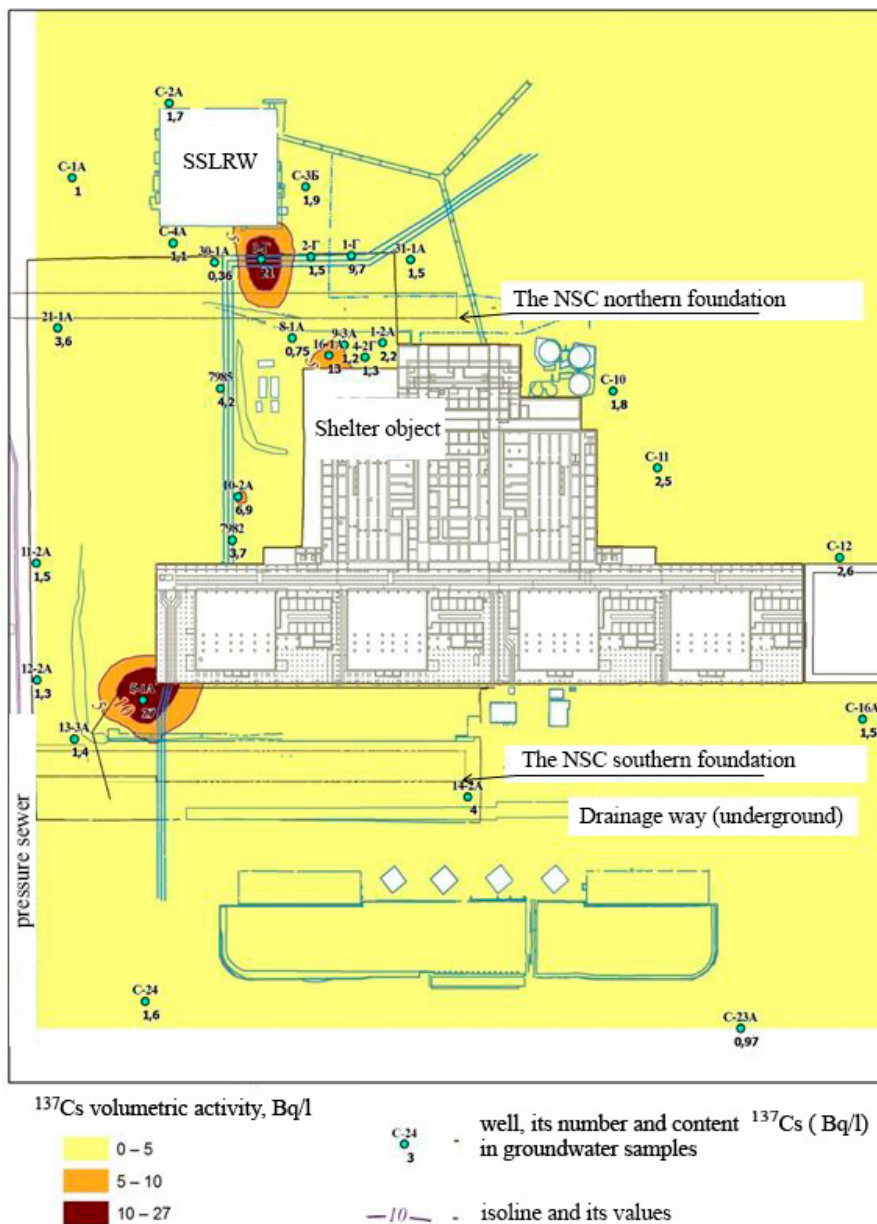


Fig. 4.17 — Map of ^{137}Cs volumetric activity in groundwater near the Shelter object, first quarter of 2017 [100]

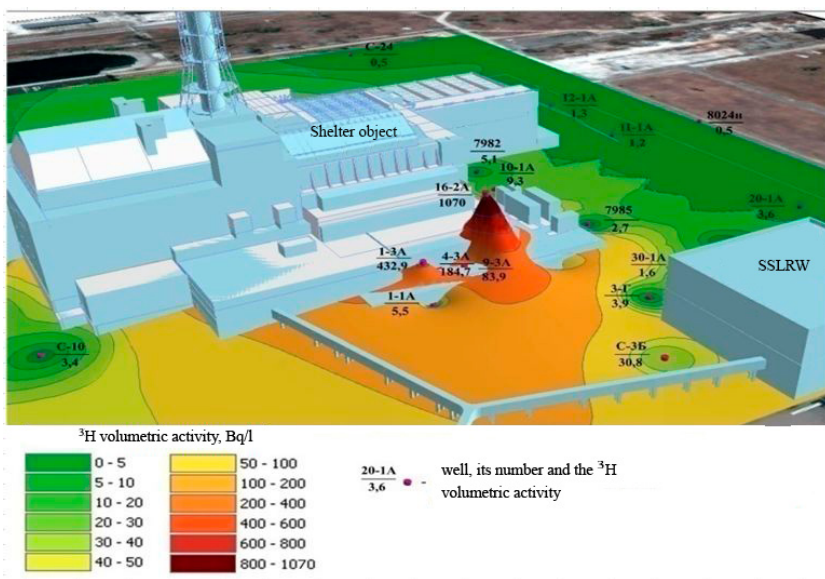


Fig. 4.18 — Area of tritium spreading in groundwater in 2013 [100]

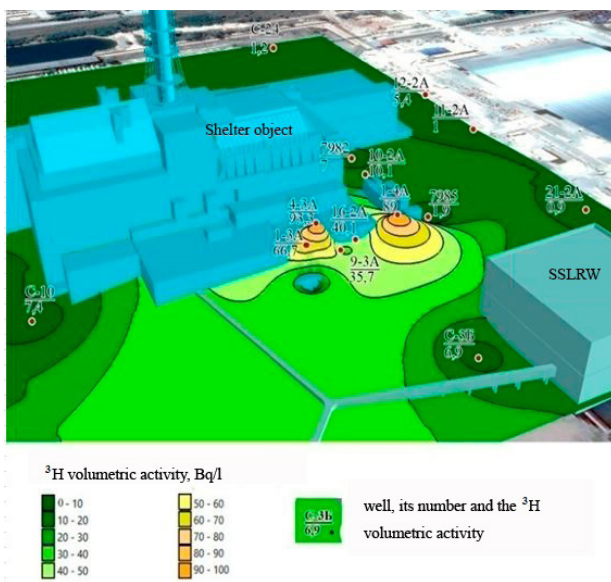


Fig. 4.19 — Area of tritium spreading in groundwater in 2018 (after the arch installation) [100]

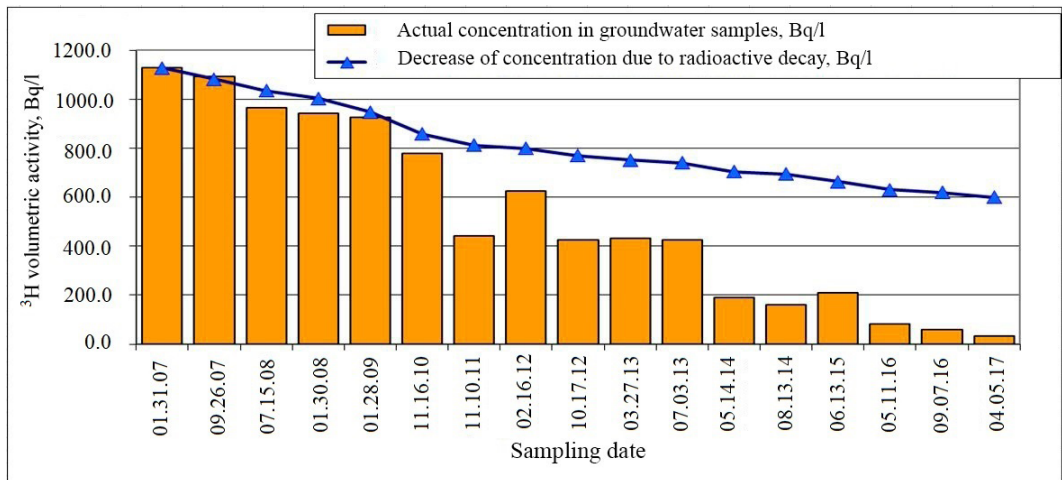


Fig. 4.20 — The tritium volumetric activity in the groundwater samples from the well 1-3A [100]

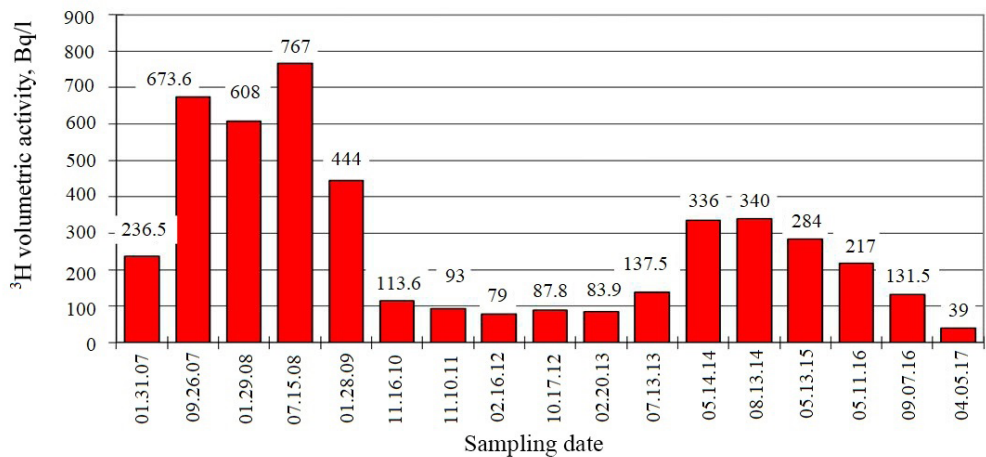


Fig. 4.21 — The tritium volumetric activity in the groundwater samples from the well 9-3A [100]

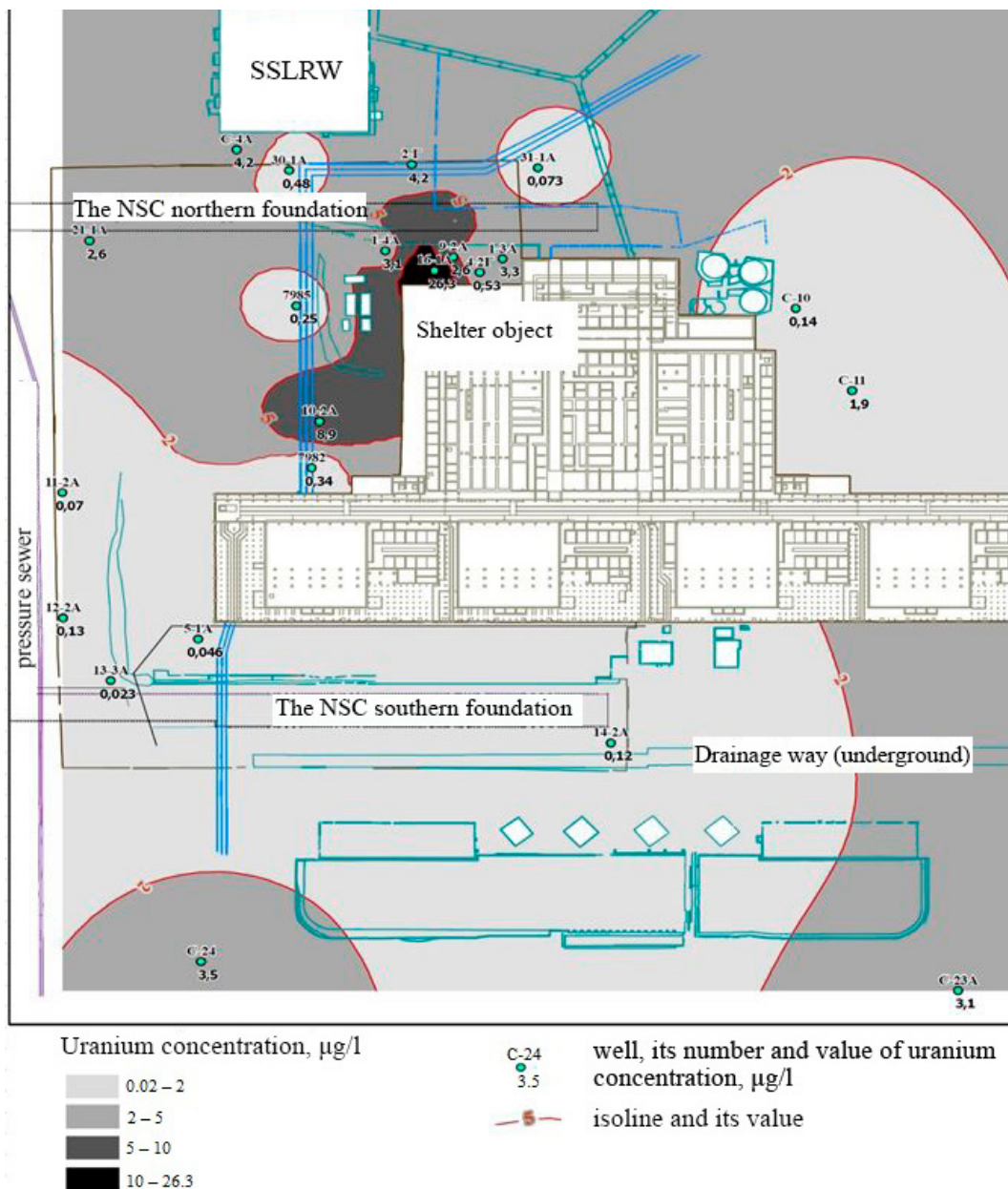


Fig. 4.22 — Map of the uranium concentration distribution in the groundwater near the NSC [100]

Since 2010 the uranium concentration increased in water samples from the well 2-G (from 0.18 to 11.5 μg) located near the northern foundation of the arch. On this site, intensive excavation works on the pit for the northern foundation of the NSC were performed. When rainwater got on the radioactively contaminated soils, radioactively contaminated water masses were formed and entered the groundwater. After the finishing construction works and installation of the NSC into design position in 2017, the uranium concentration decreased to 4.2 $\mu\text{g}/\text{l}$ (Fig. 4.23).

The distribution of the ^{238}Pu concentration in the groundwater around the Shelter object is shown in Fig. 4.24, and the distribution of the $^{239} + ^{240}\text{Pu}$ concentration in Fig. 4.25. After installation of the NSC, the highest values of the ^{238}Pu volumetric activity (up to 0.053 Bq/l) and the $^{239} + ^{240}\text{Pu}$ volumetric activity (up to 0.14 Bq/l) were recorded in 2017 in wells located at the north side of the Shelter object. The ^{241}Am volumetric activity (Fig. 4.26) in the groundwater samples varies from 0.00058 to 0.14 Bq/l.

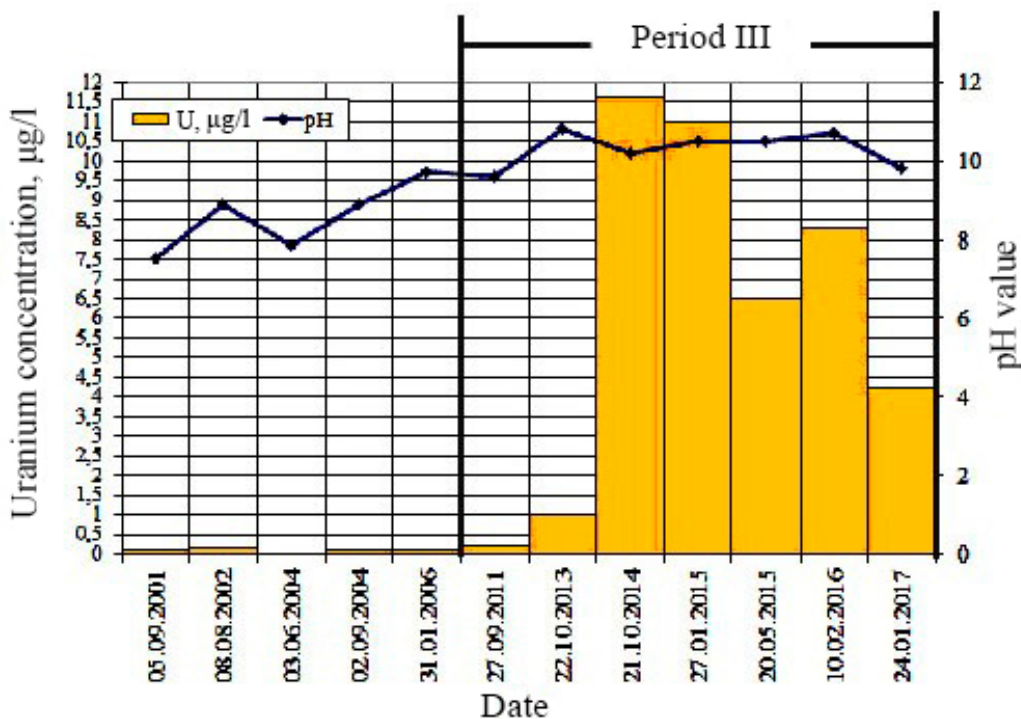


Fig. 4.23 — Uranium concentration in the groundwater samples from the well 2-G [138]

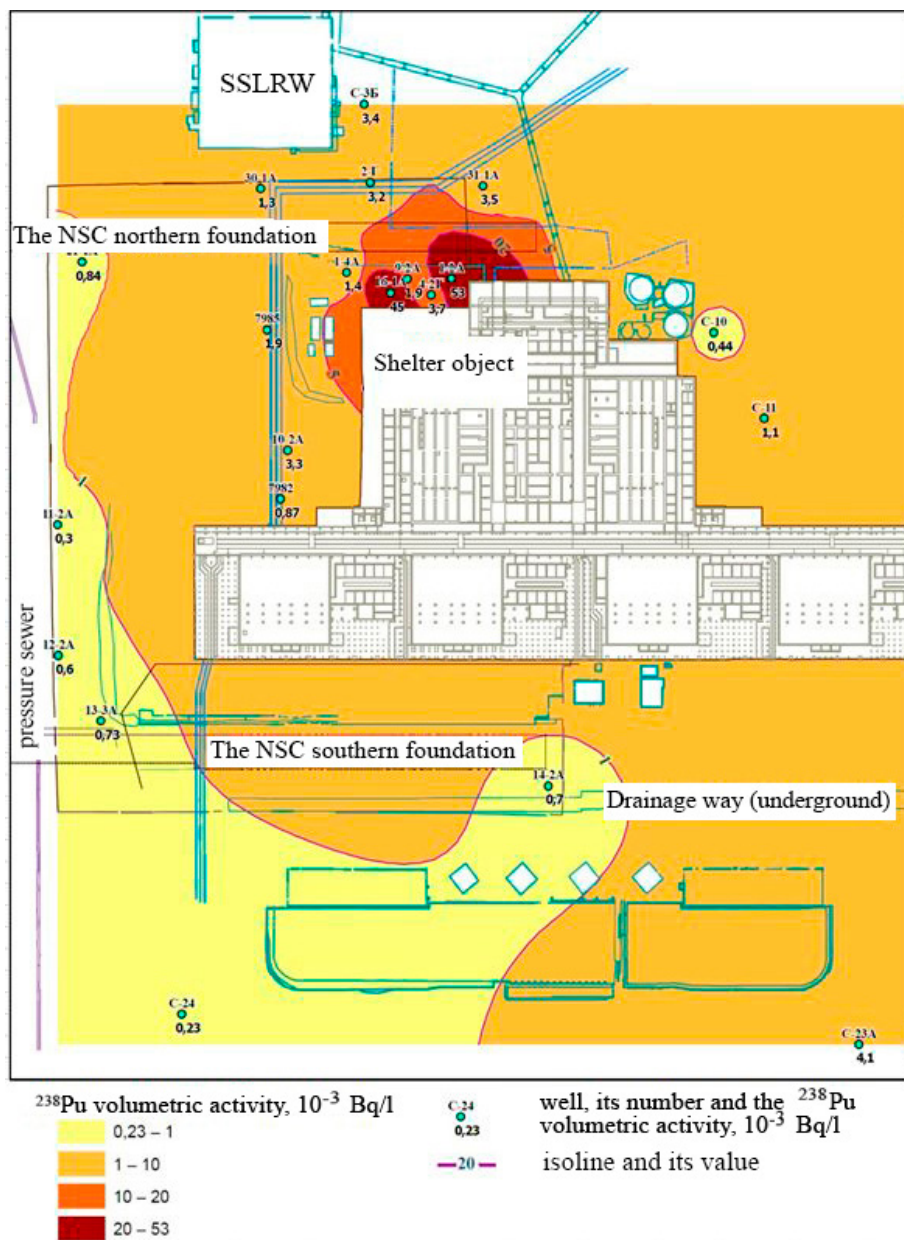


Fig. 4.24 — Map of ^{238}Pu volumetric activity distribution in groundwater near the Shelter object [100]

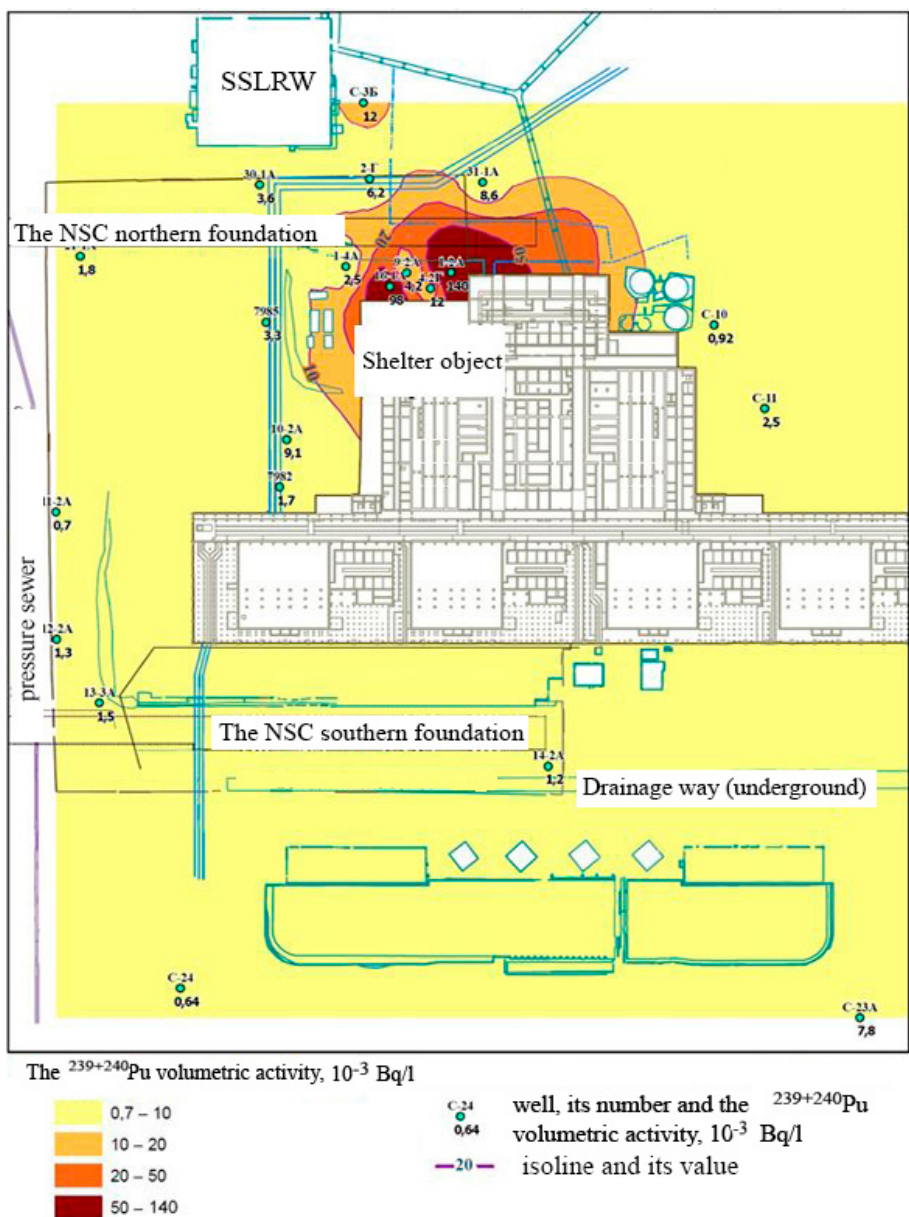


Fig. 4.25 — Map of the $^{239+240}\text{Pu}$ volumetric activity distribution in groundwater near the Shelter object [100]

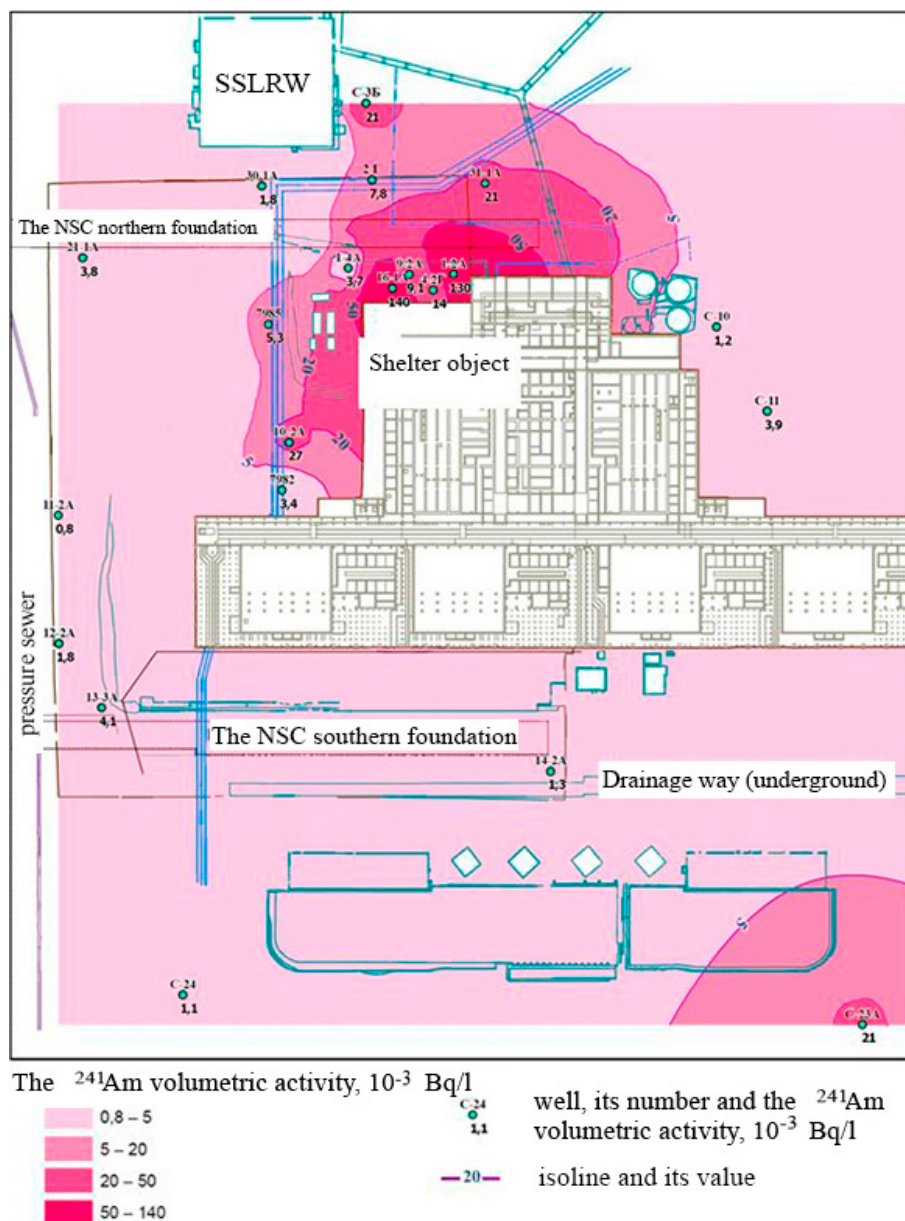


Fig. 4.26 — Map of the ^{241}Am volumetric activity distribution in groundwater near the Shelter object [100]

Taking into account the ^{238}Pu , $^{239} + ^{240}\text{Pu}$ and ^{241}Am concentration distribution in groundwater, its maximum values are found at the northern side of the Shelter object, i.e. in the direction of the groundwater movement, and were formed due to the outflow of the unit water before the NSC installation. It is expected that the concentration of these radionuclides will decrease over time.

According to the results of conducted researches [100, 135—138], we can draw the following conclusions about the NSC impact on the groundwater state:

after the NSC installation into design position, the impact of the unit water of the Shelter object on groundwater contamination became practically negligible. The main source of radionuclides intake into the groundwater became precipitation infiltration through the radioactively contaminated soils of the aeration zone, as well as water loss from the water supply systems. It improved significantly the hydrochemical and radioecological conditions in the groundwater;

as a result of the Chornobyl NPP CP decommissioning, the direction of the groundwater movement at the NSC site has changed from the north to the northeast;

one of the reasons for radionuclides concentration increase, in particular ^{90}Sr , in groundwater in some parts of the NSC site was the formation of alkaline medium ($\text{pH} > 9.5$) and high concentration of calcium ion in groundwater. As a result, a ^{90}Sr migration ability abruptly increases due to the decrease of sorption properties of the soil skeleton;

it is previously stated that high pH values are formed under the contact of groundwater with concrete of buildings foundations at the NSC site. If groundwater pH increases to 9.5—10.0 due to the corrosion of pile foundation concrete in the NSC service zone, which covers part of the aquifer, a significant increase of the ^{90}Sr , uranium and transuranium elements volumetric activity is possible. However, this statement needs additional substantiation in the course of radiohydroecological monitoring;

in some parts of the NSC site surface, there are favorable conditions for concentrated infiltration of precipitation through the radioactively contaminated soils of the aeration zone into the groundwater. Therefore, regulation of precipitation runoff by an arrangement of draining sewers is one of the measures to reduce radioactive contamination of the groundwater;

since the ^{90}Sr volumetric activity decreases when groundwater pH is 8.5...9.5, it is necessary to analyze possibility to maintain these values in the groundwater, which will slow down ^{90}Sr spread with groundwater outside the NSC and as a whole outside the Chornobyl NPP industrial site.

Chapter 5. SCIENTIFIC AND TECHNICAL SUPPORT OF THE SHELTER OBJECT TRANSFORMATION INTO AN ECOLOGICALLY SAFE SYSTEM

Uniqueness and complexity of the scientific and technical problems related to the elimination of the accident happened on April 26, 1986, at the fourth power unit of the Chornobyl NPP and its consequences brought to the involvement of the best scientists and engineers to their solution. Scientific and technical support of works at the destroyed unit commenced in 1986, jointly with the design and construction of the Shelter object [2].

In early May 1986, the operative group of the Kurchatov IAE was created to fulfill scientific supervision of work to eliminate the accident consequences. The main work scopes of the team were the following: studies in the destroyed unit, assessment of nuclear and radiation safety level, preparation of recommendations for their reduction, determination of activity and radionuclide composition of the release during accident active stage, and development of recommendations for decontamination of facilities and territory. As a scientific supervisor, the KIAE conducted researches and provided engineers and constructors with calculation results and other data during the whole period of designing and construction of the Shelter object [1].

In mid-May 1986, the Government Commission decided on long-term mothballing of the destroyed power unit to prevent radionuclide release into the environment and to reduce penetrating radiation impact at the Chornobyl NPP site.

With considering the need for scientific support of the Shelter object operation, Valeriy Legasov, Academician, Deputy Director of the KIAE, initialized creating the Institute's Complex Expedition in Chornobyl. By the order of the Ministry of Medium-Machine Building of the USSR, in the last days of 1987, to provide scientific and design support of the Shelter object and coordinate the research and development work at the Chornobyl NPP, the Complex Expedition of the KIAE was created. The main tasks of the Complex Expedition were the following: conducting the researches to provide a safe state for the Shelter object and



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V. S. Karasev

elaborating recommendations for a monitoring system improvement, studying radiation situation within the controllable area, arrangement and implementation of engineering and design work, and support of scientific researches.

After the independence of Ukraine, Yevhen Velikhov, Academician, the President of the Russian Scientific Centre “Kurchatov Institute”, jointly with Viktor Bar'yakhtar, Academician, the Vice-President of the NAS of Ukraine, suggested creating the ISTC “Shelter” in Chornobyl.

The ISTC “Shelter” of the NAS of Ukraine, established according to the Resolution of the Cabinet of Ministers of Ukraine No. 55 dated 04.02.1992, became a legal successor of the Complex Expedition of the KIAE. From the first days of the accident at the fourth power unit, Volodymyr Karasev, Dr. Sci., professor, the first Director of the ISTC “Shelter”, was an active participant in the accident consequences elimination. He performed huge work on the diagnosis of the post-accident state of the third power unit and analysis of possibilities of its further operation. Under his supervision, the staff of the ISTC “Shelter” in the shortest possible time created a technical basis and began activity to solve complex tasks of scientific supervision of works to ensure the current and long-term safety of the object [140].

Since 1992, the ISTC “Shelter” has been the scientific supervisor and the general design engineer of works on the Shelter object transformation into an ecologically safe system, and since 1993 it has also been the scientific supervisor of works on the Chornobyl NPP power units decommissioning. The main scientific and practical result of the ISTC “Shelter” activity is the development of solutions concerning the current maintenance of the Shelter object throughout its existence.

In May 1993, Volodymyr Tokarevskyi, Dr. Sci., professor, was appointed the Director General of the ISTC “Shelter” by the Decision of the NAS of Ukraine.

In 1996, the ISTC “Shelter” was headed by Oleksandr Kliuchnykov, Corresponding Member of the NAS of Ukraine, Dr. Sci., professor. Under his scientific supervision, complex researches were carried out, which resulted in the development of more than 100 samples of unique devices and installations used in various fields of science and technology. As a leader of the headquarters of the Academy of Sciences of Ukraine in Chornobyl, he conducted research directly at the destroyed power unit. In 2011, by the Decree of the President of Ukraine, O. Kliuchnykov was awarded the title of Hero of Ukraine for outstanding personal contribution in strengthening the safety of the national nuclear power as well as many years of fruitful scientific activity.

To implement works under the SIP project in 1997, the Ukrainian consortium “KSK” was set up, which consisted of the ISTC “Shelter”, the Kyiv Scientific Research and Design Institute “Energoproekt” and the State Research Institute of Building Constructions. Later in cooperation with companies Morrison Knudsen Ltd. (the USA) and BNFL Engineering Ltd. (the UK), an International Consortium CHERNOBYL was set up. Specialists of the Consortium analyzed in detail the state of the Shelter object building structures. According to its results, the scope of stabilization measures was substantiated, a conceptual design for their implementation was developed, conceptual design criteria and requirements for the New Safe Confinement were stated, and strategy of its construction was suggested.



V. V. Tokarevskyi



O. O. Kliuchnykov

Later an International Consortium, consisting of Bechtel International Systems (the USA), Electricite' de France (France), Battelle Memorial Institute (the USA), the ISTC "Shelter", the Kyiv Scientific Research and Design Institute "Energo-project" and the State Research Institute of Building Constructions, performed feasibility study (conceptual design) of the NSC based on the variant "Arch", which was approved by the Order of the Cabinet of Ministers of Ukraine.

As a result of primary projects, a range of measures is proposed and implemented to extend the lifetime, reliability and efficiency of structures to maintain or improve the safety level of the object. The stage of preparation for the Shelter object transformation into an ecologically safe system includes the NSC construction, development of remotely controlled systems, practical approval of the technology for FCM retrieval, development of infrastructure for waste management. Consortium "KSK" developed project documentation for building structures stabilization, which was the first major project in the implementation of the main scopes of the SIP.

During its existence, the ISTC "Shelter" had achieved significant results in the researches to ensure nuclear and radioactive safety of the Shelter object and the Chornobyl NPP power units, design of facilities for nuclear materials and RAW management, etc. The ISTC "Shelter" was transformed into an up-to-date institution with high-qualified specialists, whose subdivisions were provided by equipment, stands and monitoring systems. Therefore, in 2004 by the Resolution of the NAS of Ukraine, the ISTC "Shelter" was transformed into the Institute for Safety Problems of Nuclear Power Plants and integrated as a structural unit into Physical and Technical Problems of Power Engineering Division of the NAS of Ukraine. According to this Resolution, O. O. Kliuchnykov was appointed as Director of the Institute, and the main scientific directions of the Institute activity were approved. They included: the NPPs efficiency and safety, RAW utilization technologies, development and implementation of the NPP power units decommissioning procedures as well as directions of scientific and applied researches, which were defined for the ISTC "Shelter".

The social implication of the scientific and technical support of all works on the Shelter object transformation into an ecologically safe system, provided by the ISP NPP staff, is the protection of humans and the environment against potential risks of radioactively hazardous the Shelter object.

In 2016 Anatolii Nosovskyi, an Academician of the NAS of Ukraine, Doctor of Technical Sciences, Professor, was appointed as a director of the ISP NPP. He has great practical experience in management and scientific work at the Chornobyl NPP in the post-accidental period, participated in the elimination of the accident consequences in a staff of the specialized body "Construction Board US-605" of Ministry of Medium Machine-Building of the USSR, where he dealt with the problems of radiation protection during the Shelter object construction, and preparation to post-accident commissioning of Chornobyl NPP units. Under his direct supervision, radiation parameters in the areas of building and reconstruction

works were measured, organizing and technical measures aimed at the provision of radiation safety were developed and implemented.

The scientific and technical activity of the Institute covers practically all kinds of work on building structures stabilization, development of the safety systems and the Shelter object transformation into an ecologically safe system. Routine monitoring of the Shelter object, detection and study of hazard factors, analysis of nuclear and radiation safety are carried out. Based on the received data, the Institute develops scientifically substantiated recommendations for improvement of the Shelter object safety.

During its existence, the ISP NPP accumulated scientific potential for implementation of tasks assigned to the Institute by the NAS of Ukraine. The staff, who stood near the origins of the Institute, and the one, who works today, determined the success of the scientific institution as a whole. The basis of all achievements of the ISP NPP is the hard work and creative effort of the staff, who carry out complex scientific and applied tasks working with leading national and international scientific and technical institutions.

Specialists of the Institute have a high professional level in fields of safe operation of facilities with nuclear technologies, elimination of consequences of radioactive accidents, nuclear facilities decommissioning, spent nuclear fuel treatment, RAW management, conduction of works in radioactive hazardous conditions.

The priority established in the Institute's personnel policy of continuity and consistency of knowledge transfer contributes to the growth of the number of highly qualified specialists and provides a high-quality implementation of scientific tasks. Experience and knowledge, team spirit, striving for the rise of the level of activity effectiveness and vision of development paths of scientific potential is a basis, on which the ISP NPP generates scientific and technical high-level products.

Heads of the NAS of Ukraine — academicians B. Ye. Paton, V. H. Bar'yakhtar, O. V. Kyrylenko, V. P. Kukhar, A. H. Naumovets, B. S. Stohnii, V. P. Shestopalov, A. K. Shydlovskiy and others played a significant role in the formation of the ISP NPP as a scientific organization.

Consolidated knowledge, exclusive experience and practical skills of many specialists of the ISP NPP form the basis of unique possibilities of the Institute as a whole and are the key



A. V. Nosovskyi



B. Ye. Paton

to success in achievement of the set goals. In the implementation of its activity, the ISP NPP has all necessary resources: the research site in Chornobyl, division for nuclear power engineering in Kyiv, high qualified scientific staff, research laboratories, unique database and FCM samples from the Shelter object, the knowledge base on the nuclear fuel state, building structures, radiation conditions of the Shelter object and adjacent territories, as well as licenses and certified quality management system.

The scientific and technical support of the NSC commissioning and operation substantially is the continuation of works, which were performed for a long time to make the Shelter object safe. The completion of the NSC construction significantly affected the Shelter object state and conditions of its operation, in particular:

- nature and intensity of the load on the building structures of the Shelter object have changed;

- operating conditions of the systems (elements) of beyond design-basis accident management important for safety at the Shelter object have changed;

- moisture and temperature conditions in the Shelter object premises have changed, which will affect the state of its nuclear and radiation safety (formation of additional RA, change of the subcriticality of some FCM accumulations, etc.).

It determines the necessity of solving many new scientific and technical problems concerning both the current safety and safety of its unstable structures dismantling, as well as further FCM retrieval/transfer into a controlled state.

5.1 Scientific and technical support at the stages of commissioning and operation of the New Safe Confinement

Commissioning and operation of the unique NSC complex require permanent scientific and technical support to take technically substantiated decisions and provide safety at every stage. On this basis, long before the completion of the NSC construction, a decision on the development of the program of scientific and technical support at the stages of the NSC commissioning and operation was made (hereinafter — the Program) at the session of the scientific and technical council of the Chornobyl NPP.

The aim and purpose of works on scientific and technical support at the stages of commissioning and operation of the NSC are to resolve issues unregulated by current normative and other documents related to the NSC commissioning with minimum risk of failures and operation of the unique NSC complex in the absence of sufficient experience and direct analogs in the national and world practice.

Before the start of the development of the Program, complex analysis of initial data was conducted:

- factors, which have an impact on the state of nuclear and radiation safety of the Shelter object under conditions of its operation inside the NSC;

- factors, which have an impact on the state of building structures of the Shelter object after the NSC installation into design position;

- design decisions concerning the functioning of the NSC systems and components, which are important for safety, and their interaction with existing systems and components of the Shelter object;

- planned activity at the stages of commissioning and operation of the NSC.

Thereafter, a list of works, which need scientific and technical support, was substantiated. Planned activity on scientific and technical support includes the following stages of the NSC lifecycle:

- commissioning;

- operation of the NSC before finishing primary dismantling/reinforcement of unstable structures of the Shelter object;

- further transformation of the Shelter object into an ecologically safe system.

Measures of scientific and technical support at the stages of commissioning and operation of the NSC are implemented two-way: 1) support of building structures reliability; 2) ensuring radiation and nuclear safety [8].

Components of the activity on the support of building structures reliability:

- control of the NSC building structures state using the building structures control system (BSCS) and the seismic monitoring system (SMS);

- control of the Shelter object building structures state using the building structures state control system (BSSCS) that is part of the IACS;

- control of the building structures state using geodesic observations;

- development of the three-dimensional model of the NSC for visualization of readings of the BSSCS IACS and the BSCS of the NSC;

- support of the database on the building structures state.

Components of the activity on radiation and nuclear safety support:

- study of the impact of the FCM state change in new conditions of the Shelter object operation on the nuclear safety level;

- study of the impact of new conditions of the Shelter object operation on the radiation safety level;

- routine monitoring of the behavior of FCM accumulations.

Areas of research on the impact of changes in the state of FCM on the level of nuclear safety:

creation of an additional system of local control of nuclear hazardous accumulations subcriticality;

creation and support of unified database of the nuclear safety monitoring system of the IACS and local control system of subcriticality of nuclear hazardous accumulations;

development of procedures of subcritical anomaly identification in readings of neutron detectors and heat sensors;

analysis of work of standard systems for the suppression of criticality parameters of nuclear hazardous accumulations; preparation of technical proposals for criticality suppression by the introduction of liquid or solid neutron absorbers;

control of neutron activity dynamics and FCM temperature during the change of moisture and temperature regime.

Areas of research of the impact of new operating conditions of the Shelter object on the radiation safety level:

study of spatial, angular and energy characteristics of the ionizing radiation fields, in particular during the Shelter object opening after unstable structures dismantling; determination of the main sources forming radiation situation inside the NSC, development of recommendations on their shielding or retrieval;

assessment of radioactive aerosol emissions from the Shelter object to the volume under the NSC (before and during the dismantling of the Shelter object unstable structures);

analysis of airflows and related changes of radiation situation due to dust transport inside the Shelter object;

assessment of radionuclide and element composition change of water accumulations and sediments in the Shelter object premises;

monitoring of surface air at the NSC industrial site, development of the three-dimensional model of radioactive emission transport including the air shadow and development of methodology of the NSC leakproofness control;

substantiation of the observation wells system at the NSC site and radioecological monitoring implementation;

selection of effective methods of decontamination of dismantled structures and contaminated surfaces.

Systematic monitoring of FCM accumulations behavior:

study for assessment of the fuel state in the CH and the south CP;

study of the impact of FCM state change on the dynamic of their degradation;

study of RA, in particular, nuclide and particle size composition, near the FCM accumulations.



Session of the Presidium of the NAS of Ukraine dated 08.02.2017

Scientific and technical support of the further Shelter object transformation into an ecologically safe system involves a study aimed at developing scientific principles and concept design to solve the problems of the Shelter object in the long-term outlook, namely:

- complex analysis of potential strategies of the Shelter object transformation into an ecologically safe system and substantiation of the best scenario on retrieval/transfer of the FCM in the controlled state and their further treatment (taking into account an experience of operation, in particular dismantling unstable structures of the Shelter object);

- analysis of requirements of the national statutory legal acts and international norms, rules and standards as well as assessment of their sufficiency for solving problems of the Shelter object transformation;

- development of proposals concerning the extension of the NSC infrastructure for activity on safe retrieval/transfer of the FCM in the controlled state and their further treatment;

- advanced study of physical and chemical properties of FCM to forecast their degradation and quantitative assessment of dust formation parameters;

improvement of the FCM certification methods, in particular, direct measurement methods of nuclear materials content;

development of fuel conditioning methods for long-term conservation considering requirements of their disposal;

development of technical proposals on unmanned technologies implementation to use them under conditions of the Shelter object.

On February 8, 2017, the Presidium of the NAS of Ukraine considered and approved “Program of scientific and technical support at the stages of the NSC commissioning and operation”, as well as obliged the ISP NPP to organize and coordinate the participation of institutions of the NAS of Ukraine in the Program implementation at its every stage.

5.2 Monitoring program of fuel containing materials

The need to study the issue of FCM behavior monitoring and control for the whole period of their presence in the Shelter object was emphasized in the SIP, developed in 1997 when dealing with the Commission of the European Communities, the USA, Ukraine and groups of international experts.

According to the SIP, FCM analysis was carried out as of 1997, concept designs were developed concerning an instrumentation monitoring of FCM state (video surveillance, radiation measurements, surveillance over airflows and RA of the Shelter object, sampling and analysis of water) [139]. In 2005, the document “Strategy of management of FCM and radioactive waste of the Shelter object” was developed, where it was stated that full-scale FCM characterization, which involves sampling and hot cells creation, results in high dose- and labour costs, and according to the radiation protection principles is pointless. Therefore, it was proposed to develop a monitoring program of fuel containing materials behavior before and during their retrieval. Considering that FCM retrieval is fairly long-term, a monitoring program of FCM state could enable to control the FCM state and provide an opportunity to take measures to limit an adverse course of events.

According to the document, the monitoring system of FCM behavior, along with the NSMS of the IACS, was to provide data for FCM state assessment to define the necessity of preventive measures to reduce the hazard of spread, as well as to reliably forecast the long-term FCM behavior to develop and adopt the final strategy of FCM retrieval.

When the NSC was installed over the Shelter object, there have been changes in processes, which define the state and behavior of FCM. First, it prevents precipitation entry in the Shelter object, which involves drying up of RW accumulations, an outcrop of sediments with the formation of additional sources of radioactive dust. Second, it is water loss by nuclear hazardous accumulations of FCM that causes the potential threat of inverse criticality and nuclear incident.

To date, data on the FCM state (chemical, radiochemical, physical and mechanical properties, degradation) and their resistance to destruction are insufficiently studied, which does not allow to predict exactly the behavior of such materials with time.

Therefore, the concept of the ISP NPP “Monitoring program of the Shelter object FCM” [78] developed in 2018 was to develop new approaches and methods of assessment of nuclear and radiation safety of FCM treatment, RW and dust handling at all stages of the NSC operation (Fig. 5.1). One of the main tasks of the program was to obtain maximum information for forecasting assessments of nuclear and radiation safety without additional dose commitment on the personnel (photo, video filming of FCM accumulations, sampling).

Assessment of fuel containing materials behavior under the Monitoring program of FCM is conducted according to indirect information on their change over time, namely:

- radiation situation change — ER of γ -radiation and aerosol activity;
- change of physical, chemical and mechanical characteristics on FCM samples in laboratory conditions;
- change in behavior of fuel dust and RW accumulations;
- change of temperature, NFD and γ -DR in potential nuclear hazardous FCM accumulations according to the data of monitoring systems.

The urgency of FCM monitoring is specified by the need for the long-term forecast of FCM behavior to develop the final strategy of FCM retrieval and significant changes of conditions inside the Shelter object, which can have an impact on the safety state over time. At the same time, obtained information will allow taking remedial measures on FCM maintenance in subcritical state, reduction of dust formation, and control FCM state. Besides, a database of the main FCM parameters, the establishment of which is provided in the Program of FCM monitoring, will be useful at the stages of preparation for FCM retrieval and their retrieval from the Shelter object.

The monitoring program (see Fig. 5.1) consists of two main modules: radiation and nuclear safety of FCM. During the implementation of the Program of FCM monitoring, the ultimate goal is to obtain information for further development of preventive measures on radiation and nuclear hazard prevention. The Program includes substantiation of volumes and periodicity of control, location of the monitoring objects and control points, and monitoring methods. Monitoring objects for obtaining information are RA, their depositions, radioactively contaminated water, fields of γ -radiation, as well as neutron and temperature fields in the Shelter object, FCM accumulations, FCM samples, the microclimate in the NSC.

The following requirements are stated in the Program: to the monitoring methods and its information value on the FCM state; objects of control; execution of field and laboratory works (methods, periodicity of sampling and measurements, sites of works and assessment

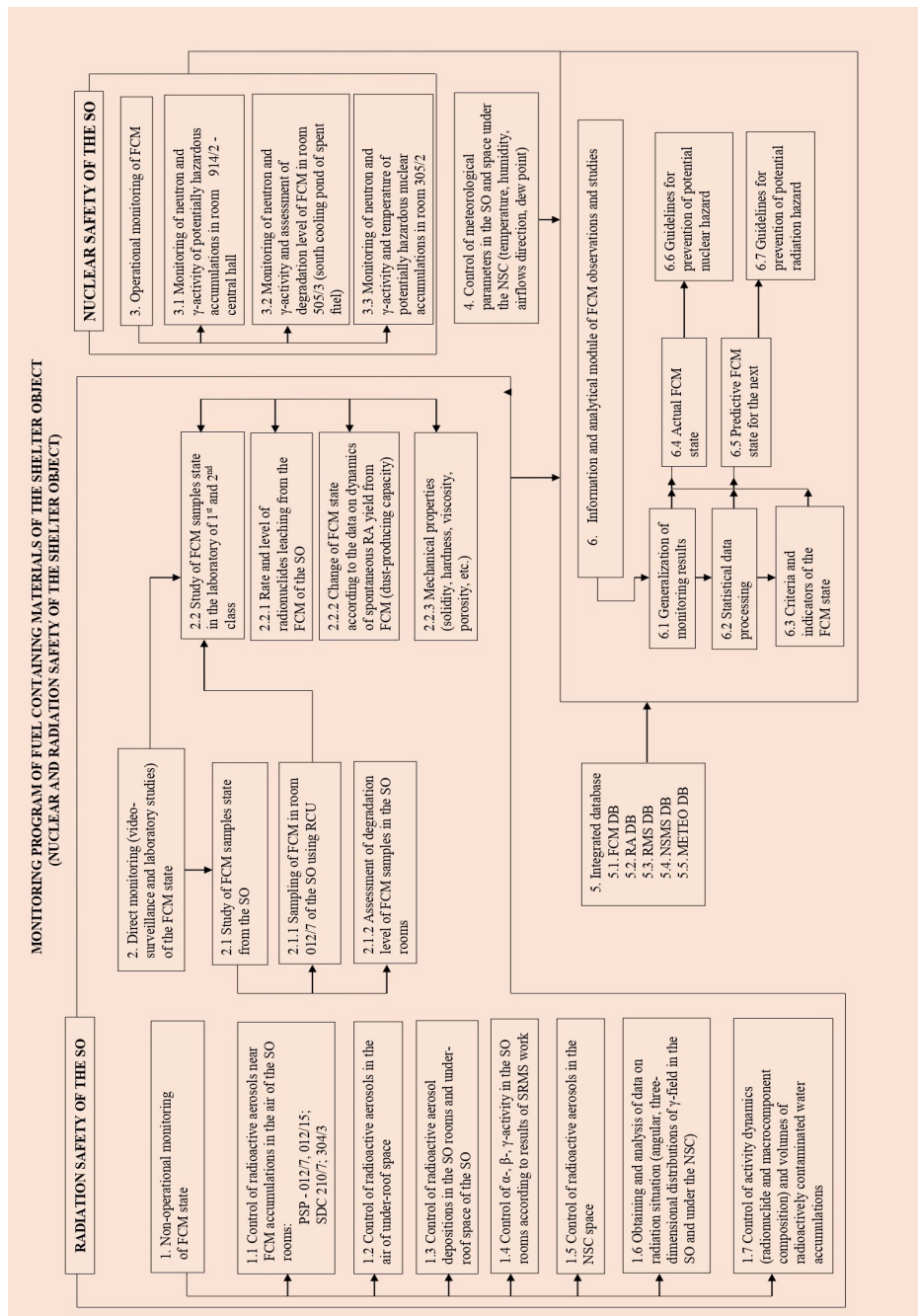


Fig. 5.1 — Monitoring program of the Shelter object fuel containing materials

criteria for the FCM degradation levels); field and laboratory equipment; organizational and technical measures to provide quality of works during FCM monitoring, which contain list and technological order of works; normative-technical documentation as well as general requirements to the safety, protection of personnel and the environment.

5.2.1 Radiation safety

Non-operational (indirect) monitoring of FCM state is developed taking into account that information medium on the FCM state can be:

- aerosols in the Shelter object rooms and the NSC (dynamics of aerosols activity in the air, particle size and radionuclide composition of RA and their depositions (^{90}Sr , ^{137}Cs , ^{154}Eu , ^{155}Eu , ^{241}Am , ^{238}Pu , $^{239} + ^{240}\text{Pu}$) on the surrounding surfaces;

- analysis of dynamics of α -, β -activity of aerosols in the Shelter object rooms according to results of the stationary RMS;

- radioactive water in the Shelter object rooms (radionuclide, macrocomponent and phase composition);

- three-dimensional and angle distributions of γ -radiation under the NSC, which contain information on FCM accumulations movement under emergencies (change of FCM location in case of building structures fall) or during natural disasters (earthquake).

Non-operational monitoring of FCM state includes:

- control of the volume activity concentration and disperse composition of aerosols near open FCM accumulations in the Shelter object rooms 012/7, 012/15, 210/7 and 304/3;

- control of RA (radionuclide and particle size composition) in the under-roof space of the Shelter object;

- control of RA at the upper marks of the Shelter object in the space under the NSC (releases due to leakiness of the light roof);

- control of RA in the surface air of the space under the NSC.

The main criteria of FCM degradation are an increase of the volumetric activity of basic radionuclides and the ratio of radionuclides activities in the fuel matrix of FCM accumulations in a certain room of the Shelter object to the similar ratio of radionuclides in aerosol samples or deposition samples in the same room. In other words, if after some time an increase of the aerosol activity is observed, then if the radionuclides ratio is similar to one in FCM, it will mean that degradation processes have intensified. The particle size distribution of RA in this room is an additional criterion.

Control of α -, β -activity of aerosols and γ -radiation in rooms (another kind of non-operational monitoring of FCM state) is conducted by stationary RMS as part of an integrated automated control system (Table 5.1). Results of control of the stationary RMS are additional information for complex and integral estimation of FCM state in the Shelter object.

Table 5.1 — Control points of the volumetric α - and β -activity, information from which will be used for integral estimation of FCM state in the Shelter object

ER detector	Room, unit, mark	Axis	Row	Height of installation above the floor, m
SRMS-S-AIR-001	006/2, Б, 0.000	50 ₊₂₅₀₀	Д ₊₅₀₀	1.5
SRMS-S-AIR-002	Г-109/3, Г, +1.000	55 ₊₁₀₀₀	Б ₋₄₀₀₀	1.4
SRMS-S-AIR-003	206/2, Б, +6.000	50	Д ₋₁₀₀₀	1.3
SRMS-S-AIR-004	Г-274, Г, +5.800	55 ₋₂₅₀₀	Б ₊₁₅₀₀	1.6
SRMS-S-AIR-005	Г-347, Г, +10.000	55 ₊₃₀₀₀	Б'	1.6
SRMS-S-AIR-006	Г-350, Г, +10.000	66 ₊₈₀₀	Б	1.6
SRMS-S-AIR-007	3.30, Г, +10.000	40 ₊₂₀₀₀	Б ₋₅₀₀₀	1.6
SRMS-S-AIR-008	Г-557, Г, +16.400	54 ₋₁₀₀₀	Б	1.6
SRMS-S-AIR-009	Г-526/2, Г, +19.500	54 ₊₃₀₀₀	Б'	1.6
SRMS-S-AIR-010	615/2, Б, +24.000	50	Д ₋₂₀₀₀	0.5
SRMS-S-AIR-011	Г-632, Г, +24.270	53 ₊₃₀₀₀	Б'	1.2

Stationary RMS controls (Fig. 5.2):

exposure rate of γ -radiation in the air of rooms of permanent and periodic stay of personnel;

volumetric α -activity of RA in the range of $2 \cdot 10^{-2}—10^5 \text{ Bq/m}^3$ ($^{238}, ^{239}, ^{240}\text{Pu}$, ^{241}Am);

volumetric β -activity of RA in the range of $2 \cdot 10^{-1}—10^7 \text{ Bq/m}^3$ (^{137}Cs , ^{90}Sr + ^{90}Y).

An assessment of the FCM state is carried out according to the data of statistical analysis on the α - and β -volumetric activity. Approximative regularity is determined by the obtained results, according to which current and predictive assessments of the FCM behavior are given.

The criterion of FCM degradation is the exit of the aerosol α -, β -activity in rooms of the Shelter object beyond the confidence interval, which is estimated with the confidence level of 0.95 based on the stationary RMS data and the α -, β -activities ratio.

Non-operational monitoring of FCM state is formed taking into account that information on radionuclide and phase composition of RW accumulations, which are near FCM accumulations of the Shelter object (Table 5.2), may be information medium on FCM degradation of the Shelter object.

Before the construction of the NSC, due to atmospheric moisture entry from the upper marks of the Shelter object to the bottom one and radionuclides leaching from FCM, water contained information on the FCM state. Under the NSC condition, without atmospheric moisture entry to the Shelter object, radionuclides leaching from the FCM have slowed

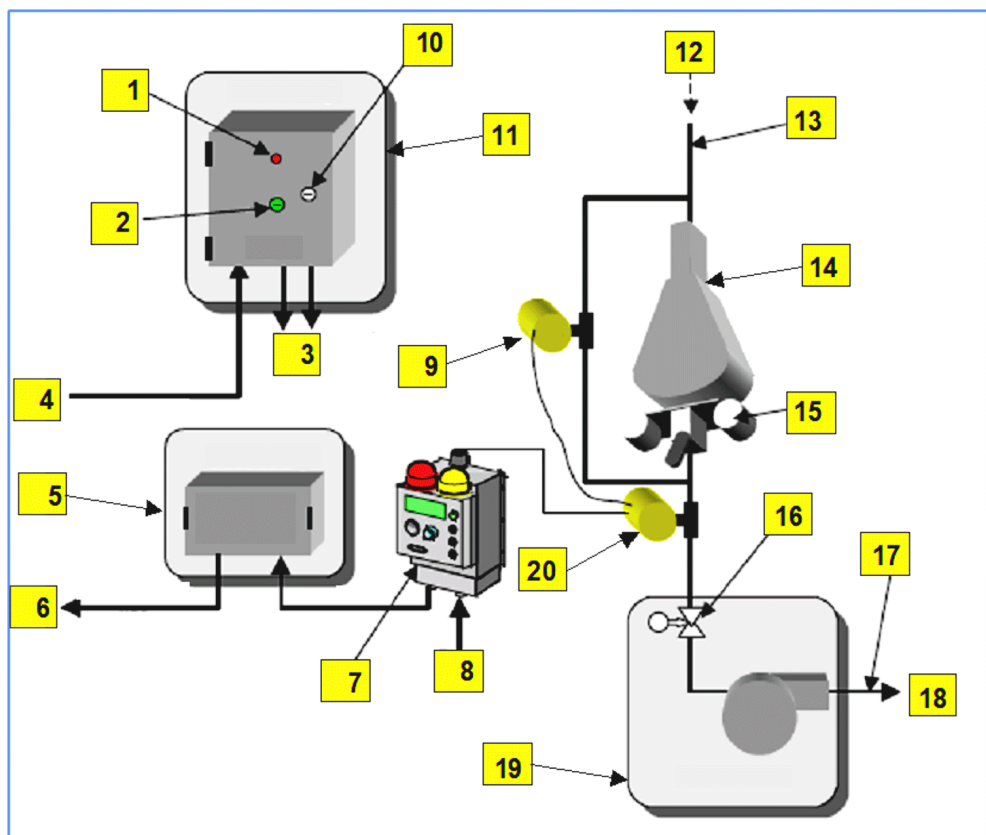


Fig. 5.2 — Module of radioactive aerosols control of the stationary RMS of the IACS [139]:
 1 — power indicator; 2 — arm/disarm button of a pump; 3 — the power of a pump;
 4, 8 — power line; 5 — distribution box; 6 — data line to the communication device with the
 object; 7 — local processor; 9 — membrane switch; 10 — lock; 11 — electrical unit;
 12 — access port; 13 — OD pipe; 14 — measuring installation for RA volumetric activity;
 15 — filter cassette and switch; 16 — control valves; 17 — 12-mm OD pipe; 18 — outlet;
 19 — pump; 20 — flowmeter

down significantly, but in the next four-five years, they may still be important due to the formation of condensation moisture. This will allow the use of RW contamination characteristics to assess the FCM state in the Shelter object.

Sampling for assessment of activity and nuclide composition of RW is recommended to conduct in rooms of the Shelter object once a month. Volumes of water are controlled in parallel with sampling.

Table 5.2 — Recommended points (places) of radioactive water sampling

Sampling point number	Room number	Construction coordinates			Notes
		mark, m	row	axis	
6	012/16	+2.20	Ж	48–49	
7	009/4	0.00	Ж	49–50	
18	017/2	0.00	Г–Д	43–44	
20	01/3	+1.25	T	47–48	Pipe from SDC
21	012/13	+2.20	P	45–46	
30	001/3, ECOR	–2.60	Y–Y1	49–50	
31	012/6	–0.95	C–T	45–46	Pit
32	012/7	–0.65	E–Ж	47–48	
35	012/8	0.00	Ж _{–1500}	49–500	Collector at the mark of +9.00

The change in the ratio of $^{241}\text{Am}/^{239} + ^{240}\text{Pu}$, $^{90}\text{Sr}/^{239} + ^{240}\text{Pu}$, $^{238}\text{Pu}/^{239} + ^{240}\text{Pu}$ radionuclides concentrations and increase of uranium concentration in RW samples are criteria of FCM degradation.

Criteria and indicators of the assessment are given in Tables 5.3 and 5.4.

Table 5.3 — Assessment criteria of the degradation state of fuel containing materials

Ratio of radionuclides concentrations	Assessment criterion	Indicator of assessment criterion (01.07.2018)
$^{241}\text{Am}/^{239} + ^{240}\text{Pu}$	$(^{241}\text{Am}/^{239} + ^{240}\text{Pu})_{\text{water}} > (^{241}\text{Am}/^{239} + ^{240}\text{Pu})_{\text{FCM}}$	1.9
$^{90}\text{Sr}/^{239} + ^{240}\text{Pu}$	$(^{90}\text{Sr}/^{239} + ^{240}\text{Pu})_{\text{water}} > (^{90}\text{Sr}/^{239} + ^{240}\text{Pu})_{\text{FCM}}$	42
$^{238}\text{Pu}/^{239} + ^{240}\text{Pu}$	$(^{238}\text{Pu}/^{239} + ^{240}\text{Pu})_{\text{water}} > (^{238}\text{Pu}/^{239} + ^{240}\text{Pu})_{\text{FCM}}$	0.457

The γ -radiation ER inside the NSC is determined, first, by FCM accumulations contained in the Shelter object. A three-dimensional pattern of dislocation of the main FCM masses and monitoring of the three-dimensional and angular distributions of γ -radiation ER field will allow obtaining data on possible movement of heavy FCM masses in the facility due to fall of supporting structures or earthquake.

The monitoring of angular distribution and energy (E_γ) characteristics of γ -radiation ER is conducted at all stages of the Shelter object transformation into an ecologically safe system (dismantling of unstable structures, FCM retrieval and their treatment).

Table 5.4 — Assessment criteria of the degradation state of fuel containing material by uranium concentration in radioactive water

No. of sampling point	Uranium concentration, mg/dm ³ (average for 2017)	Indicator of assessment criteria as of 01.07.2018 (uranium, mg/dm ³)	No. of sampling point	Uranium concentration, mg/dm ³ (average for 2017)	Indicator of assessment criteria as of 01.07.2018 (uranium, mg/dm ³)
6	11 ± 2	15	30	7.4 ± 0.9	7.6
7	13 ± 2	30	31	32 ± 3	34
18	0.59 ± 0.18	3.8	32	56 ± 15	104
20	13 ± 3	18	35	12 ± 8	8.8
21	2.1 ± 0.3	3.3			

Tasks of measurements are the following: determination of directions to the intensive sources of γ -radiation; determination of γ -spectrum of radiation; control of geometry change and location of radiation sources.

Due to the high radiation fields in control places, immediate vicinity to FCM accumulations on external structures of the Shelter object and at the sites under the NSC, research equipment for angular distribution and E_γ should be autonomous (without human presence and use of exterior electrical network), easy to carry and decontaminate, have means for spatial orientation.

Operational (direct, immediate) monitoring of FCM is conducted to assess the level of FCM degradation based on visual observation and laboratory research of FCM samples and carried out once a year in three main areas:

- visual control of destruction using video surveillance in places of FCM localization;
- laboratory research of physical and chemical properties of FCM samples;
- study of radiochemical properties of FCM samples.

The degradation level of FCM in rooms of the Shelter object is assessed according to the following scheme: visual control of destruction using video surveillance devices in places of FCM localization (twice a year) → sampling of FCM in the Shelter object using remotely controlled unit (RCU) (samples in rooms are collected in an amount, which does not contradict safety requirements during works in the Shelter object under the separate program of safe works) → control of dust generation capacity: sampling of aerosols by “blow-off” from the surface of the sample to the impactor (in lab environment) and determination of particle size and radionuclide composition of aerosols in samples (twice a year in laboratory environment) → control of destruction degree by amount of fine-grained fraction (determination of fraction number using radiography); sampling on film adhesive backing at FCM location using remotely controlled technologies (telescopic arm, RCU) and in amount, which does not contradict safety requirements during works in the Shelter object.

Laboratory researches of physical and chemical properties in FCM samples, in particular radionuclide composition of FCM samples from rooms, are carried out in radiochemical laboratory: preparation of samples for analyses → radiochemical analysis → α -, γ -spectrometric analysis → determination of ^{90}Sr , ^{137}Cs , ^{154}Eu , ^{155}Eu , ^{241}Am , ^{238}Pu , $^{239} + ^{240}\text{Pu}$ radionuclides activity based on analyses results.

The results of laboratory tests are included in the database for use in the complex analysis of the FCM monitoring data.

The rate and degree of radionuclides leaching from FCM with distilled and unit water are determined by the degree of dissolution of i -radionuclide as the ratio of activity (A_i) in solution to the activity of this radionuclide in the primary sample of FCM (A_{i0}).

The main stages of determination of leaching degree of radionuclides from LFCM are the following: 1) samples preparation, γ -spectrometric measurements of ^{137}Cs , 154 , ^{155}Eu and ^{241}Am activity in reference FCM samples; 2) radiochemical determination of ^{90}Sr , ^{238}Pu , $^{239} + ^{240}\text{Pu}$ and ^{241}Am content in the leached solution. In all solutions and solid residues after exposure, the content of ^{90}Sr , ^{137}Cs , ^{238}Pu , $^{239} + ^{240}\text{Pu}$ and ^{241}Am radionuclides is determined.

The rate and degree of leaching of radionuclides from FCM depend, first of all, on the area of the specific surface of FCM samples and the rate of radionuclide diffusion from the depth to the contact area. The assessment criteria of the state of FCM destruction by leaching rate are given in Table 5.5.

Table 5.5 — The assessment criteria of the state of FCM destruction by the leaching rate of radionuclides with distilled water

FCM	Assessment criterion	Value of assessment criterion
Polychromatic	Constants of ^{137}Cs leaching from LFCM, day^{-1}	$1.7 \cdot 10^{-6}$
Brown	Constants of ^{137}Cs leaching from LFCM, day^{-1}	$5.6 \cdot 10^{-6}$
Black	Constants of ^{137}Cs leaching from LFCM, day^{-1}	$7.8 \cdot 10^{-6}$

The mechanical properties of FCM samples are studied in the laboratory by the following indicators: strength, microhardness, viscosity, porosity, characteristics of components of pore space, components of crystalline phases in the glass matrix, rate of nuclei formation and growth rate of crystalline nuclei in the glass phase, radionuclides distribution on the microlevel in all phases, ion mobility (in particular of radionuclides ^{137}Cs , ^{90}Sr , uranium, plutonium, americium).

The studied mechanical characteristics of FCM will allow a deeper understanding of physical and chemical processes, occurring in FCM, and thus developing a model of FCM microstructure and providing both short-term and long-term more realistic predictions of transformation of microstructure and basic physical and chemical properties.

5.2.2 Nuclear safety

The basic principle, which determines activity to ensure nuclear safety at the Shelter object, is to make impossible the SSCR under existing conditions and all predictable their changes [51]. The SSCR is always considered as a hypothetical event, which is the result of such conditions that are impossible to predict at the level of available knowledge and experience.

If the SSCR is impossible to exclude as a hypothetical event, then it is still a potentially nuclear hazardous factor. Objects such as the Shelter require constant monitoring of the neutron activity and determination of procedures for detection and interpretation of anomalies in NFD dynamics related to deviations from safe and acceptable values of the criticality parameters [27].

Based on experimental and calculated assessments, the classification of rooms according to the level of nuclear hazard of FCM accumulations, which are contained in them, was carried out.

Potentially nuclear hazardous rooms are the under reactor room 305/2, the CH, the SCP, in which the presence of FCM compositions was allowed, where the occurrence of NFD is fundamentally possible.

The dynamics of neutron and γ -activity of potentially nuclear hazardous FCM accumulations in the Shelter object is controlled according to the data of the NSMS every minute and the dispersion of their average is recorded. Those particular results of measurements by the NSMS system are taken for the complex assessment and prediction of the FCM nuclear safety state. Obtained information allows composing representative

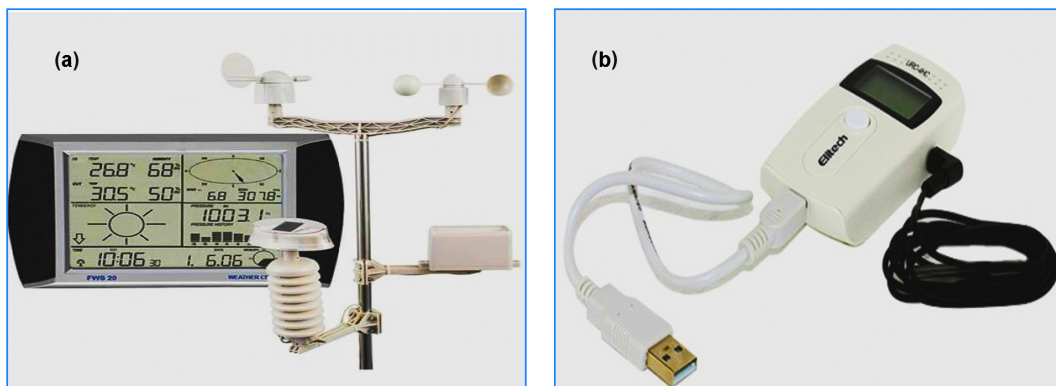


Fig. 5.3 — Equipment of meteorological parameters control
a — autonomous meteorological station PCE FWS; b — recorder of temperature
and moisture Elitech RC-4HA/C

statistical samples of the ER and NFD monitoring studies as well as carrying out statistical analysis of the time series of observations, correlation and regression analyses, and predictive assessments.

To improve an information value, the monitoring covers the data on the temperature in the potentially nuclear hazardous FCM accumulations from an expert-research system developed and implemented at the Chornobyl NPP by the ISP NPP. This system has 11 measuring channels of the temperature and 4 additional channels of the NFD.

The meteorological parameters are controlled in the mode of monitoring of temperature, moisture, speed and direction of airflows by the autonomous weather stations PCE FWS as well as temperature and moisture recorders during the year with a time step of three hours (Fig. 5.3). The task of monitoring is to obtain information on the change of microclimate in the space of the NSC and assess its impact on nuclear and radiation safety, FCM state, as well as develop and implement corrective actions on work of ventilation system.

An integrated database is built according to the results of all types of monitoring, based on which systematic analysis and assessment of FCM state are carried out further. Parameters, which determine the current state and predictive assessments of FCM behavior for the future, are substantiated using statistical processing of results obtained from all the above-mentioned research areas.

Chapter 6. FURTHER TRANSFORMATION OF THE SHELTER OBJECT INTO AN ECOLOGICALLY SAFE SYSTEM

The construction of the NSC has significantly mitigated the risk of potential radioactive contamination of the territory due to the fall of unstable building structures of the Shelter object. Thus, this is only an interim step on the way to the creation of an ecologically safe system to achieve the ultimate goal — to transfer fuel containing materials in a controlled state.

In the near term, it is necessary to dismantle building structures of the Shelter object, the lifetime of which will end in 2023, and then to start work on the delayed dismantling of other building structures.

Fuel containing materials, formed due to the accident, are the main source of the Shelter object hazard. In their state and composition, they belong to long-lived RAW, and for some of them, there is still no confirmation that they are nuclear safe. The potential hazard of the FCM can increase in time due to the spontaneous destruction of their surface with the formation of high activity dust. Therefore, it is extremely important to develop technological solutions for FCM retrieval using the NSC systems and safety substantiation during their implementation.

Fuel containing materials must be transferred into a controlled state and placed under controlled temporary storage with further disposal. First of all, it is required by Ukrainian Law “On General Principles of Further Operation and Decommissioning of the Chornobyl NPP and Transformation of the Destroyed Fourth Power Unit of this NPP into an Environmentally Safe System”, secondly, all nuclear materials of the Shelter object should be registered under constant control of the IAEA. There is a positive experience of FCM retrieval at the Three Mile Island NPP in the USA. Besides, in Japan at the Fukushima NPP, the strategy of nuclear materials retrieval has been adopted and studies in this direction are carried out.

The Shelter object transformation into an ecologically safe system and its decommissioning will be possible only when FCM will be transferred into a nuclear safe state and registered for controllable storage or transferred for disposal. To start FCM retrieval, it is necessary to take the following measures:

- to develop general technological solutions and projects of work on the retrieval and conditioning of FCM;

to develop remotely controlled robotics;
to build infrastructure for FCM and RAW management, specifically, technologies and systems of sorting, monitoring, characterization, decontamination, to prepare the site for temporary FCM and RAW storage, a pool of containers for FCM, etc.

The issue of nuclear safety of some nuclear materials accumulations of the Shelter object also remains unresolved. Due to the lack of available scientific knowledge about them, there are many misunderstandings, different opinions and criticisms. Additional studies are necessary, the results of which can provide the basis for substantiating nuclear safety and convincing the public of the impossibility of a nuclear accident, as well as providing constant monitoring of the main FCM accumulations.

The FCM retrieved from the Shelter object are long-lived waste and subject to disposal only in storage facilities located in stable geological formations. Since there are no such storage facilities in Ukraine and it is possible to build them only in the long-term, it is necessary to adopt a decision on temporary long-term FCM storage, i.e. on the building of an interim FCM storage facility.

6.1 Analysis of the national normative legal acts and assessment of their sufficiency

The practical activity on the Shelter object transformation into an ecologically safe system is carried out according to the requirements of the Law of Ukraine “On General Principles of Further Operation and Decommissioning of the Chornobyl NPP and Transformation of the Destroyed Fourth Power Unit of this NPP into an Environmentally Safe System” [11], the Law of Ukraine “On the State Program of the Chornobyl NPP Decommissioning and the Shelter Object Transformation into an Ecologically Safe System” [141] and “Strategy of the Shelter Object Transformation” [142].

Transformation of the Shelter object into an ecologically safe system is achieved through the implementation of three main stages [142]:

stage 1 — stabilization of the Shelter object state, an increase of the operation reliability and life of structures and systems, which ensure its stabilization and control of safety indicators;

stage 2 — a creation of additional protective barriers (first of all, the confinement) that provide necessary conditions for dismantling of unstable building structures and technical activity at stage 3, the safety of personnel, population and the environment, as well as the implementation of preliminary engineering work on the development of FCM retrieval technologies at stage 3 and development of infrastructure for RAW management of the Shelter object;

stage 3 — retrieval of FCM and long-lived RAW from the Shelter object, their conditioning with further storage and disposal in RAW storage facilities following current standards, Shelter object decommissioning.

The first and second stages were successfully completed. At the end of November 2016, the main work on installation and movement into the design position of the arch was performed, and in July 2020, an individual permit was obtained for the research and industrial operation of the first NSC launch system.

After the commissioning of the NSC, the unstable structures of the Shelter object will be dismantled. Further measures for the Shelter object transformation into an ecologically safe system should be aimed at the retrieval/transfer of FCM into a controlled state and RAW management. Such activity at the object suffered from the beyond design-basis accident and has no analogs in the world practice, is unique and requires corresponding regulatory support.

According to the Law of Ukraine “On General Principles of Further Operation and Decommissioning of the Chornobyl NPP and Transformation of the Destroyed Fourth Power Unit of this NPP into an Environmentally Safe System” [11], one of the aims of the Shelter object transformation into an ecologically safe system *is a retrieval of fuel containing materials and RAW from it*. Before the retrieval of fuel containing materials and RAW from the Shelter object, it is necessary to transfer them into a controlled state.

The same Law defines that “confinement is a protective structure that includes a set of technological equipment *for retrieval from the destroyed fourth power unit of the Chornobyl NPP of fuel containing materials*, RAW management and other systems designed to perform an activity on the transformation of the power unit into an ecologically safe system and protection of personnel, population and the environment”¹.

According to the Law of Ukraine “On the State Program of the Chornobyl NPP Decommissioning and the Shelter Object Transformation into an Ecologically Safe System” [141], it is necessary *to retrieve fuel containing materials, high-active and long-lived RAW from the Shelter object and transfer them into a controlled state*, interim controlled storage and disposal in the deep storage facilities (stable geological formations) unless an alternative method for the safe storage of materials in the Shelter is proposed before retrieval (after about 30—50 years).

The task of the Shelter object transformation into an ecologically safe system should be resolved by the consecutive development and implementation of certain measures, in particular:

- the development and approval of the normative and design documentation on the object transformation into an ecologically safe system;

- the creation of additional protective barriers (first of all, the confinement) providing conditions for technical works at the stage of the object transformation into an ecologically safe system as well as protection of personnel, population and the environment;

- the development of technologies on FCM retrieval;

- the construction of the storage facilities for disposal (particularly in the geological formations) of FCM and long-lived RAW;

¹ Author's italics

the retrieval of FCM and long-lived RAW from the object (or transfer into the controlled state), their conditioning with further storage and disposal in the corresponding storage facilities;

the dismantling of the object structures and confinement elements.

It is stated in the “Strategy of the Shelter Object Transformation” [142] that: to achieve complete control over sources of nuclear and radiation hazard, *it is necessary to retrieve FCM* and store them in beforehand prepared controlled conditions providing multi-barrier protection, which should be substantiated according to the requirements of current legislation.

Thus, *the necessity of FCM retrieval* is stated in three basic documents, which define the main direction of the activity on the Shelter object transformation into an ecologically safe system. At the same time, in compliance with the “Strategy of the Shelter Object Transformation” [142], FCM include damaged nuclear fuel of the former fourth power unit of the Chornobyl NPP due to the beyond design-basis accident, regardless of its physical and chemical state, fuel assemblies from the cooling pond, as well as any other materials (fragments of the active core, mixtures, melts, solutions, chemical species, dust, etc.) containing nuclear fuel in the noticeable amount (i.e. its concentration is 1% and more).

And now let us focus on some provisions of documents [11, 141, 142].

The condition is stated in the document [11] that fuel containing materials and RAW of the Shelter object should be transferred in the controlled state before the retrieval. In other words, the transfer of FCM in the controlled state is a prerequisite, but not an alternative to the activity on FCM retrieval.

The document [141] states that the task of the Shelter object transformation into an ecologically safe system is retrieval from it (or transfer in the controlled state) of FCM and long-lived RAW, their conditioning with further storage and disposal in the corresponding storage facilities. In this case, FCM transfer in the controlled state is an alternative to its retrieval.

The document [142] gives the term “controlled state of FCM”: it is the state when the FCM subcriticality established by normative documents is provided, as well as the possibility of maintenance of FCM safety indicators at the prescribed level due to conditioning or creation of additional engineering barriers. As regards FCM conditioning, according to the term “radioactive waste conditioning” stated in the Law of Ukraine “On Radioactive Waste Management” [143], it can be implemented by containerization or immobilization, which is in principle impossible without the prior retrieval of FCM from their locations. At the same time, additional engineering barriers can be created inside the Shelter object without FCM retrieval, but it does not resolve the problem of safety, in particular in the long-term outlook: “...In hazardous conditions of an emergency object it is impossible to achieve a controlled and nuclear safe state of FCM. To achieve complete control over the sources of nuclear and radiation hazards, FCM retrieval is necessary...” [142, art. 3.2].

Thus, there are some contradictions and uncertainty in documents [11, 141, 142] in the part of requirements concerning future activity on FCM retrieval from the Shelter object after the NSC commissioning.

To date, the status of the Shelter object regardless of the NSC has been described by NRBU-97/D-2000 [144] as “*place of the surface storage of unorganized RAW (temporary storage of unorganized RAW, which is at the stage of stabilization and reconstruction)*”. The reason for qualifying the Shelter object as temporary RAW storage was the assumption that fuel containing materials could be used neither now, nor in the future. In our view, such a status is not proper, taking into account that FCM contained in the Shelter object are included in the inventory list of nuclear materials and the IAEA safeguards are applied to them.

Besides, taking into account that FCM is the main source of the Shelter object hazard, as well as its some kind of visiting card, then it would be logical when determining the status of the Shelter object to say about the presence of fuel containing materials in it. After the Confinement commissioning, the Shelter object will be integrated into the NSC complex, which requires determination of the status of this new formation.

6.1.1 Nuclear materials management

The state safeguards system in Ukraine (safeguards of nuclear weapon non-proliferation) is created according to provision 67 of the Law of Ukraine “On the Use of Nuclear Energy and Radiation Safety” [145]. Its aim is a control that nuclear materials, equipment and technologies, used for peaceful purposes, would not be used in military ends. The state safeguards system is based on this Law, the provisions of international and bilateral agreements, of which Ukraine is one of the participants, and has two components:

- the state system of registration and control of nuclear materials;

- the state system of export-import control of nuclear materials, equipment, and technologies.

According to the Law [145], the management and maintenance of the state registration and control of nuclear materials in Ukraine are carried out by the SNRIU, and the liability for registration and control of nuclear materials at nuclear facilities is under operating organization.

All nuclear materials of Ukraine are subject to registration and control by the IAEA based on the “Agreement between Ukraine and International Atomic Energy Agency on Application of Safeguards according to the Agreement on Non-proliferation of Nuclear Weapon” (the Agreement is ratified by Law No. 737/97 dated 17.12.97 [146]).

At the Chornobyl NPP, in particular, at the Shelter object, registration of nuclear materials is carried out according to the Law of Ukraine “On Ratification of Additional Protocol to the Agreement between Ukraine and International Atomic Energy Agency on Application of Safeguards under the Agreement on Non-proliferation of Nuclear Weapon” [147] and

“Regulation on the State System of Registration and Control of Nuclear Materials”, approved by the Resolution of the Cabinet of Ministers of Ukraine dated 18.12.1996 No. 1525 (with changes, introduced based on Resolutions of Cabinet of Ministers No. 1006 dated 08.08.2001 and No. 257 dated 25.03.2009) [148].

From the beginning of the IAEA safeguards application on nuclear materials of the Shelter object, complications arose concerning their setting under safeguards [149]. Above all, it was related to the inability to use the standard procedure of registration applied to non-emergency nuclear materials of the Chornobyl NPP, as well as the inability to identify the claimed nuclear materials. Therefore, while setting the Shelter object nuclear materials under the safeguards of the IAEA, the trade-off decision was made to declare the number of nuclear materials at the moment before the accident, i.e. on April 25, 1986. For the future, it was planned to register nuclear materials during their retrieval from the Shelter object in compliance with all registration procedures of nuclear materials stated in the normative legal and technological documentation in force in Ukraine and approved by the IAEA. It was supposed that at the beginning of FCM retrieval from the Shelter object in Ukraine, normative legal and technological documentation on the treatment with emergency waste containing nuclear materials would be developed and approved by the IAEA.

Current normative legal and technological normative documents in Ukraine do not regulate treatment with emergency RAW containing fissile nuclear materials. Among all current Ukraine normative legal documents, only the definition “waste subject to storage” can be applied to emergency nuclear materials of the Shelter object [146].

In article 98 of the Agreement [146], it is stated that waste subject to the storage is nuclear material obtained due to the treatment or technological emergency and is currently considered not to be recovered but to be stored. According to the given definition, nuclear material is considered as waste subject to storage; changes of inventory amount of the material are determined in the inventory records and reports as material “transferred into waste subject to the storage”. The material transferred into waste subject to the storage is stored in the material balance area and remains subject to the IAEA safeguards, but is not included in the inventory list of nuclear material of the material balance area.

Thus, the Agreement [146], as well as approved by the IAEA normative legal and technological documents does not contain recommendations on the procedure of transfer of emergency nuclear waste into waste subject to the storage. Therefore, when planning FCM retrieval during the Shelter object transformation into an ecologically safe system, considering the stated above, as well as due to an absence of normative-technical documentation in Ukraine, which provides procedures for the transfer of emergency nuclear materials to the waste subject to the storage, first of all, it is necessary to develop normative legal and normative-technical documentation, which provides and supports FCM retrieval. In particular, it is necessary to describe the procedures for FCM transfer to the category of “waste subject to the storage”, and the requirements on the technology of their treatment. The development of the

documentation should be completed before the start of FCM retrieval from the Shelter object. The development and approval of the methodology for estimation of nuclear materials amount in FCM of the Shelter object should be included in the list of prior tasks.

Only a small amount of the Shelter object nuclear materials can be measured using methodologies and measuring equipment existing today to assess the number of nuclear materials in the nuclear fuel of RBMK type reactors. Such nuclear materials include spent FA from the SCP and fresh FA that were on the eastern wall of the central hall of the fourth power unit at the moment of the accident. It is assumed that during the active phase of the accident, FA from the SCP could remain undamaged, and FA that were on the eastern wall of the central hall of the fourth power unit at the moment of the accident received only mechanical damage [149]. This allows us to assess the number of nuclear materials using existing methodologies and equipment, but only in case of existing accessibility to them.

Today, there are no requirements to the choice of equipment for emergency nuclear materials measurement, as well as for methodology of assessment of nuclear materials amount.

The development of a methodology for an amount determination of nuclear materials in emergency formations of the Shelter object (mainly for LFCM and fragments of reactor active core) should be focused on the substantiation of possibility or impossibility of perspective of enriched uranium and plutonium regeneration to create nuclear weapons. Thus, at first, it is necessary to evaluate perspectives of enriched uranium and plutonium regeneration from the Shelter object FCM, considering all known in the world practice methods of nuclear materials regeneration, and give feasibility study of the regeneration process. The methodology also should include requirements for equipment for evaluation of nuclear materials amount in emergency formations of the Shelter object.

The next stage, after the development of methodology for evaluation of nuclear materials amount in emergency formations of the Shelter object (FCM), should be the development of the normative-technical documentation, which will determine procedures for allocation of the Shelter object nuclear materials into the separate group of waste subject to the storage, and grouping criteria of such nuclear materials into the separate batches. In particular, the normative-technical documentation should cover the issues of nuclear safety in the field of waste management subject to storage, as well as their classification. The classification can probably be based on the application of ER criteria, taking into account the percentage of isotopes of enriched uranium and plutonium in the waste.

The normative-technical documentation to be developed should show how to evaluate the possibility of using currently available containers for the storage/transportation of RAW for waste subject to the storage; according to the results of assessment to predict as the need arises the possibility of their modernization or development of radically new containers for the storage/transportation of waste subject to the storage.

The amount of the Shelter object nuclear materials, which may be among waste subject to storage is assessed at the level of from 127.6 to 140 t (U) [149]. This is a considerable amount of emergency waste, which by their physico-chemical properties do not meet the criteria for acceptance of any of the available RAW storage facilities in Ukraine. Therefore, even before the start of the process of FCM retrieval from the Shelter object, it is necessary to determine the organization of temporary storage and/or disposal of waste subject to the storage, as well as the rules of their transportation. Requirements for temporary storage and/or disposal of waste subject to the storage should provide the possibility of inspection by the IAEA specialists. Such sites should be located within the Chornobyl NPP industrial site since according to the Agreement [146] the material transferred to the waste subject to the storage is stored in the area of material balance and remains the subject of the IAEA safeguards.

In the Shelter object in addition to emergency nuclear materials that can be included in the waste subject to the storage, there is some part of emergency nuclear materials, to which it is impossible to apply procedures of the state registration and control as well as inspection by the IAEA representatives neither now nor in the future. Such nuclear materials include dust of the active core fragments (particles of micron size) and compounds of uranium and plutonium in water solutions. Therefore, these nuclear materials need a revolutionary another approach providing development of criteria and procedures of removal from the state register.

As we can see, now regulatory and normative-technical documentation of Ukraine in the field of nuclear materials management does not in full measure cover some problems of the Shelter object transformation into an ecologically safe system. There is still an open-ended question of the IAEA safeguards compliance during FCM retrieval and emergency nuclear materials management, particularly there is no documentation on the registration and control of emergency nuclear materials providing the IAEA safeguards fulfillment.

Several normative documents [150—156] were developed in Ukraine concerning general requirements, criteria and principles for safety in the field of treatment with nuclear fuel of nuclear power plants, research reactors, critical and subcritical assemblies, and spent nuclear fuel storage facilities. Requirements on criticality at all stages of their lifecycle as well as requirements to the safe geometry of their accumulations were set to such nuclear materials.

At the Shelter object, we are dealing with unorganized, chaotic accumulations of nuclear hazardous materials in the form of FCM that are at risk of being critical. Besides, these accumulations are subject to the process of constant destruction with the formation of the fuel dust, deposition of which on building structures worsens the radiation situation inside the Shelter object.

The problem of uncontrolled precipitation intake, which created a risk of criticality, after the NSC installation has lost its relevance. But there is still the problem of natural destruction of FCM accumulations under the impact of external factors in the condition of the

NSC, as well as due to the failure of the Shelter object building structures. It is impossible to exclude this problem even in the view of the implementation of stabilizing measures on their reinforcement. The uncontrolled change of FCM accumulations geometry with the dust release into the NSC space can be the consequence of such a process.

To implement the retrieval and FCM containerization, the regulatory and legal framework on its regulation for the NSC is necessary. Thus, it is necessary to produce the regulatory document with requirements to the nuclear safety of the NSC, which should cover all stages of FCM management in the confinement: retrieval, containerization, organization of places of temporary storage and/or disposal, performing transport and technological operations. If necessary, requirements to the long-term mothballing of some FCM accumulations, retrieval of which is not an urgent task, should be given in the document.

The spent FA from the SCP and fragmented fresh FA located on the east wall of the fourth power unit central hall at the moment of the accident may be considered as the most problematic FCM. Now these FCM are in the safe subcritical state, but the risk of increase of the subcriticality level can not be excluded during their retrieval and further temporary storage. To protect this technological process, it is necessary to calculate safe geometric parameters during the storage (temporary storage) of retrieved spent and parts of fresh FA.

It should be noted that currently there are FCM accumulations in a deeply subcritical state, as well as accumulations that are outside the risk of building structures fall, and these accumulations should not be immediately (urgently) retrieved. It is advantageous to provide for them the possibility of mothballing for a long time.

For FCM subject to immediate retrieval, it is necessary to develop a set of technology solutions on their transport outside the NSC and their placement for long-term storage and/or disposal, as well as temporary storage in the space under the NSC. The issue of temporary storage in the space under the NSC is escalated due to the deficiency of storage facilities capable of accepting for storage of a significant amount of waste of this type. Decision on the organization of temporary storage in the space under the NSC can apply to FCM belonging to waste subject to the storage taking into account classification of the waste type. It should be noted that the development of the classification of waste subject to the storage can be useful for registration of the Shelter object nuclear materials, as well as an accomplishment of measures in the field of FCM management. For example, according to the classification of waste subject to the storage, places of temporary storage are organized only for FCM with the minimum possible level of the DR of the ionizing radiation and a small percent of nuclear material content (less than 1).

Given the above, we can conclude that it is necessary to conduct a set of researches for the creation of the normative document to support nuclear safety of the NSC, such as:
the assessment of all FCM accumulations taking into account their subcriticality;

the assessment of physical security of FCM accumulations (in terms of the risk of building structures collapse);

predictive assessment of the stability of FCM accumulations (taking into account the risk of FCM destroy under the influence of natural external factors);

the calculation of safe geometry of storage of all types of FCM, in particular classified as waste subject to the storage.

The document, suggested to the development, should include requirements to provide criticality at all stages of transport and technological actions on FCM management.

6.1.2 Radioactive waste management

The RAW classification system in Ukraine. One of the key tasks in providing the further Shelter object transformation is a determination of clear criteria of the long-term storage and disposal of FCM and other RAW after their retrieval.

According to [143, 144, 157—159], RAW are divided into two types, four groups and three categories: into types by the criterion of admissible disposal; into groups by the criterion of the retrieval level; into categories by the criterion of the specific activity.

According to the criteria of admissible disposal, there are short-lived and long-lived types of RAW. The short-lived RAW can be disposed in the surface and near-surface storage facilities, and the long-lived RAW in the stable deep geological formations. To divide RAW into types, it is necessary to assess expected potential exposure doses (PED) of the population in 300 years after their disposal by analyzing five reference scenarios of exposure, which correspond to five main ways of the dose formation [144]:

the intake of radionuclides with the drinking water;

the intake of radionuclides with food;

the inhalation;

an external γ -radiation, remote and contact β -irradiation of the skin;

accidental ingestion of the fine fragments of RAW substance.

For each of the five scenarios, the corresponding reference parameters and characteristics for assessment of the exposure doses are given in NRB-97/D-200 [144]. Obtained according to the results of scenarios analysis the dose values are compared with levels set by NRB-97/D-2000 [144], and in this way, RAW type and type of admissible disposal of RAW are defined:

$PED < 1 \mu\text{Sv} \cdot \text{year}^{-1}$ — short-lived RAW (subject to the disposal in the surface and near-surface storage facilities);

$PED > 50 \mu\text{Sv} \cdot \text{year}^{-1}$ — long-lived RAW (subject to the disposal in the stable deep geological formations);

$1 \leq PED \leq 50 \mu\text{Sv} \cdot \text{year}^{-1}$ — the type of RAW and admissible type of disposal are determined by the agreement with the regulatory agencies.

The RAW categories established in OSPU-2005 [157] by the criterion of level of RAW group retrieval and by the criterion of the specific activity are given in Tables 6.1 and 6.2.

Table 6.1— Classification of RAW according to the criterion of retrieval level

RAW group	Solid RAW	Level of retrieval, kBq · kg ⁻¹
1	Transuranic α-emitting radionuclides	0.1
2	α-emitting radionuclides	1.0
3	β-, γ-emitting radionuclides (except classified to the group 4)	10
4	³ H, ¹⁴ C, ³⁶ Cl, ⁴⁵ Ca, ⁵³ Mn, ⁵⁵ Fe, ⁵⁹ Ni, ⁶³ Ni, ^{93m} Nb, ⁹⁹ Tc, ¹⁰⁹ Cd, ¹³⁵ Cs, ¹⁴⁷ Pm, ¹⁵¹ Sm, ¹⁷¹ Tm, ²⁰⁴ Tl	100

Table 6.2 — Classification of RAW according to the criterion of the specific activity

RAW category	Value of the specific activity, kBq/kg			
	α-radionuclides		β-, γ-radionuclides	
	group 1	group 2	group 3	group 4
Low-level (LLW)	$> 10^{-1} < 10^1$	$> 10^0 < 10^2$	$> 10^1 < 10^3$	$> 10^2 < 10^4$
Intermediate-level (ILW)	$\geq 10^1 < 10^5$	$\geq 10^2 < 10^6$	$\geq 10^3 < 10^7$	$\geq 10^4 < 10^8$
High-level (HLW)	$\geq 10^5$	$\geq 10^6$	$\geq 10^7$	$\geq 10^8$

The analysis of available in Ukraine RAW classification system shows its inherent significant shortcomings, namely:

1. There is no clear relation between categories and types of RAW. The classification of RAW on categories of low-, intermediate- and high-level (LLW, ILW and HLW) by the criterion of the specific activity (see Table 6.2), implemented in enterprises (objects) where RAW are formed, does not set the admissible type of disposal in no case. For example, ILW depending on radionuclide composition and according to the analysis results of five reference scenarios of irradiation (according to requirements [144]) can be disposed in the near-surface storage facilities, as well as stable deep geological formations. It means that before the transfer of RAW for disposal, it is necessary to carry out their re-sorting with consideration of acceptance criteria for RAW disposal in one storage facility or another.

2. Requirement of NRB-97/D-2000 [144] on the mandatory analysis of five reference scenarios of irradiation and corresponding reference parameters and characteristics for these scenarios is too conservative because available and future storage facilities for RAW disposal locate in the exclusion zone, in particular in that part, which is planned for the industrial use and where the habitual residence of people is not allowed. It is hard to imagine, that

in 300 years the source of drinking water supply will be constructed directly over the storage facility body or at an insignificant distance from it, or the scenario of “accidental ingestion of the fine fragments of RAW substance” with an annual intake of radioactive materials of 0.05 kg will be realized. Taking into account the requirements of NRB-97/D-2000 [144], after FCM retrieval, the Shelter object will never be transformed into the surface storage facility of RAW. Therefore, a set of scenarios of the potential irradiation of the population should be specified by taking into account the placement of RAW storage facilities concerning the habitual residence of the population.

3. Despite that Ukraine has accumulated an enormous amount of RAW due to the Chornobyl NPP accident, RAW classification by the criterion of the specific activity is more conservative than in the IAEA recommendations. In particular, the IAEA Standard [160] defines typical values of the radionuclides volume concentration for HLW in 10^4 — 10^6 TBq · m⁻³, which for FCM at the conservative values of their specific weight of 3,000 kgs · m⁻³ is approximately $3 \cdot 10^9$ — $3 \cdot 10^{11}$ kBq · kg⁻¹. According to the data given in Table 6.2, HLW include waste of group 3 with the specific activity of 10^7 and higher, which is lower than in the IAEA standard [160] by more than two orders of magnitude. Moreover, according to the IAEA standard [160], HLW include waste with a heat release of over 2 kW · m⁻³. Instead, according to OSPO-2005 [157], HLW also include “low-temperature” waste, the heat release of which in places of temporary storage or disposal does not exceed 2 kW · m⁻³. So, the system of RAW classification adopted in Ukraine, based on the use of too conservative criteria, can lead to significant economic expenditure for RAW disposal, if left unchanged.

4. According to the effective until recently in Ukraine “Sanitary rules of radioactive waste management” (SPORO-85), the level of the surface contamination was taken for one of the RAW classification criteria. Since most materials, structures and equipment in the Shelter object have surface contamination, the introduction of RAW classification criteria by the level of the surface contamination would sufficiently simplify and hasten their sorting.

Improvement of the RAW classification system. With the support of the European Commission under the International Cooperation Program in the field of Nuclear Safety in 2011—2012, experts from the consortium DBE TECHNOLOGY GmbH (Germany), ANDRA (France), COVRA (the Netherlands), ENRESA (Spain) and SKB International AB (Sweden), with wide involvement of Ukrainian specialists, developed the project INSC U4.01/08-C “Improvement of the RAW classification system in Ukraine”. The main results of this project implementation are given in [161, 162].

The first step to improve the RAW classification system was implementation of very low-level waste (VLLW) class that reflected in the adopted Law of Ukraine “On the introduction of changes to some laws of Ukraine on the improvement of the legislation in the field of radioactive waste management” [163]. This Law will be effective from November 7, 2021.

VLLW include RAW, in which the activity of radionuclides exceeds the levels of retrieval or liberation from the regulatory control (lower bound is classified as VLLW), but with regards to their radiological characteristics, they can be transferred for disposal in the simplest surface storage facilities.

The introduction of VLLW class will have a positive influence on the process of the Shelter object transformation since some RAW generated during the work execution will be classified as VLLW according to the contamination level. First of all, it is the secondary waste, represented by contaminated PPE, instruments and other equipment, which is not eligible for decontamination.

According to the proposals given in [161, 162], LLW should include waste, the disposal of which in near-surface storage facilities equipped with the multi-barrier protection system will give the possibility to achieve the safety goal with a duration of management control of not more than 300 years. LLW class approximately corresponds to the type of “short-lived waste” according to the accepted classification [144, 157]. In compliance with the IAEA recommendations [160], the maximum permissible total specific activity of α -emitting radionuclides of 4,000 kBq/kg (in the separate package) at the end of management control under 400 kBq/kg in the average for the storage facility is accepted as the upper limit of LLW class.

Thus, a significant part of the RAW of the Shelter object, which in compliance with the documents [144, 157] is classified as short-lived waste, after the introduction of the suggested classification scheme will be included to VLLW.

According to the suggested modified classification [161, 162], ILW will include RAW subject to disposal in the storage facilities at the intermediate depths or great depths with HLW. ILW class approximately corresponds to the “long-lived waste” [144, 157] type. It is recommended to use the specific activity of α -emitting radionuclides (at least 4,000 kBq/kg) as the lower limit of reference to ILW. The upper limit is determined by the level of the heat release up to 2 kW/m³.

In keeping with such a classification system, ILW will include a significant part of the Shelter object waste. HLW will include RAW, which can be disposed only in the deep storage facilities; they are characterized by the high specific activity (10^4 — 10^6 TBq · m⁻³), higher than 2 kW/m³ of heat release and high content of long-lived radionuclides.

The previous results of calculations [164] showed that the heat release of FCM in 2060 will be 0.36 kW/m³ and in 2120 — 0.12 kW/m³. Thus, at the time when FCM is most likely to be retrieved, according to the suggested modified classification [161, 162], there will be no HLW in the Shelter object that will require disposal in the stable deep geological formations. FCM can be classified as ILW (according to [161, 162]) and disposed in storage facilities at medium depths.

The Law of Ukraine [163] gives the following definition for the storage facility at the medium depths: it is the structure built at the depth of several dozens to hundreds of meters

from the ground surface to provide the maintenance and isolation of RAW from the biosphere. Adoption of the Law of Ukraine [163] creates prerequisites for the introduction of the corresponding changes to the other normative documents in the field of RAW management, in particular to NRBU-97/D-2000 [144] and OSPU-2005 [157].

The implementation of a modified RAW classification system suggested according to the results [161, 162] will positively influence the further Shelter object transformation, since it will help to significantly reduce costs for RAW disposal due to the use of more economical options of their isolation from the biosphere.

6.2 Dismantling of the Shelter object unstable structures

6.2.1 Conceptual designs on the dismantling of unstable structures

According to the results of on-site inspections and calculated assessments of the technical state of the Shelter object building structures, there were identified structures with an unacceptably high probability of collapse (so-called unstable structures).

Implemented in 2004—2008 urgent stabilization measures will provide an acceptable safety level of the Shelter object taking into account the 15-year operation term of the stabilized structures (to the end of 2023). In the future, the problem of unstable structures should be resolved by their dismantling inside the NSC. The necessity in the dismantling of the Shelter object unstable structures is due to the following reasons:

- the possibility of the structures collapse even in conditions of operation inside the NSC is high enough and will increase each year.

- in case of a potential collapse of unstable structures, radioactive dust and aerosols will be resuspended intensively, due to which the NSC structures and technological systems will be significantly radioactively contaminated. It will worsen the radiation situation and will lead to additional irradiation of the operating personnel, as well as cause the need for costly decontamination works;

- the collapse of unstable structures will have negative consequences for the environment since part of radioactive substances through the ventilation system and gaps will be released outside the NSC;

- the collapse of the unstable structures of the Shelter object on the damaged structures of the fourth power unit can lead to their collapse and destruction of existing engineering barriers around FCM accumulations that will have negative consequences for the level of nuclear and radiation safety;

- the collapse of unstable structures will subsequently create some problems in the activity of the Shelter object transformation since it will complicate the access to FCM with the purpose of their transfer into the controlled state, in particular retrieval.

The previous list of the unstable building structures of the Shelter object subject to the dismantling was determined during the studies at the initial stage of works provided for by

the SIP [165]. This list was made according to the evaluation of the reliability of the structures regardless of radiation consequences of their potential collapse, as well as without consideration that after the completion of the NSC construction, the seismic impact will be a decisive external factor in the assessment of failure probability of the Shelter object building structures. Other types of impact (snow, wind and tornado) lose their urgency. On this basis, the revaluation of the composition of the unstable structures subject to the so-called early or delayed dismantling was carried out [5, 166, 167].

Early dismantling is the first stage of prior works on the dismantling of unstable structures, which should start immediately after the NSC commissioning and finish by the end of 2023.

Delayed dismantling is the second stage of dismantling works, which should start immediately after the completion of the first stage and is a continuation of early dismantling.

The revaluation of the composition of the unstable structures subject to the early or delayed dismantling was carried out with consideration of the following criteria and requirements:

- if the collapse possibility is $10^{-2} \text{ year}^{-1}$ and more, the structures are subject to early dismantling;

- if the collapse possibility of responsible bearing structure is in the range from $10^{-2} \text{ year}^{-1}$ to $10^{-4} \text{ year}^{-1}$ and more, the issue on its early or delayed dismantling is resolved based on analysis of radiation consequences of collapse;

- if the possibility of structures collapse is lower than $10^{-4} \text{ year}^{-1}$, the structure is subject to the delayed dismantling;

- it is mandatory to provide the stability or dismantling of adjacent structures connected to the structures to be dismantled (for example, if the bearing structure is dismantled, the structures that support it are also dismantled).

According to the results of performed revaluation, the list of structures for the early dismantling includes 17 structures; of these 14 metal structures and one concrete eastern support of “Mammoth” beam were erected during the Shelter object construction and formed its external outline (Fig. 6.1), as well as blockages on the DS and emergency slabs of the DS surface.

The delayed dismantling included beams B1, B2, B3 and B5, a volume unit “Dog’s house”, blockages and floor slabs over room 805/3, reinforced concrete wall along the axis 50 above the mark +49.00 (Fig. 6.2).

The developed conceptual designs on dismantling of the Shelter object unstable building structures [168, 169] determine the volume and sequence of dismantling, offer the principal technological schemes on the management of different types of RAW, and also provide:

- creation of infrastructure for the dismantling of unstable structures inside the NSC;

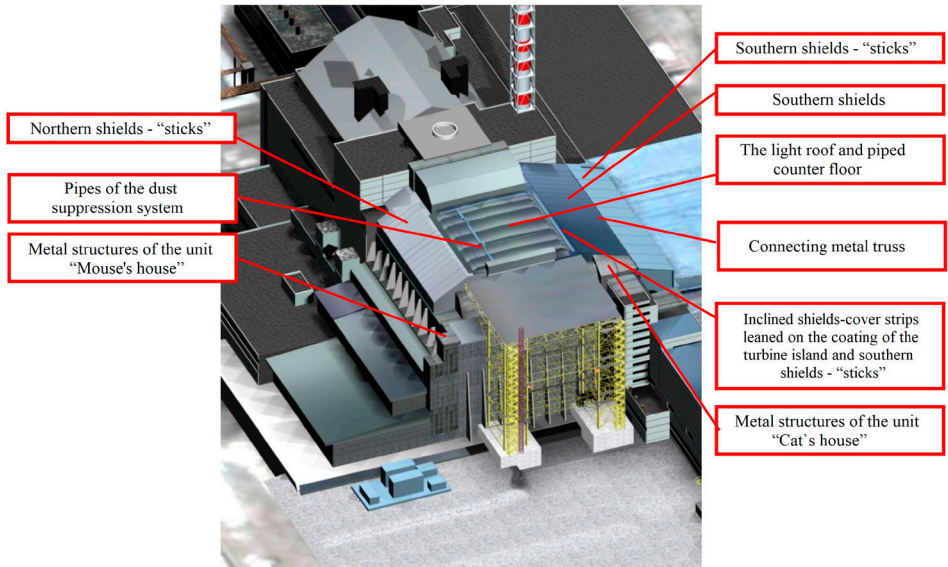


Fig. 6.1 — The list of structures for the early dismantling

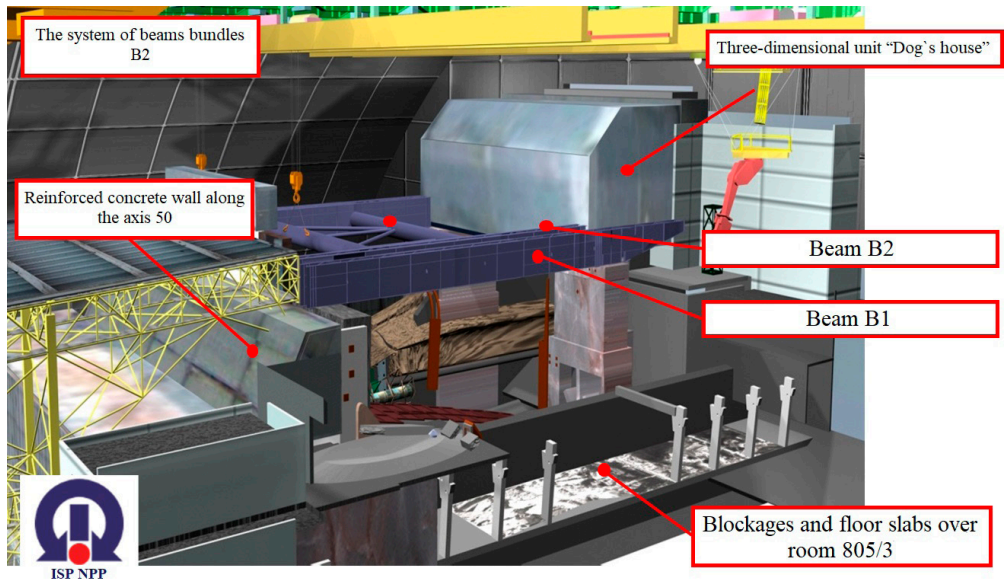


Fig. 6.2 — The list of structures for the delayed dismantling

extension and modernization of the available RAW management infrastructure at the Chornobyl NPP site for the management of RAW of all types, especially HLW, the formation of which is predicted during the blockages dismantling at the upper marks of the Shelter object;

the possibility of temporary storage of RAW, which does not meet the criteria for acceptance of RAW for the disposal at the storage facility “Buryakivka” or complex “Vektor”, on a special site located inside the NSC (near the pioneer wall along the turbine island).

Structures subject to the dismantling are radioactively contaminated and hence are classified as RAW. The formation of four main fluxes of RAW is expected:

1. Radioactively contaminated metal structures are massive structure elements installed after the accident. They have significant dimensions and require a large amount of work on fragmentation for the possibility of further management.

2. Radioactively contaminated reinforced concrete structures are large elements of the concrete and reinforced concrete structures of the destroyed fourth power unit and supporting structures of the Shelter object. These structures can be in their design places, as well as in blockages.

3. Mixed RAW is fine fragments of building structures, systems and communications formed due to the accident of 1986; materials used during the elimination of consequences (filling materials thrown from the helicopters, “fresh” concrete and sacks with concrete mix used during the Shelter object construction); materials formed as a result of stabilization measures, etc. Mixed RAW has mostly volumetric contamination.

4. HLW are fragments of structures and blockage elements, which by the radioactive characteristics classified as highly active RAW.

Objects (sites) within the NSC, where management of dismantling RAW will be conducted, are shown in Fig. 6.3

Since the dismantling of unstable structures will be conducted in the conditions of the Shelter object with a difficult radiation situation and the presence of other hazardous factors (risks of destruction of the damaged structures and some elements, altitude difference, the existence of holes, etc.), it is necessary to implement comprehensively balanced technological solutions on the organization of safe dismantling and selection of effective measures for the support of radiation protection of personnel and the environment. To implement such tasks, the ISP NPP offers to use up-to-date methods of computer simulation, which provide:

- the spatial simulation of building structures of the Shelter object and NSC, technological operations on the dismantling of unstable structures and RAW management using computer-aided design system and three-dimensional graphics and animation;

- the simulation of radiation conditions in work areas (WA);

- the simulation of the personnel transportation to the WA and implementation of their planned operations with consideration of timetable;

- the calculation of the accumulated doses of the personnel during work performance.

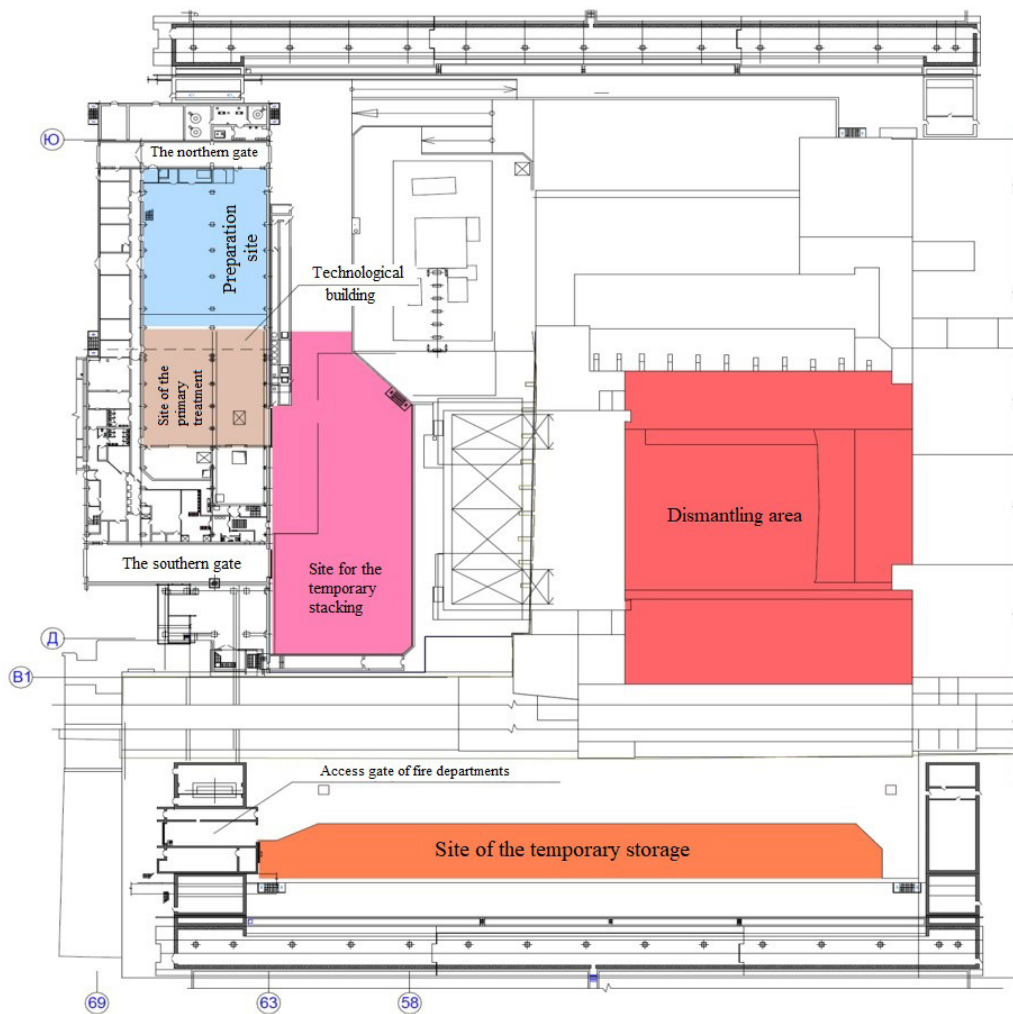


Fig. 6.3 — Objects (sites) for radioactive waste management

For example, to simulate radiation conditions, technological operations and assessment of the personnel doses during the dismantling of metal reinforcement truss of the Shelter object, the software package HVRC VRdose Planner, developed by the Institute for Energy Technology (Norway), was tested. Using the software package, the alternative scenarios of dismantling were simulated and comprehensively analyzed, and the best scenario of safe work with minimum radiation impact on the personnel and environment was selected.

The Shelter object state after step-by-step implementation of the early and delayed dismantling is shown in Fig. 6.4.

Despite the positive results related to the significant decrease of risk of the Shelter object structures collapse after the unstable structures dismantling, there are still negative ones. Structures to be dismantled currently act as barriers towards the emission of ionizing radiation and radioactive particles outside the Shelter object. According to the data [86], after the dismantling of unstable structures, the dose rate in some areas of the NSC service will increase approximately three times, and radioactive dust will be the main source of contamination of the NSC structures and equipment. Therefore, there is a necessity for urgent retrieval and/or shielding of the open FCM accumulations localized at the upper marks of the uncovered Shelter object.

After the implementation of the unstable structures dismantling, the problem of reliability of the Shelter object building structures will be resolved only partially. The reason is that planned dismantling is predominantly concerned with structures, which form the outer shell of the Shelter object. There is much less information on the technical state of the internal structures of the destroyed fourth power unit, in particular, the structures of rooms where FCM are concentrated. The goal-seeking research in this direction was not conducted due to the high radiation level and lack of access. The significance of obtaining such information is because possible destruction of internal structures can lead to unacceptable radiation consequences for personnel and the environment.

Taking into account the results of inspections of the internal structures of the destroyed fourth power unit conducted before 1996, we can define three zones, which characterize their technical state (Fig. 6.5):

zone 1 — structures located below the mark +12.500;

zone 2 — structures located between marks +12.500 and +35.500;

zone 3 — structures located above the mark +35.500.

Available data shows that there is no significant damage to the bearing structures up to the mark +12.500 (zone 1) except local destructive breakdowns of the upper layer of the concrete of the lap under room 305/2 as a result of high-temperature impact and cracks in one of the walls. Lack of the significant damage is explained by the fact that the constructive solution of the reactor room building up to the mark +12.500 is carried out in the form of the hard volumetric structure of the cast-in-situ reinforced concrete. Rooms located up to the mark +12.500 form the system of hermetic rooms (so-called strong-hermetic boxes) with bearing structures more than 1 m thick. Therefore, we can make a preliminary conclusion that the reliability of these structures will be maintained during the NSC lifecycle, as well as for a longer time.

Bearing structures of the reactor room located above the mark +12.500 (zone 2) are the combination of precast and cast-in-situ reinforced concrete structures (in the central part) and precast structures (at the peripheral area). These structures have sustained greater

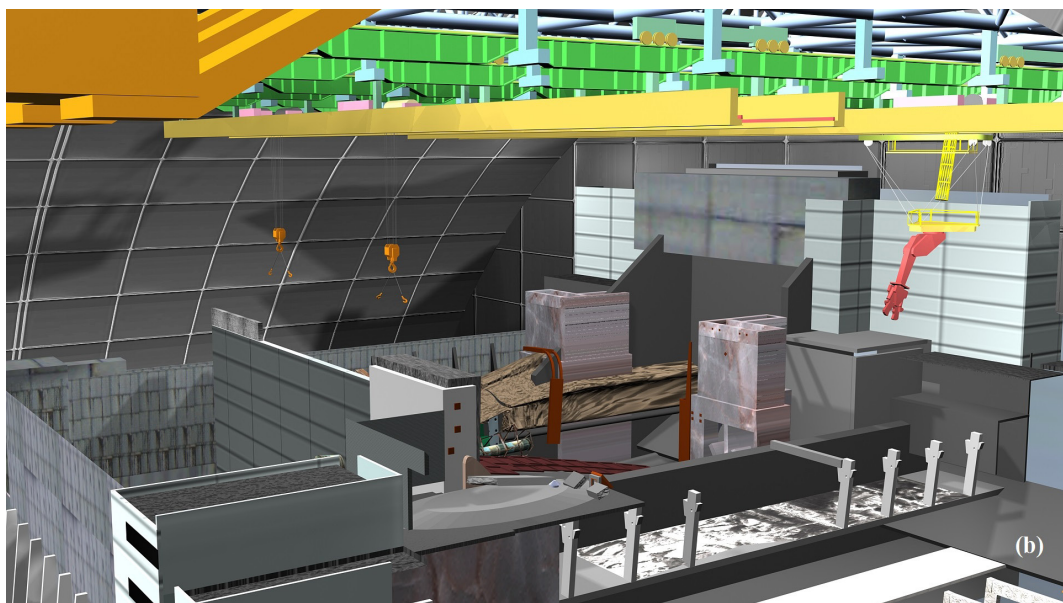
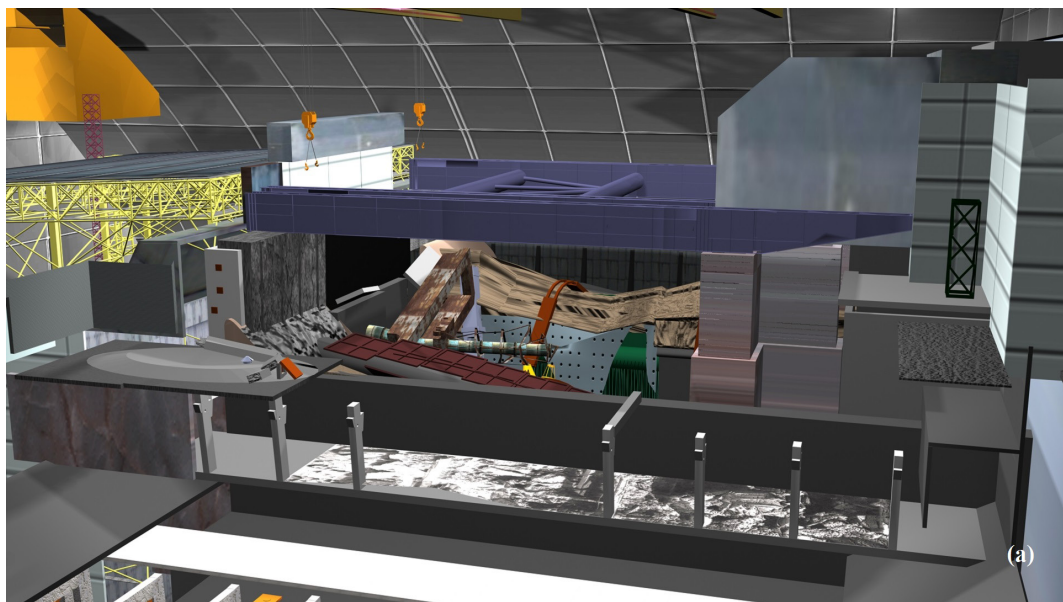


Fig. 6.4 — View of the Shelter object at the different stages of the unstable structures dismantling:
a — after the early dismantling; *b* — after the delayed dismantling

damage/destruction compared to the structures below. From the mark +12.500 to the floor level of the central hall (mark +35.500), the most problematic is the state of the laps structures at the mark +30.900 (the lap under the southern and northern steam-drums), as well as at the mark +35.500 (at the sites of the central hall, in particular above the cooling ponds rooms), which is due to damages of the slaps structures as well as a considerable load from blockages on these structures. It is almost impossible to stabilize the structures (extremely difficult radiation situation, lack of access paths, etc.). The most promising variant of their reliability improvement is load decrease on them due to blockages removal and dismantling of the damaged and destroyed structures located above (zone 3). It is possible only after dismantling of the Shelter object unstable structures using the NSC main cranes system.

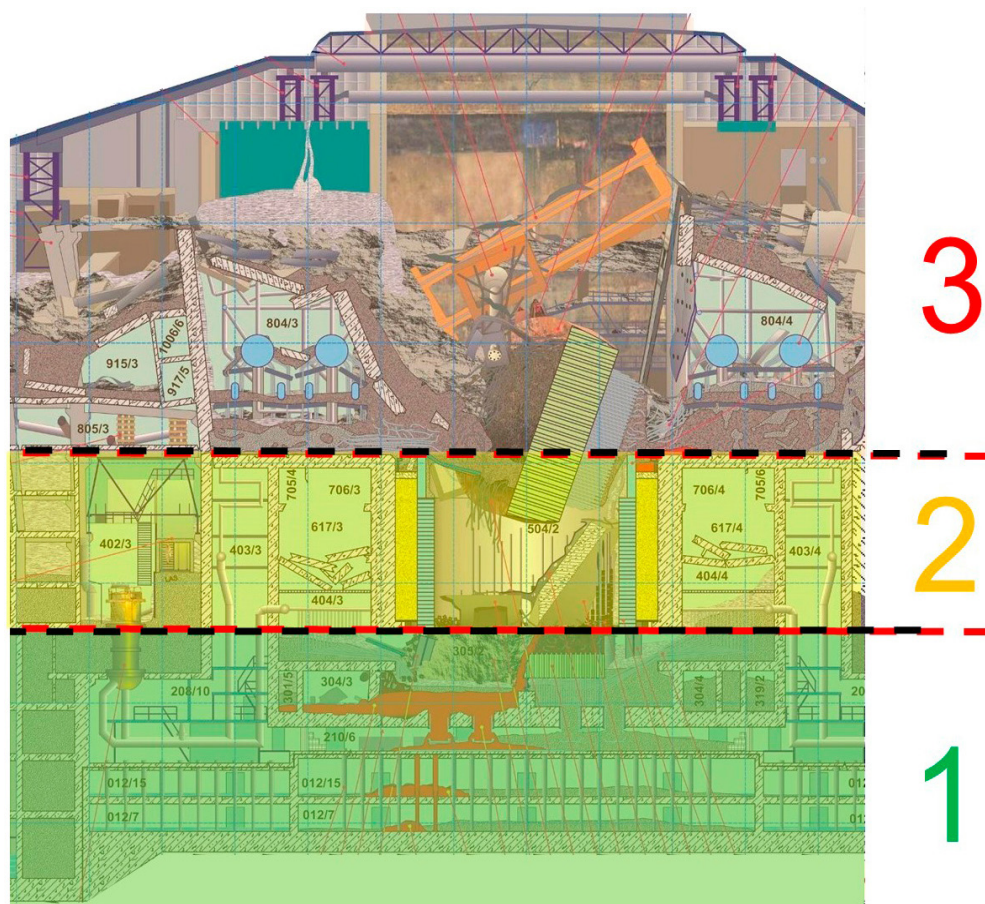


Fig. 6.5 — The state of building structures of the destroyed fourth power unit

The particular problem is the unstable position of the upper slab of the biological shield of the reactor (“E” scheme) [170]. In time, the possibility of the “E” scheme collapse into the reactor pit increases, in particular as a result of the corrosive damage development. The collapse can destroy the lower structures. It should be noted that currently no geodesic or other observations of the “E” scheme state is conducted.

Summarizing what has been said, the following plan of the further actions for the next 30—50 years is suggested:

- creation of the infrastructure for the Shelter object unstable structures dismantling, in particular, the infrastructure for FCM treatment, which will be found during the dismantling;

- dismantling of the Shelter object unstable structures;

- retrieval and/or shielding of the intensive ionizing radiation sources (FCM fragments), localized on the upper marks of open sites of the uncovered Shelter object;

- dismantling of blockages and damaged and destroyed structures of the fourth power unit located on the upper marks (above the floor of the central hall). During the dismantling of blockages, FCM and other HLW will be found, which should be taken into account when planning the organization of such work. The experience gained will be extremely useful for the further activity on the other FCM accumulations retrieval during the Shelter object transformation into an ecologically safe system.

6.2.2 Dismantling of the connecting metal truss

The connecting metal truss (hereinafter — metal truss) was installed during the stabilization of the Shelter object southern roof to connect flat shields and shields-sticks (Fig. 6.6).

According to the results of conducted revaluation of the composition of unstable structures subject to the early or delayed dismantling, the metal truss was included in the list of structures for the early dismantling. It should be noted that the technical state of the metal truss is wholly satisfactory, and the need in its early dismantling is conditioned only by the technological factors: without it, it is impossible to dismantle other structures of the Shelter object southern zone, referred to the early dismantling (southern shields, southern shields-sticks, “Mammoth” and “Octopus” beams).

Project of the metal truss dismantling is the first in the list of projects on the dismantling of the other unstable structures subject to the early dismantling. One of the tasks on the development and implementation of this project is to present the possibility and effectiveness of the use of infrastructure created within the NSC, as well as to substantiate the need for the additional equipment of the NSC sites/systems for the dismantling of the Shelter object unstable structures.

The general view of the metal truss in the design position is shown in Fig. 6.7.

The metal structures of the reinforcement truss on the Shelter object roof are located on the same site with the pipelines of the MDSS and ladders on the access paths to its input injectors. Therefore, the special bridges were fastened to go over through the truss metal structures to the ladders of the MDSS (Fig. 6.8). During the stabilization of the Shelter object

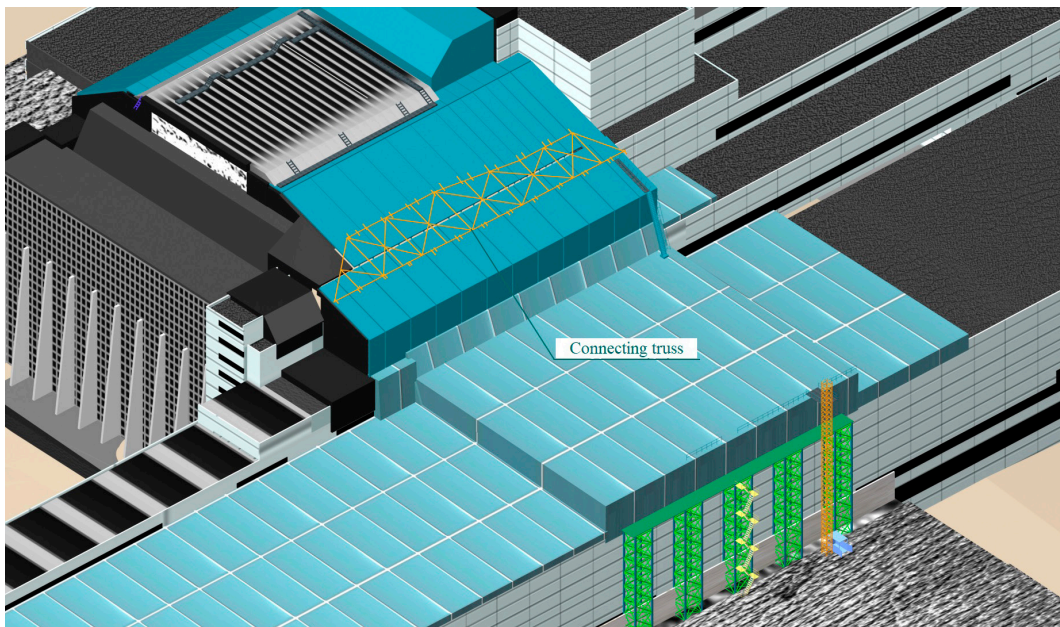


Fig. 6.6 — Metal truss on the southern roof of the Shelter object

southern roof, in addition to the metal truss, longitudinal ladders of the access paths with handrails, bridges for the passage through the top or bottom chord of the truss, a bridge for the passage through the diagonal member of the truss were additionally assembled.

Technological designs for the dismantling and a set of measures on the support of the personnel radiation protection were introduced in the project on the metal truss dismantling [171, 172].

It is proposed to dismantle the metal truss using the NSC systems, in particular, the MCS of the NSC and equipment that will allow carrying out technological operations remotely, i.e. with minimum involvement of personnel. One of the main technical means of dismantling will be the MIP of the MCS. The MCS is equipped with a mechanical arm with a radius of 6.7 m. The mechanical arm can remotely replace hinged instruments and equipment for technological operations (tinsnips, disk saw, air plasma cutter, equipment for air plasma cutter).

To provide safe access for personnel in the zone of metal truss dismantling and temporary stay during technological breaks in work it is planned to install a shielded cabin. The cabin will have a special tie-down point for its unchangeable orientation in the east-west and north-south directions that will promote the maximum effective use of biological protection against known radiation sources of the Shelter object.



Fig. 6.7 — Metal truss in the design position



Fig. 6.8 — Assembled metal truss with bridges for the passage to ladders and injectors of the modernized dust suppression system

The shielded cabin will be equipped with a lamp of directional light (on the external surface) and a power pack (inside), from which electric tools and devices of supplementary illumination will be turned on by extension cords in the WA. The cabin will be connected to a power supply from the hook positioner of the special wagon of the MCS, on which the cabin will be hung up.

Dismantling of the metal truss will be conducted in the radioactively hazardous conditions of the Shelter object. Radiation situation in the WA and on the access paths was studied at the stage of pre-project researches. According to the results of the carried out measurements, the cartogram of γ -radiation DR on the southern roof of the Shelter object was created (Fig. 6.9). By the results of the carried out researches (Fig. 6.10), it was determined that general β -active contamination of the external part of the southern shields and southern shields-sticks changes in the range from 4,000 to 10,000 $(\text{cm}^2 \cdot \text{minute})^{-1}$; and the removing surface radioactive contamination is 15—310 β -particles/ $(\text{cm}^2 \cdot \text{minute})$ and up to 3 α -particles/ $(\text{cm}^2 \cdot \text{minute})$.

Angular distributions of the γ -radiation intensity at the specific workplaces on the metal truss dismantling were not studied. The main directions of the γ -radiation forming the DR

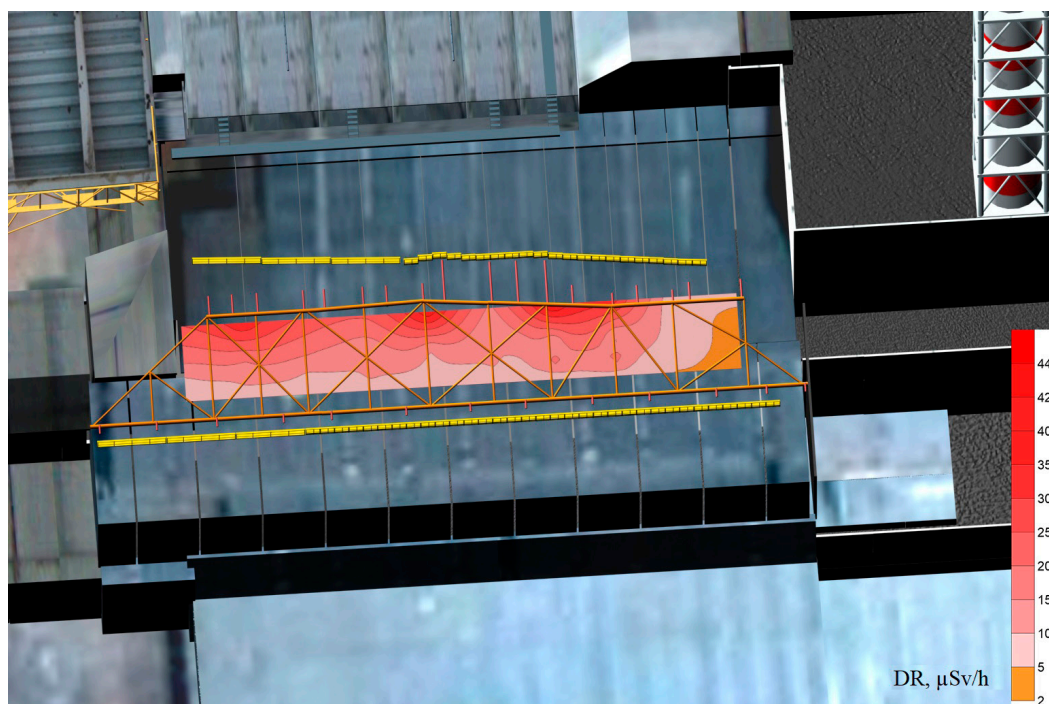


Fig. 6.9 — Cartogram of the γ -radiation dose rate in the work area



Fig. 6.10 — Measurement of the surface radioactive contamination:
a — measurement of the total surface radioactive contamination;
b — a sampling of the smear from the area of 10 cm²

at the workplaces were assessed by the materials of the previous measurements (during the project implementation on the Shelter object building structures stabilization, the NSC construction, etc.), using the DKS-04K and ShD-1 devices. The scheme of location and coordinates of the measurement points of the angular distributions of γ -radiation intensity is given in Fig. 6.11, and measurement results in points 1—8 are in Figs. 6.12 and 6.13.

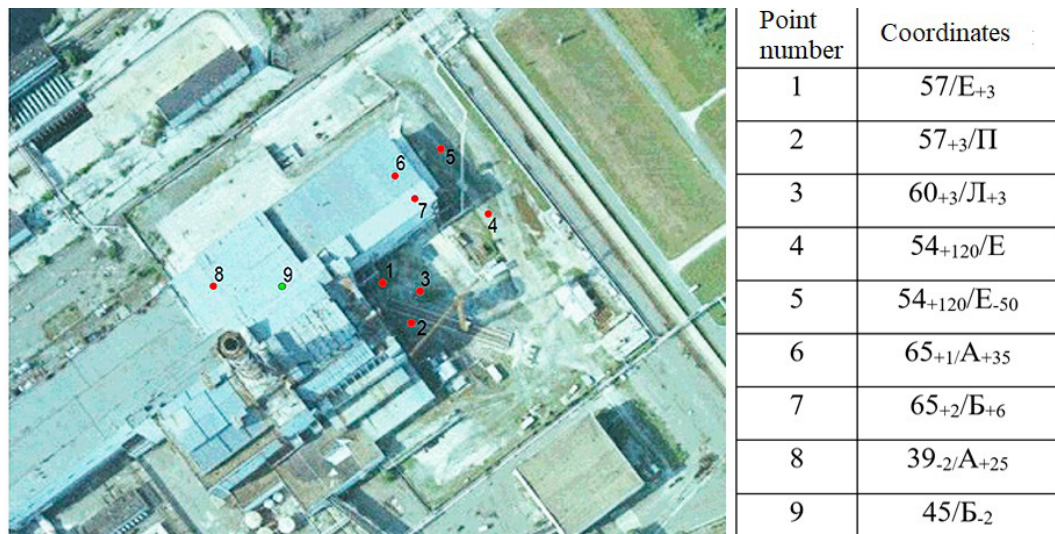


Fig. 6.11 — Location of measurement points of the γ -radiation angular distribution

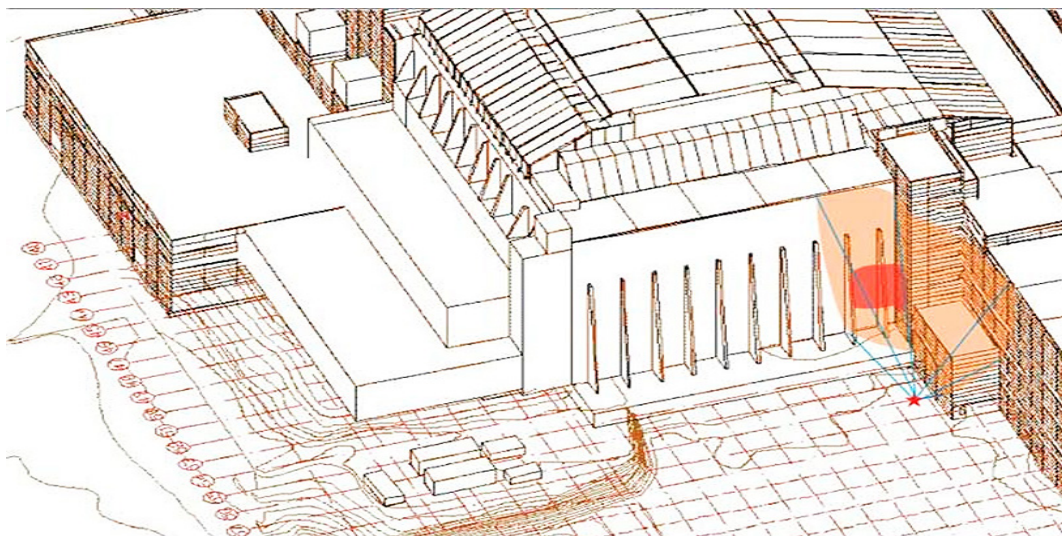


Fig. 6.12 — The direction on the major radiation sources,
which form the DR in point 1

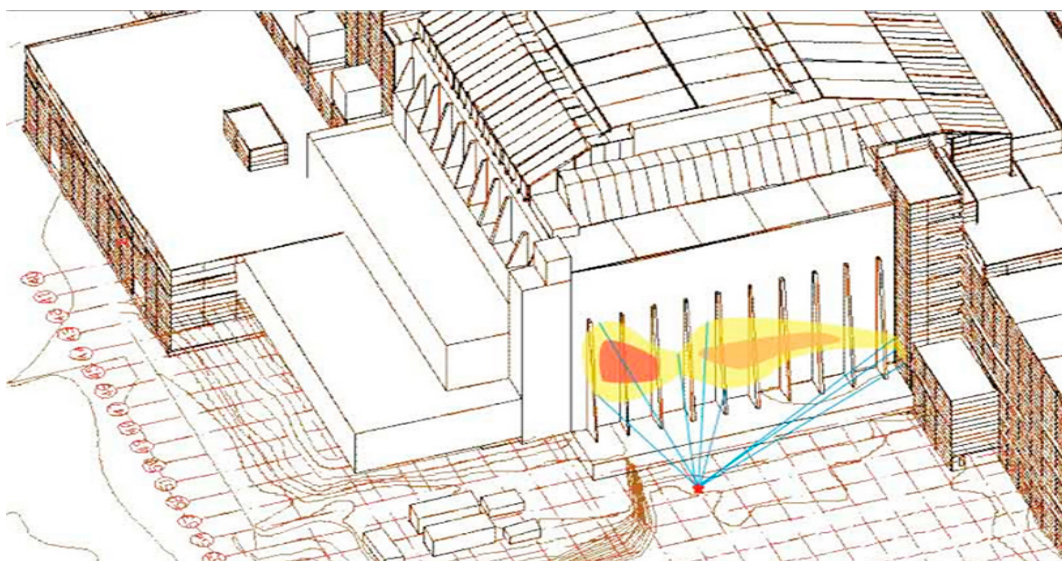


Fig. 6.13 — The direction on the major radiation sources,
which form the DR in point 2

Obtained data shows that in the WA at the site of temporary storage (points 1—3), the DR is formed basically by the radiation sources located in the direction of CH (on the east in the horizontal plane at the angle of 45° above the skyline — the center of the buttress wall as well as near the ladder-elevator unit).

The measurement results at points 4—8 define mostly the main directions, in which doses are formed along the access paths to the WA.

Angular distributions in the WA on the south roof of the Shelter object were determined according to the measurement results in point 9, obtained during studies before the metal truss erection. It was determined that the main sources of the γ -radiation are located in the north (near the cooling ponds in the CH) and to a less degree in the north-east (location of sources which are under the “Dog’s house” structure).

One of the main factors of the radiation impact on personnel and the air in the space under the NSC will be the high RA concentrations in the air due to the mechanical impact on the surfaces of the contaminated structures and equipment. Thus, the main source of the air contamination and further contamination of other components in the space under the NSC are surfaces of rooms and equipment contaminated by radioactive substances during work using the technological equipment.

Taking into account the special hazard of works related to the contaminated metal structures cutting, it was proposed to assess their contribution to the RA concentration with the assumption that all the surface contamination from the area of the intensive impact will transfer into the aerosol form during the cutting and the aerosol will be evenly distributed between the volume of the WA and airflow, which is evacuated by the ventilation system. Then according to the proposed approach, the RA concentration in the air of the WA during works can be calculated by the following formula

$$C = S \cdot d \cdot L / (V + qt),$$

where S is the surface contamination density in the place of cutting, Bq/m²; d is the width of the active heating (processing) zone, m; L is the weld length, m; V is the volume of the working area, m³; q is the flow rate of the NSC exhaust ventilation system, m³/h; t is working time, h.

According to the results of calculations [171], the forecasted RA concentration in the WA during the plasma cutting was taken at the level of 1.23 Bq/m³, which is significantly lower than the control level of 9 Bq/m³ for β -active nuclides [173]. Such an increase of the air activity in a short period (dismantling time) will not lead to the considerable worsening of the radiation situation inside the NSC arch. Besides, to reduce the RA formation, it is recommended to decontaminate the cutting areas.

We should emphasize that the study of the radiation situation in the area of the metal truss dismantling and on the access paths was carried out before the NSC installation in the

design position and build up of the sites inside the NSC. Therefore before the dismantling of the metal truss as well as other unstable structures, it is necessary to conduct new studies to specify the radiation situation.

To provide the radiation protection of the personnel who will dismantle the metal truss, a set of organizational, radiation-sanitary and technical measures were developed and substantiated. The organizational measures include personnel training, development of specific procedures on the organization of safe dismantling, constant control over the following requirements of radiation and technical safety. It was taken into account in the measures on the radiation safety support that dismantling is an activity with open sources of ionizing radiation.

The radiation-sanitary and technical measures include radiation and medical monitoring; application of PPE; organization of the sanitary-inspection regime; shielding; use of remotely controlled equipment; decontamination and dust suppression; ventilation regime; providing with personal hygiene means.

Using the available data on the radiation situation in different zones of the Shelter object, the possibility of the shielding of workplaces and access paths for the metal truss dismantling was analyzed. The analysis of technological designs for the truss dismantling, as well as radiation conditions on the access paths and directly in the WA showed:

- radiation conditions in the WA and on the access paths are sufficiently complicated, the value of DR is in the range from 40 to 39,000 $\mu\text{Sv/h}$;

- the main volume of dismantling will need application of unmanned technologies using remotely controlled equipment installed in the MIP of the MCS;

- the personnel who will dismantle the metal truss directly will deal with a much less volume of the technological operations as compared to the work carried out by the hinged equipment with remote control;

- technological operations, which will be performed by the personnel at one workplace, are short-term;

- technological operations, which will be performed by the personnel by hand, will be carried out using up-to-date high-productive equipment (cutting of metal structures) or devices for rapid erection and connection (emergency lighting);

- delivery of the shielding materials, their installation and transportation from one workplace to another will require additional labor costs and, accordingly, will lead to the additional exposure doses of the personnel.

Taking into account the sparseness of places where the works will be carried out, as well as the inconsistency of operations along with the upper and bottom chords of the truss, a decision was made on the inexpediency of using shields in the WA. Instead, considering the DR values on the access paths, the safe transportation of the personnel to the WA for the metal truss dismantling is reasonable in a shielded cabin, which will be transferred from the temporary storage site to the southern roof using the MCS.

At the temporary stacking site, the fragmentation and placement of the metal truss fragments in a transportation cask — a platform for the radioactively contaminated metal structures — are planned. Before the beginning of fragmentation, places of the metal truss cutting will be treated using the foam aerosol self-contained decontamination equipment, which minimizes the formation of additional RAW. Only a small amount of the secondary solid RAW, represented by wiping materials, will be formed, and there will be no liquid RAW at all.

Works on the temporary storage site may cause radioactive contamination of its surfaces. Therefore, after their completion, it is necessary to conduct a radioactivity survey of the site and make a decision on its decontamination.

The dust suppression (if necessary) will be carried out in two ways:

- spraying water or solution for the dust deposition in the area of the metal truss dismantling on the Shelter object roof and access paths;

- applying the solution on the fragments of the dismantled metal truss, placed in a transport container-platform on the temporary stacking site.

The volumes of the generated solid and liquid RAW and their characteristics are assessed in the project. Transport and technological schemes of the treatment with different types of RAW are developed. The predictive amount of the solid RAW, classified as the low-level RAW, is approximately 275 kg or 1.3 m³. The predictive amount of the liquid RAW, classified as the low-level RAW is the following: from the decontamination of the contaminated additional PPE is approximately 0.2 m³; from the decontamination of the personnel in the SIR-1430 is approximately 50 m³.

As a result of the calculations, the following data were obtained: labor costs for the work will be 486 people · h; the total collective effective dose is 1.075 people · Sv, of which 0.12 people · Sv (approximately 0.1%) is accounted for by the inhalation component (internal exposure).

The measures proposed in the project for the implementation of unmanned technologies for the work and organization of the personnel transportation to the WA in the shielded cabin will help to reduce the collective dose of the personnel by approximately 1.5 people · Sv.

6.3 Reconstruction of part of the deaerator stack and turbine island

After the construction of the NSC EP and installation of the arch into the design position, the part of the Chornobyl NPP, which is a part of the Shelter object, appeared to be outside the NSC. The building structures on the western and eastern sides of the NSC, which were not included in its volume, were called “protruding sections” (PS). On the western side of the NSC, the PS have a length of 18 m and include part of the turbine island and the DS. On the eastern side, the PS have a length of 30 m and also include part of the turbine island and the DS. The scheme of the Shelter object PS is shown in Fig. 6.14.

In 2012—2013, special studies on the technical state of the building structures of the turbine island and the DS were conducted and the data for the assessment of the possibility of failure-free operation of the PS building structures during the whole period of the NSC operation were obtained (100 years). Having considered the specific features of the main bearing structures, enclosing structures and materials of the PS buildings surfaces, a bearing capacity was calculated taking into account factors of weakening during the operation time after the Chornobyl NPP accident in 1986.

Based on the obtained data, it is determined that, on the one side, risks, which potentially can appear in case of uncontrolled fall of these structures, in particular radiation consequences and financial costs for elimination of the accident, and, on the other side, the level of involvement of these structures to the need of the current NSC operation make an impact on the choice of the decision on the prospect of the Shelter object PS.

The general view of the PS of the Shelter object is given in Figs. 6.15 and 6.16.

We should mention that currently many rooms of the DS are in operation. On the bottom marks of the western part of the DS, rooms are located, where the system of the LRW treatment is functioning, and rooms of the sanitary lock, ladder-elevator unit, used for the organization of access paths of the personnel in the Shelter object rooms to the DS roof and turbine island, are operated.

In most of the DS eastern rooms, main power supply cable lines are laid, transformer substations are operated, control panels are located, in particular, panels of the IACS and the physical protection and access control system. The access paths to the rooms of Unit B, unit of the auxiliary systems of the reactor room of Chornobyl NPP third power unit are laid through the DS.

Unlike the DS, in the eastern and western parts of the turbine island, there are no rooms in operation. At the same time, the protruding section of the turbine island in the west borders on the operating component of the NSC — the access gate of fire departments to the southern sector of the NSC. Any incident related to the accident of the structures of the turbine island western PS can lead to a long-term blocking of the passage under the NSC that has negative consequences. Moreover, in this part of the NSC industrial site, the aboveground lines of the NSC are held on trestles with high and low supports, which can also be damaged in case of unpredictable destruction of the Shelter object PS structures. Finally, along with the western PS, there are access paths for the personnel to the NSC entrance, for which safety must be guaranteed in all cases.

Therefore, based on the studies results of the structures technical state and calculations, it was concluded that protruding outside the NSC sections of the Chornobyl NPP do not meet requirements for the NSC structures, and hence it is necessary to reinforce or dismantle the PS structures.

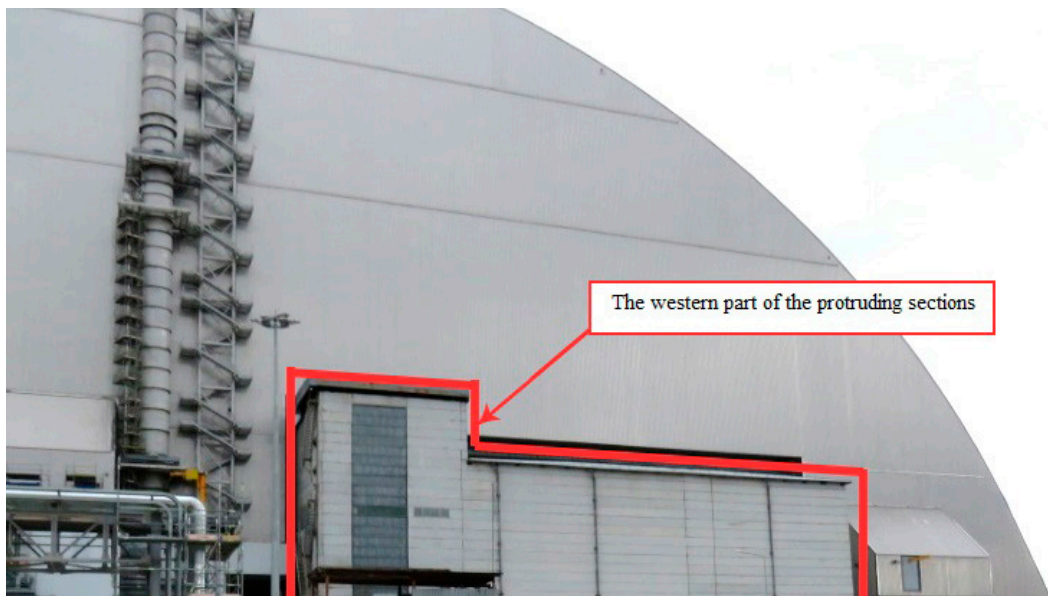


Fig. 6.15 — The protruding section of the Shelter object on the western side of the NSC

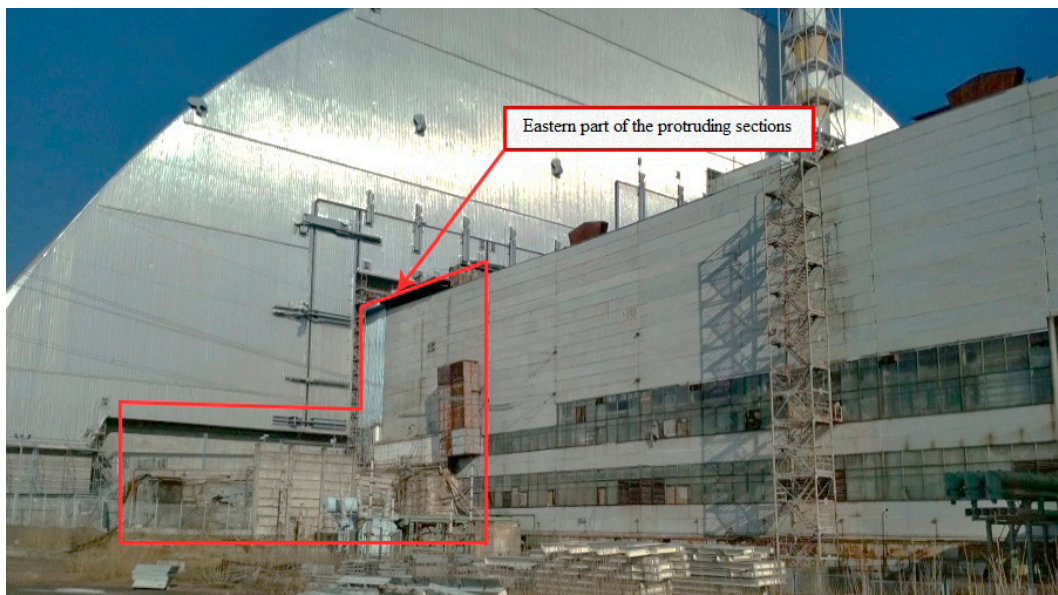


Fig. 6.16 — The protruding section of the Shelter object on the eastern side of the NSC

The following variants of the PS reconstruction with reinforcement and/or dismantling of the bearing structures were proposed to prevent possible accidents [174]:

reinforcement with partial dismantling and replacement of building structures while maintaining current marks of the turbine island and the DS (variants 13 and 1c);

reinforcement with partial dismantling and replacement of building structures while changing current marks of the turbine island building (variants 23 and 2c).

According to the technology, variants 13 and 1c of the PS reconstruction without changing the current marks of the turbine island building and for the western as well as the eastern PS have the following view in the larger scale:

dismantling of shields of the DS additional metal roof → dismantling/reinforcement of the DS roof panels, installation of a new roof → dismantling/reinforcement of wall fence panels of the DS → finishing work;

dismantling of shields of the turbine island additional metal roof → dismantling/reinforcement of the complex panels of the turbine island roof, installation of a new roof;

dismantling/reinforcement of the turbine island skeleton elements → dismantling/reinforcement of the turbine island wall fence panels → finishing work.

The technical state of the eastern PS structures, as the most remote from the accident epicenter, is better than the technical state of the same structures of the western PS, hence for the reconstruction by the variant 1c the most typical works are related to the reinforcement of the structures without their dismantling.

According to the variants 23 and 2c, the reconstruction of the DS protruding sections is similar to the variants 13 and 1c, and the change of the current marks inherent only to the turbine island building, so variants 23 and 2c are considered only for the turbine island.

The reconstruction of the western/eastern PS of the turbine island has the following sequence: dismantling of the additional metal roof shields, elements of the wall fence, complex slabs of the coating and trusses → dismantling of the skeleton elements → erection of the turbine island trusses on the shortened parts of columns → erection of the complex slabs of the coating, installation of a new roof → erection of the wall fence of the remained turbine island part → finishing work.

The general view of the western and eastern PS of the Shelter object after work conducted by one of the reconstruction variants is given using computer graphics in Figs. 6.17 and 6.18.

Taking into account difficult radiation conditions in the Shelter object premises, the proximity of the PS structures to the building and the built infrastructure of the NSC, the reconstruction of the Shelter object PS is a complicated task, which will involve the significant physical and financial costs.

The reconstruction variants of the western and eastern parts of the turbine island, which protrude outside the NSC EP are compared based on the multicriteria approach [175, 176] considering recommendations of the International Commission on radiological

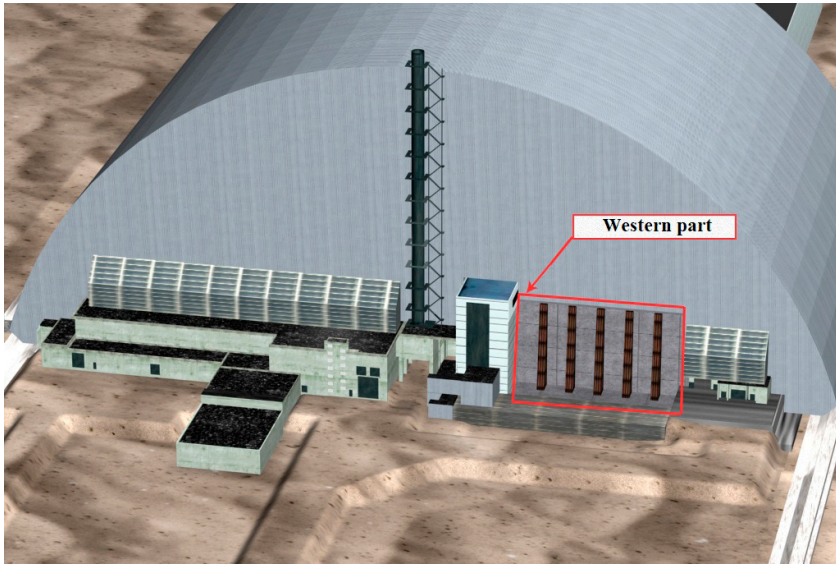


Fig. 6.17 — Protruding section of the Shelter object from the western side of the NSC after the reconstruction, variant 2s

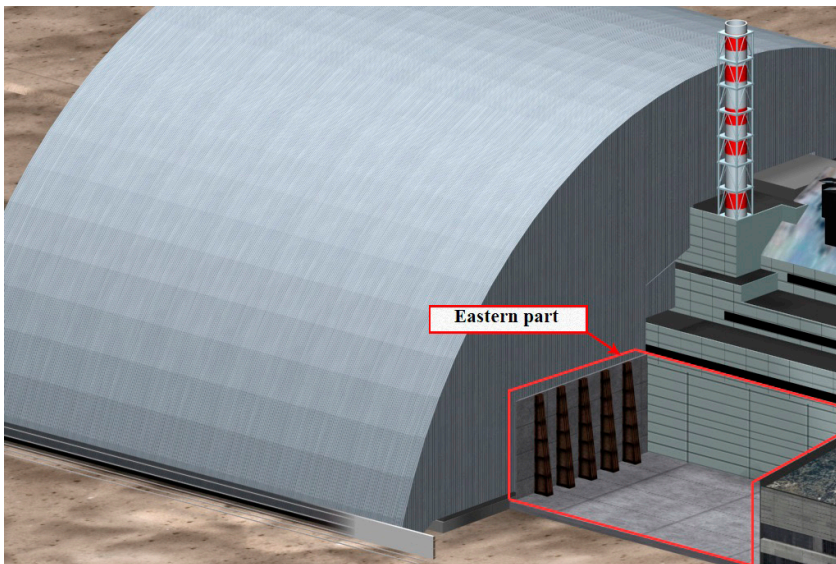


Fig. 6.18 — Protruding section of the Shelter object from the eastern side of the NSC after the reconstruction, variant 2c

protection (ICRP) and NRB-97 requirements. The essence of the method is to build the generalized indicator of the decision effectiveness in the form of the sum of the individual criteria with certain weight coefficients determining the importance of each criterion for the decision making. With this purpose for each separate criteria, a desirability function $u_j(x)$ is built, which represents the domain of variation of each criteria x in the range from 0 to 1 [174, 177]. For each variant, the generalized desirability indicator is determined as a sum of the corresponding desirability functions

$$U_i = \sum_{j=1}^n k_j \cdot u_j(x_j)$$

with the weighted coefficients k_j , which are chosen so that $\sum_{j=1}^n k_j = 1$.

The type of the desirability function u_j and values of the weighted coefficients k_j are chosen following the decision theory under many criteria.

To compare the reconstruction variants of the turbine island western and eastern parts, protruding outside the NSC EP, the following criteria were taken: C — work cost; T — labor costs for work; D — collective effective exposure dose of the personnel; R — volumes of the formed RAW; L — impact on the NSC operation; Q — the value of the risk of potential accident during works.

According to these studies and calculations of the bearing capacity of structures of the Shelter object PS, and taking into account factors of weakening for the period of the post-accident operation, failure-free functioning of the PS building structures during the whole operation period of the NSC (100 years) is impossible to guarantee. So, protruding outside the NSC parts of the Chornobyl NPP structure do not meet requirements to the NSC structure — they should be reinforced or dismantled. This problem needs resolving in the short term.

Based on the conducted analysis results of the proposed variants for the Shelter object western and eastern PS without or with the change of the turbine island project marks, chosen variants differ insignificantly on the generalized desirability indicator value, so they can be considered equivalent.

According to the results of the work, the Technical decision “On the choice of the reconstruction variants of parts of the deaerator stack and turbine island of the Shelter object protruding outside the NSC enclosing perimeter” was adopted and approved by the SNRI of Ukraine. The following plan of action was outlined in the Technical decision:

- reconstruction of the eastern and western parts of the Shelter object DS, protruding outside the NSC enclosing perimeter, should be performed by the structure’s reinforcement;

- reconstruction of the western part of the Shelter object turbine island, protruding outside the NSC EP, should be performed by the structures dismantling;

the storage site of the dismantled structures of the turbine island western part should be organized in the Shelter object turbine island rooms with further installation of a new roof;

reconstruction of the Shelter object turbine island eastern part, protruding outside the NSC EP, should be performed by the structure's reinforcement.

6.4 Analysis of the potential strategies of the Shelter object transformation

Almost immediately after the Shelter object construction was completed and accepted for maintenance, it was clear that the issue of the object safety had been resolved only for the short term. The problem of where and how to move forward became urgent.

Various ideas for the Shelter object transformation have been proposed since 1989: first of all, as part of the “Shelter-2” feasibility study, carried out by the All-Russian Scientific Research and Design Institute of Energy Technology, and later within the framework of the international competition “Kyiv-92”, for which 394 proposals were received [3]. In time, variants of the Shelter object transformation were worked out by the “Alliance” group, and later they were studied as part of the SIP tasks.

Currently, the practical activity on the Shelter object transformation into an ecologically safe system is carried out according to the requirements of the Law of Ukraine “On the general principles of the further operation and decommissioning of the Chornobyl NPP and transformation of the destroyed fourth power unit of this NPP into an ecologically safe system” [11], the Law of Ukraine “On the national program of the Chornobyl NPP decommissioning and the Shelter object transformation into an ecologically safe system” [141] and “the Strategy of the Shelter object transformation” [142]. The main result of this activity was a stabilization of the Shelter object building structures, construction, and putting the NSC into the research and industrial operation.

The construction of the NSC is an extremely important stage in the implementation of strategy on the Shelter object transformation, but it does not mean that after commissioning of the NSC the problem of the Shelter object has been finally resolved. To transform the Shelter object into an ecologically safe system, it is necessary to take many more scientific and technical measures to reach the final goal — to transfer FCM into the controlled state [8]. FCM accumulations formed due to the beyond design-basis accident at the fourth power unit, and in the future will be the source of the Shelter object hazard. By its state and composition, FCM is long-lived RAW, and some FCM accumulations are nuclear hazardous. Therefore, if FCM remains inside the Shelter object in an uncontrolled state, it can never be exempted from the nuclear regulation and control at all.

For today, FCM retrieval is the condition of the Shelter object transformation into an ecologically safe system and its decommissioning. The transition to the Shelter object decommissioning can be considered complete only when FCM is transferred to the nuclear

safe state and placed into the controlled storage or transferred for disposal in stable geological formations.

According to the “Strategy of the Shelter object transformation” [142], work on FCM retrieval should be carried out at the final third stage of the Shelter object transformation into an ecologically safe system.

Within the framework of the SIP, the ways of solving the problem of FCM retrieval and further treatment were considered in the tasks of “Study and development of the strategy of FCM retrieval and RAW management” and “Development of FCM retrieval technology”. According to the results of these tasks in December 2000, the program decision was taken [178], where the preliminary strategy of FCM retrieval and RAW management was determined. The main provisions of the strategy are as follows:

- to retrieve FCM during the NSC operation term;

- time of retrieval is 40...50 years;

- to consider a transfer of FCM and other long-lived RAW to the storage for the final disposal in the stable geological formations as a prior task;

- to start selective FCM retrieval after the Shelter object unstable structures dismantling and completion of testing of FCM retrieval technologies;

- to start the mass FCM retrieval after solving the issue of their storage or disposal.

The decision [178] was considered preliminarily under the condition of its confirmation by the results of a demonstration experiment on FCM retrieval, which is registered in the program decision [179], adopted in 2001. But, in the document “Strategy of treatment with FCM and radioactive waste of the Shelter object. Plan of further actions” [180], which was adopted in 2005 and approved by the SNRIU, it is stated that:

- currently, there are no new data on the application of new FCM retrieval technologies, based on which on the conceptual level it is possible to revise the previous strategy of FCM retrieval, therefore it is useless to continue concept research of the strategy and FCM retrieval technology;

- at the current stage of the SIP implementation, no additional information has been received on FCM, which would allow deciding on their early dismantling; available information on the long-term FCM treatment indicates the need in the development of the monitoring and FCM state control program before and during their retrieval;

- detailed design and demonstration of a prototype of the FCM retrieval technology are impractical considering their cost and schedule.

At the same time, the document [180] provides a program of actions for reaching the key solution as follows:

- for the period before taking the key program decision during the stabilization of the Shelter object building structures, the NSC construction and early dismantling of the Shelter object unstable structures, RAW management, in particular, FCM will be determined within the framework of “Integrated program of radioactive waste management at the stage

of the Chornobyl NPP decommissioning and the Shelter object transformation into an ecologically safe system”;

according to the results of conducted tasks of the SIP, input data will be obtained for the development and installation of the FCM behavior control system and creation of systems, to support the optimal temperature and moisture for storing FCM inside the Shelter object; it makes it possible to obtain operative information on the negative trends of FCM behavior;

a predictive model of FCM behavior, as well as data, obtained using the FCM behavior control system and nuclear safety control system will allow taking timely preventive measures aimed at reducing the risk of adverse consequences of FCM state worsening, as well as making the decision on early FCM dismantling; based on the predictive model and results of FCM control, the strategy of FCM retrieval and RAW management will be updated.

The feature of the current situation is that the development of the Shelter object transformation scenarios must take into account constructive, space planning and technological design of the NSC. Taken decisions on the NSC at most meet requirements, stated in the Law of Ukraine “On the general principles of the further operation and decommissioning of the Chornobyl NPP and transformation of the destroyed fourth power unit of this NPP into an ecologically safe system” [151], which states: “The confinement is a protective structure that includes the set of technological equipment for fuel containing materials retrieval from the destroyed fourth power unit of the Chornobyl NPP, radioactive waste management and other systems, designed for the transformation of this power unit into an ecologically safe system and ensuring the safety of personnel, population and the environment”. However, the NSC was constructed in the condition of the lack of a determined strategy for further retrieval and FCM treatment. The key requirement to the NSC was the reservation of the technological space to place and use technological equipment for FCM retrieval and future treatment. Thus, on the whole, the NSC creates the basis for FCM treatment (protective structure of the NSC, MCS, the system of ventilation and electricity supply, and other technological systems).

The potential hazard of FCM may increase with time due to the spontaneous destruction of LFCM surfaces with the formation of high active dust, becoming not only local but also global nature. Therefore, it is extremely important to retrieve and condition FCM before their destruction becomes large-scale [65].

It should be stated that the building of several sealed barriers to prevent the impact on the environment is a mandatory condition of the spent nuclear fuel safe storage. The NSC is not a sealed structure, so the risks of the impact of the fourth power unit’s nuclear fuel residues on the environment will remain until it is retrieved from the Shelter object.

We should repeat that the construction of the NSC does not completely solve the problem of the Shelter object transformation. The guaranteed lifetime of the NSC operation is only 100 years, and the half-life periods of nuclear materials contained in it are many orders

of magnitude larger; therefore, the hazard for the environment will remain for millennia. If this problem is not addressed, its solution will be passed on to future generations. So, it is extremely important to develop and substantiate the strategic directions of the Shelter object transformation into an ecologically safe system immediately after the NSC is put into operation.

The issue of FCM retrieval from the Shelter object and their further treatment were studied in various aspects [30, 168, 181—191]. Currently, three main strategies of the Shelter object transformation are considered:

- in situ disposal by filling with concrete or other mixtures;
- temporary isolation with the purpose of the delayed FCM retrieval;
- step-by-step FCM retrieval.

Let us analyze the advantages and disadvantages of each of them.

The variant of “*in situ disposal*” (Fig. 6.19) has the oldest history and was proposed in various versions long before the decision to construct the NSC. At first, such a scenario seems to be acceptable for relatively quick solving of the problem of the Shelter object transformation. But only at first glance. This scenario is characterized by shortcomings from the construction point of view as well as non-compliance with requirements of nuclear, radiation and environmental safety, in particular:

- filling with concrete of the Shelter object rooms will lead to the significant overload and subsidence of the ground base, and consequently to the significant deformations of the damaged structures of the fourth power unit, as well as mutual structures of the third power unit in it with their possible destruction. It will negatively impact the structures state, which serves as the NSC EP, as well as on the NSC foundations (Fig. 6.20), and can decrease indicators of the operational reliability of the NSC (in particular make the operation of the main cranes impossible), and at worth to the NSC arch destruction;

- concrete pouring of FCM accumulations makes it impossible to reliably control the state of nuclear materials, which does not meet the requirements for ensuring nuclear safety;

- even in the case of successful implementation of the variant of “*in situ disposal*”, the problem of the Shelter object safety can be solved only in the short-term prospect; such a structure is not long-lived even with the quality concrete pouring of rooms, which is almost inaccessible in the condition of the Shelter object;

- in situ disposal can not be considered as the final state of the ecologically safe system of the Shelter object, since this variant does not provide reliable isolation of FCM and other long-lived RAW for the entire period of their hazard to the environment and in no case meet requirements of the regulatory legal acts in the field of the radiation and environmental safety;

- besides, a logical question arises: why was it necessary to create an extremely expensive NSC, if concrete pouring of the Shelter object rooms can be done without it?

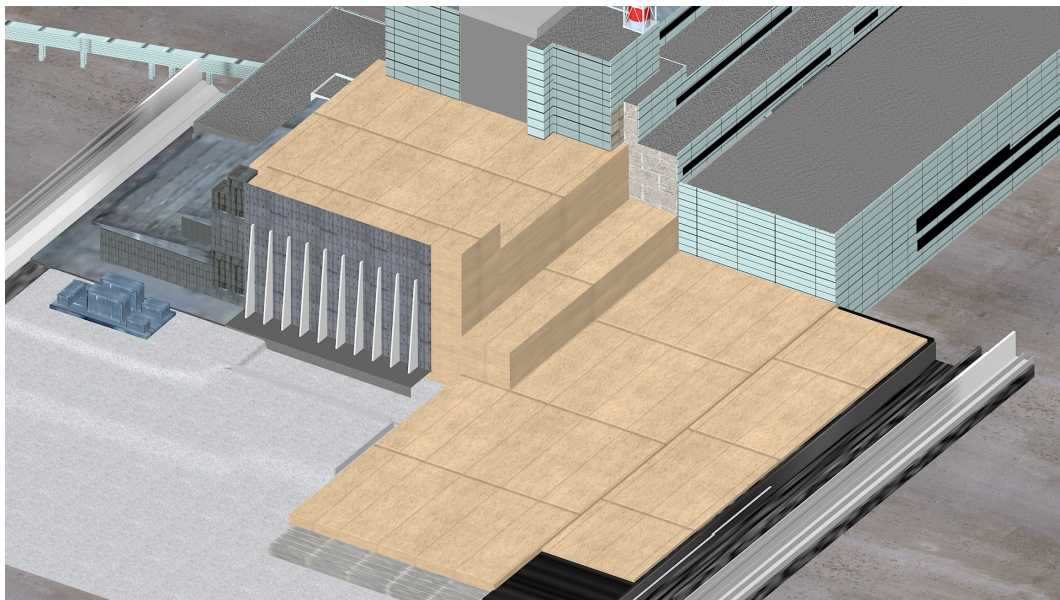


Fig. 6.19 — The variant of “in situ disposal”

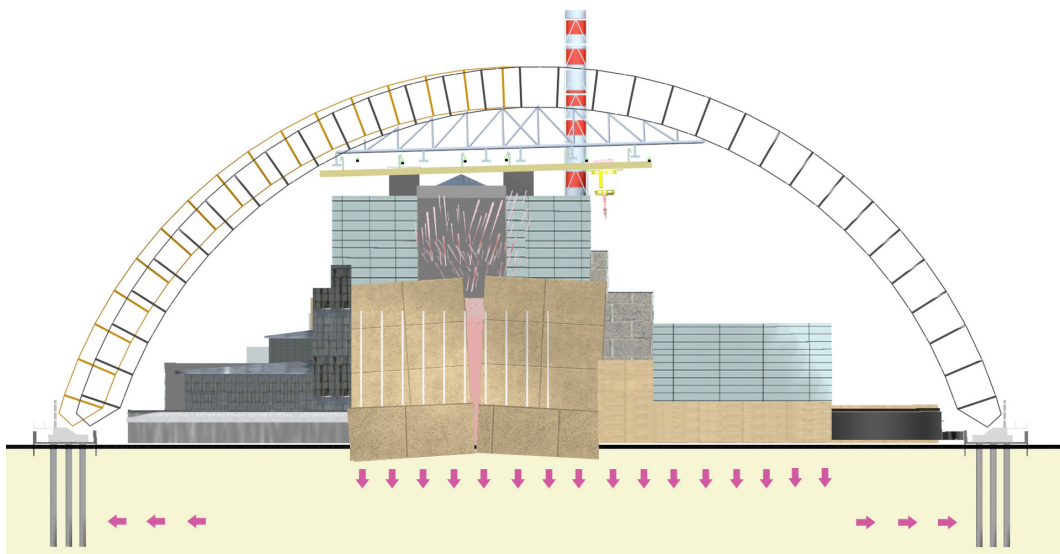


Fig. 6.20 — Overloading and subsidence of the ground base

The variant of “*temporary isolation*” also involves filling the Shelter object rooms with concrete or other mixtures, but in less amount, considering the need to provide FCM isolation for a certain time. As compared to the variant of “*in situ disposal*”, the variant of “*temporary isolation*” means the creation of additional barriers around FCM accumulations only and their further retrieval (Fig. 6.21). It is the variant of the delayed solving the Shelter object problem with aggravating circumstances caused by the creation of the additional circumstances in the future activity (the complexity and scope of work on the Shelter object dismantling increase significantly after its concreting, and volumes of formed RAW also increase accordingly, etc.).

The variant of “*step-by-step retrieval*” involves prior retrieval of the most hazardous FCM accumulations during the NSC lifecycle. Part of less hazardous FCM can be retrieved during the NSC lifecycle, as well as after its decommissioning. Considering the compliance with requirements of the nuclear, radiation, environmental and general purpose industrial grade safety, as well as the possibility of the practical implementation (taking into account the existence of the NSC), the strategy “*step-by-step retrieval*” has significant advantages and in the future will be considered as prior.

The characteristics of FCM, as well as areas of their placement or *FCM retrieval zones* impact the choice of the order and specific technological solutions for the retrieval of each FCM accumulation.

In terms of the available information on FCM location, there are seven specific zones of their retrieval in the future using different technologies (Fig. 6.22):

- 1 — upper marks of the Shelter object (central hall, cooling ponds, other rooms above the mark +18,000);
- 2 — interim marks of the Shelter object (under-reactor room, other rooms on the marks from +9,000 to +18,000);
- 3 — lower marks of the Shelter object (SDC, PSP, other rooms lower than mark +9,000);
- 4 — part of the turbine island within the Shelter object;
- 5 — space behind the pioneer walls;
- 6 — blockages under the cascade wall;
- 7 — the Shelter object local zone.

Here are the main factors, which must be taken into account in the process of the planning of FCM retrieval from zones.

Zone 1: 1) a large amount of FCM, according to the current assessments — in the range from 30 to 115 t (U); 2) difficult radiation situation (dose rate reaches 1,000 R/h in the CH and 2,000 R/h at the bottom of the southern cooling pond); 3) the presence of a large amount of the fuel dust, which requires the development of a number of measures aimed at the non-exceedance of permissible radionuclides concentrations inside the NSC, permissible emissions from the NSC, permissible contamination levels of its structures and equipment during work; 4) the presence of nuclear hazardous accumulations of FCM;

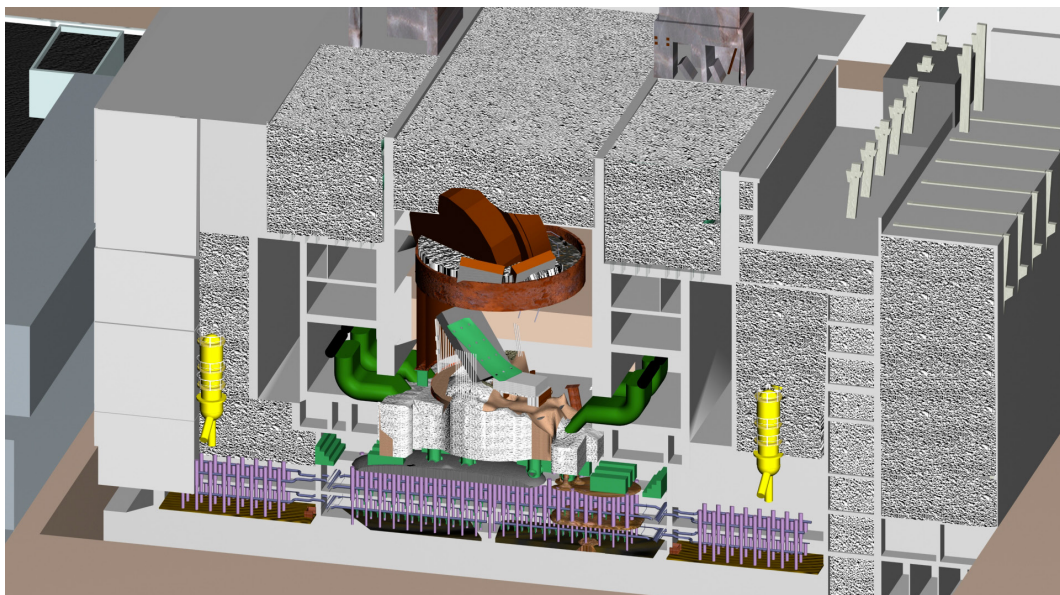


Fig. 6.21 — The variant of “temporary isolation”

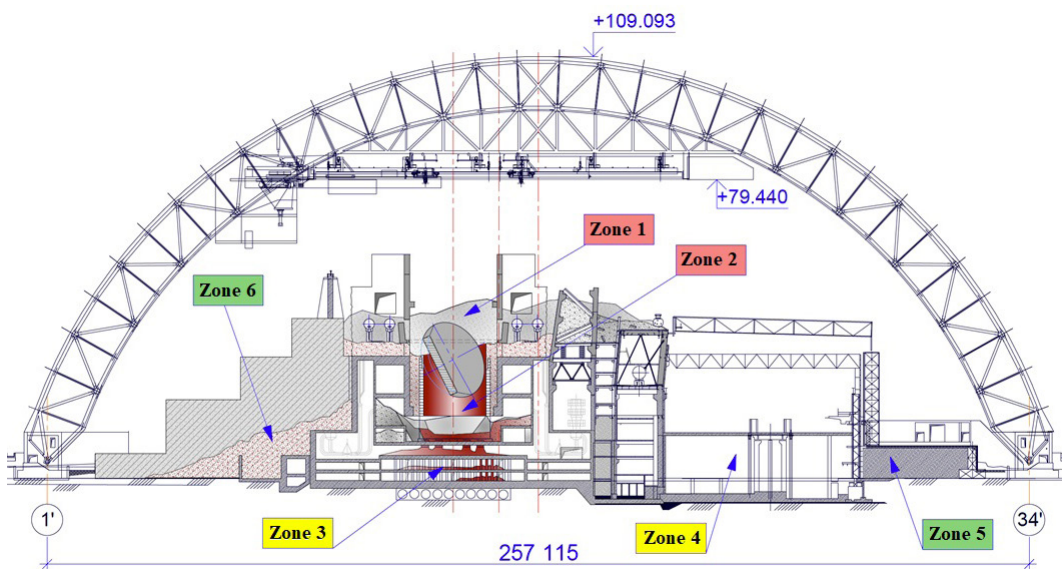


Fig. 6.22 — Zones of fuel containing materials retrieval

5) the presence of massive structures (scheme “E”, refueling machine, etc.), which can not be completely removed and which require the use of special remotely controlled equipment for their fragmentation; 6) the presence of big blockages, under which there are FCM with unidentified characteristics and amount, the need in use of the special technologies during their dismantling; 7) presence of graphite, which requires the use of special technologies for its treatment.

Zones 2 and 3: 1) surrounding the zones with numerous building structures of the destroyed fourth power unit, which perform the function of engineering barriers on the way to the emission of radioactive substances and ionizing radiation, and therefore much less radiation impact on the environment and future personnel of the NSC as compared to the zone 1; 2) the presence of such barriers significantly complicates the performance of work on FCM retrieval in these zones considering the need to dismantle certain building structures of the fourth power unit to organize the access to FCM accumulations; 3) a large amount of FCM; according to the current assessments, zone 2 contains approximately 90 ± 35 t (U), and zone 3— 22 ± 8 t (U); 4) difficult radiation situation (dose rate reaches 1,000 R/h); 5) the presence of nuclear hazardous FCM accumulations; 6) various FCM structure, represented by CF, LFCM (brown, black, polychrome), fuel dust and other FCM modifications; part of FCM diffused into the concrete at the considerable depth, which will create additional complications during their retrieval; a significant amount of FCM is filled with concrete during the Shelter object construction.

Zone 4: the presence of only some small FCM fragments, amount and characteristics of which must be installed during the special studies.

Zone 5: 1) the presence of approximately 1,700 containers (the volume is 1 m^3 each) with HLW, which are located behind the pioneer wall under the concrete width; 2) location of the zone outside the scope of the main cranes of the NSC; 3) the presence of the dismantled structures of the NSC in the temporary storage site; 4) use of the part of the zone for the access of fire-engines inside the NSC arch.

Zone 6: 1) the presence of FCM in the blockage under the cascade wall (Fig. 6.23), the amount of which is assessed to be from 0.7 to 1.2 t, with a predominant concentration in the south-eastern part of the blockage; 2) location of the zone outside the scope of main cranes of the NSC.

Zone 7: 1) the content of FCM in the technogenic ground of the Shelter object local zone under the NSC structures (western wall of the NSC arch, technological building, auxiliary structures); 2) partial retrieval of these FCM during the excavation works for the arrangement of the foundations of the NSC structures.

FCM retrieval from zone 1 is the prior task to improve the safety level during the NSC operation. FCM of this zone generally forms the radiation situation inside the NSC and in the adjacent territory. It should be taken into account that after dismantling the pipe rolling

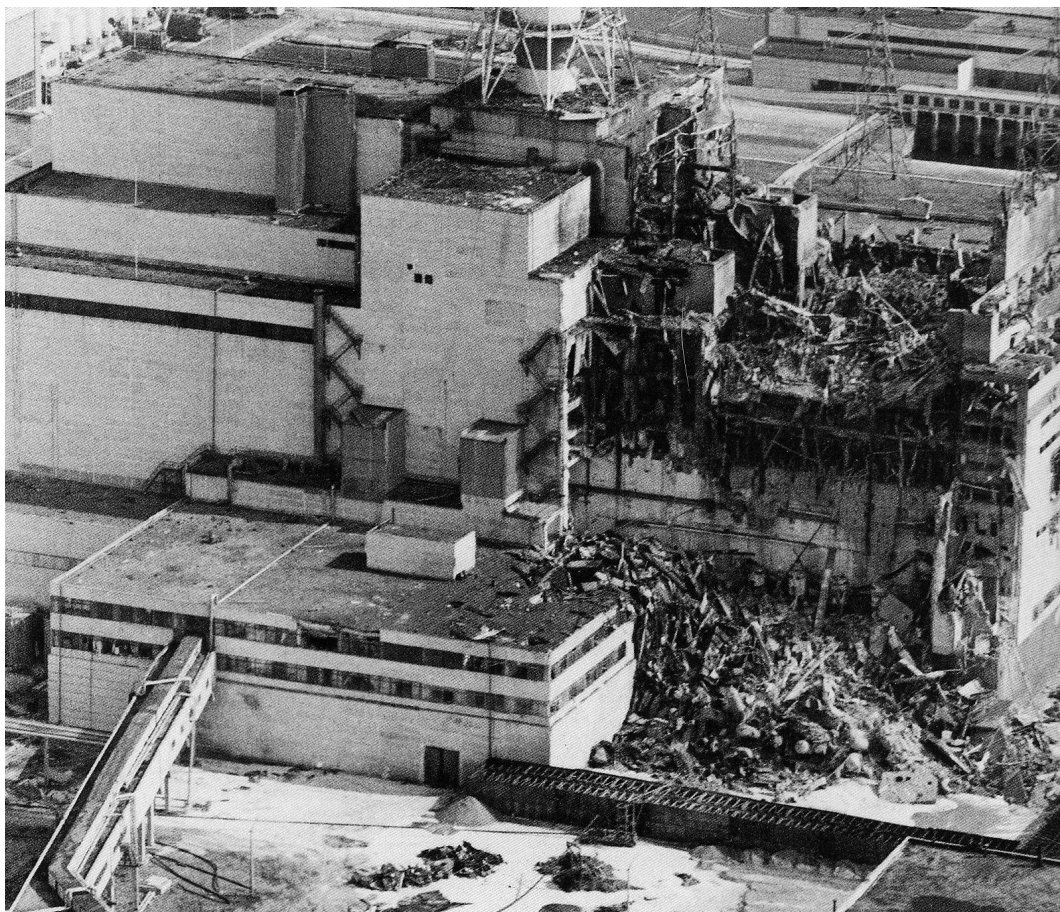


Fig. 6.23 — Fuel containing materials in the blockage under the cascade wall
(before the construction of the cascade wall)

and light roof, the DR in the zones of the NSC service will increase almost three times [146]. The radioactive dust in this zone will be the main contamination source of the NSC arch structure and equipment in normal conditions, as well as in case of possible accidents. This effect will be intensified when due to unstable structures dismantling, the upper part of the Shelter object will be open, i.e. the barrier on the way to the radioactive substances release into the NSC space will disappear. FCM retrieval from zone 1 is in principle impossible without using the NSC systems and should be over during the NSC lifecycle.

FCM retrieval from zone 2 in case of work organization according to the scheme of vertical access “from top to bottom” is possible only after FCM retrieval from zone 1, in particular after the retrieval scheme “E” and accessing into room 305/2 through the reactor pit.

FCM retrieval from zone 3 is possible, respectively, after FCM retrieval from zone 2. However, in case of accelerated degradation of LFCM, it is necessary to foresee the possibility of FCM retrieval from zones 2 and 3 simultaneously with FCM retrieval from zone 1, arranging alternative access to these accumulations. FCM retrieval from zone 2 is prior.

If for some reason during the NSC lifecycle it is impossible to retrieve individual FCM from zone 3, in particular from the pressure suppression pool, they can be conserved for up to 300 years due to the acceptable state of building structures and their function as the effective engineering barrier.

FCM retrieval from zone 4 due to its location outside the operation of the main cranes of the NSC can be carried out using other mechanisms without connection to work in other zones. This task is not prior, but it is advisable at the initial stage of the NSC operation taking into account that the reliability of structures of the turbine island surface will decrease with time and, accordingly the risks of collapse will increase. In case of a potential collapse of the turbine island surface structures, FCM retrieval will be complicated.

FCM retrieval from zone 5, as well as from zone 4, due to its location outside the operation of the main cranes of the NSC can be carried out using other mechanisms without connection to works in other zones. This task is not prior, it is potentially possible after the NSC arch decommissioning.

FCM retrieval from zone 6 as well as from zones 4 and 5, can be carried out using other mechanisms without connection to works in other zones. Work in zone 6 is possible only at the final stage of the NSC arch operation.

FCM retrieval from zone 7 is possible only after the NSC decommissioning since these materials are contained in the technogenic ground of the Shelter object local zone under the NSC structures (western wall of the NSC arch, technological building, auxiliary structures).

Therefore, considering the greatest radiation and nuclear hazard of FCM accumulations contained in *zones 1 and 2*, their retrieval *is prior* and should be completed during the NSC lifecycle.

There are no hazardous FCM accumulations in zones 3—6, their impact on the Shelter object radiation safety is much less. FCM retrieval from them is possible at any period of the NSC operation, provided that this process does not interfere with FCM retrieval from zones 1 and 2. Some of the least hazardous FCM accumulations can be retrieved after the NSC decommissioning. As for FCM retrieval from zone 7, it is possible only after the NSC decommissioning; these accumulations may also be disposed in situ after the corresponding safety substantiation.

The Shelter object transformation into an ecologically safe system based on the strategy “step-by-step FCM retrieval” can be implemented by the potential scenarios, given in Table 6.3.

Table 6.3 — Potential scenarios of the “step-by-step fuel containing materials retrieval” strategy implementation

No. of scenario	Retrieval during the NSC lifecycle	Delayed retrieval after the NSC decommissioning	In situ disposal
1	Zones 1—6	Zone 7	—
2	Zones 1, 2, 3, 4, 6	Zones 5, 7	—
3	Zones 1, 2, 3, 4, 6	Zone 5	Zone 7
4	Zones 1, 2, 3 (SDC), 4, 6	Zones 3 (PSP), 5	Zone 7
5	Zones 1, 2, 3 (SDC), 4	Zones 3 (PSP), 5, 6	Zone 7
6	Zones 1, 2, 3 (SDC)	Zones 3 (PSP), 4, 5, 6	Zone 7
7	Zones 1, 2, 3 (SDC)	Zones 3 (PSP), 5, 6	Zones 4, 7
8	Zones 1, 2, 3 (SDC)	Zones 3 (PSP), 6	Zones 4, 5, 7
9	Zones 1, 2	Zone 3	Zones 4, 5, 6, 7
10	Zones 1, 2	Zone 3 (SDC)	Zones 3 (PSP), 4, 5, 6, 7

Scenario 1, according to which FCM will be retrieved from zones 1—6 during the NSC lifecycle, and from zone 7 — after the NSC decommissioning, is the most ambitious. However, other scenarios should be considered taking into account the real possibilities of carrying out such large-scale and complex activities as FCM retrieval and their further treatment. It should be noted that the level of FCM retrieval depends on the choice and substantiation of the Shelter object final state. One of the possible variants is the Shelter object transformation into the storage of the short-lived and limited amount of long-lived RAW, retrieval of which is related to the significant difficulties. At the same time, the permissible amount of long-lived RAW is determined by the results of the safety assessment of such storage, taking into account its location in the zone of special industrial use, not suitable for human habitation.

Each of the proposed scenarios provides for the mandatory FCM retrieval from zones 1 and 2 during the NSC lifecycle.

The delayed retrieval of individual FCM accumulations after the NSC decommissioning (i.e. after 100 years and more) or their disposal in situ is possible for several reasons:

these accumulations are nuclear safe, their contribution to the radiation state outside the zones of their localization is minimal;

FCM accumulations in zone 3 are surrounded by massive structures; available data on the state of massive structures of the fourth power unit indicate the absence of their significant damage, except for local destruction of the upper layer of concrete of the lap under room 305/2. This is due to the design of the reactor room building is made in the form of rigid volumetric structure from the cast in-situ reinforced concrete. Rooms located in zone 3 form a system of sealed rooms — hermetic boxes with load-bearing structures capable of withstanding high loads, hence the need in their reinforcement is improbable;

as a consequence of the cooling pond decommissioning, the groundwater level on the NSC site decreased, which had a positive effect on the FCM accumulations safety in zones 5, 6 and 7 (distance from the bottom of these accumulations to the groundwater level exceeds 4 m).

Due to the local destructive breakdowns of the upper layer of the concrete lap under room 305/2, which is also the lap over the steam distribution corridor, as well as taking into account a significant amount of FCM in the SDC belonging to zone 3, their retrieval should be considered a prior as compared to zones 3 (PSP), 4, 5, 6 and 7.

According to the preliminary assessments, among scenarios 1—10 by the set of comparison criteria (compliance with requirements of normative documents, implementation costs, impact on the environment, term of realization, reliability of the protective barriers), scenario 6 is the best. However, the final conclusion can be made after the detailed working out of given and, probably, other scenarios and their comparison based on multicriteria analysis. Such work is currently underway.

Therefore, analyzed in Table 6.1 scenarios provide for the mandatory retrieval of FCM from zones 1 and 2 during the NSC lifecycle; as for FCM accumulations in zones 3, their retrieval may occur after the NSC decommissioning. However, the best scenario is when FCM accumulation in zone 3 will be retrieved during the NSC lifecycle, especially as it concerns FCM in the steam distribution corridor.

Let us consider the features of FCM retrieval from each zone.

Retrieval of FCM from zone 1. FCM retrieval from zone 1 can be started only after the dismantling of the Shelter object unstable structures. The dismantling of unstable structures of the lap over the reactor unit will provide access from above to FCM accumulations using MCS.

Work on FCM retrieval should be carried out remotely, in the absence of personnel, directly in the WA to prevent significant individual and collective doses in the normal mode of work and case of possible accidents, applying a complex approach using MCS and RCU.

First of all, it is necessary to retrieve FCM in the area of the upper marks of the Shelter object, i.e. FCM, which have the greatest impact on the radiation situation inside the NSC arch (running gears of the new fuel assembly transfer station, roofs of the steam drums premises, the area of the central hall near the cooling pond, etc.), as well as massive structures and equipment of the CH (refueling machine, bridge crane).

During the work, it is necessary to conduct radiological monitoring periodically, in particular using γ -visor to detect the most hazardous areas, inspect them in detail and retrieve high active fragments.

Blockages of the building structures and bulk materials will not be removed immediately from the entire WA, but in sections in order not to significantly worsen the radiation situation in the NSC due to the uncovering of the intensive IRS. After the separation of WA on the sections (by the radiation and technological criteria), the layer-by-layer method of the dismantling of blockages and FCM accumulations/associated RAW will be applied. To retrieve FCM and other RAW in areas of blockages dismantling, it is necessary to arrange sites for changeable containers. Accordingly, prepared sites should be located in the operating zones of RCU or MCS.

It is necessary to arrange sites for the protective casks installation (of different sizes and safety levels) at the maximum possible distance from the place of retrieval to hold already full changeable containers for transportation for further treatment. This method of the retrieved RAW transportation (in “clean” protective casks) will reduce radiation contamination of the NSC structures on the way of transportation and radiation impact on the NSC operating personnel.

To classify the RAW by the activity level and corresponding transfer to the technological building or the unit of “hot” chambers during works, it is necessary to the maximum effective carry out initial sorting of FCM and associated RAW separating: fragments of FE and FA with spent fuel (visual sorting and control of the DR during loading); fragments of FE and FA with fresh fuel (place of location is on the new fuel assembly transfer station and near it, visual sorting and control of DS during loading); graphite (visual sorting and control of the DR during loading); metal structures (visual sorting and the DR control); reinforced concrete structures (visual sorting and the DR control); granular RAW of different categories (layer-by-layer removal for RAW distribution of different categories, visual sorting and the DR control during loading); “emergency” concrete (visual sorting and the DR control during loading).

The assessment of the MCS capabilities for the direct FCM retrieval shows that due to the low speed of the cranes, as well as low speed of the lifting/lowering the hook of technological operations carrying out using MCS is possible only in combination with other mechanisms. It is expedient to consider the scenario, according to which the main scope of work on FCM retrieval in the Shelter object CH is performed using RCU, and MCS of the NSC is used for RCU delivery to the WA and transportation of casks with RAW, as well as for the individual operations carrying out using MIP instruments at the upper marks of the Shelter object CH (for example, when HLW are retrieved from bridges of the new fuel assembly transfer station, surfaces of the steam drum rooms). Moreover, MCS of the NSC and MIP instruments can be necessary during the arrangement of sites for RCU and casks, as well as supply in the zone of work of the additional equipment of auxiliary mechanisms.

The preliminary sorting of RAW can also be carried out using RCU. Endpoints of the RCU should be equipped with special protected devices for the control and measurement of indicators of the radiation contamination of the dismantled elements (to decide on their further treatment) and a video surveillance system (for the control of the technological process).

Radioactive waste and FCM should be transported from the WA in the Shelter object CH to the place of their treatment in protective casks containing changeable containers, which are removed for loading and reinstalled in casks. The initial sorting of RAW and FCM will be carried out by putting fragments of building structures (materials of blockages or fragments containing FCM) in the changeable containers, which will be placed on the prepared sites in the zone of work of RCU or mobile instrumental platform of MCS. At this point, the protective casks should be located outside the WA to prevent contamination during loading. The location of protective casks may be available metal structures of the reinforcement of the Shelter object western fragment. After reinforcement of some roof structures and sites arrangement, several protective casks with different protection levels can be installed. So, changeable containers with RAW (depending on RAW composition and the DR) can be installed in the protective casks with corresponding protection level and transported to the site of temporary storage of the NSC for the reloading and transportation to the technological building of the NSC or “hot” chambers.

Protective reverse casks of two types will be used: 1) protective casks for transportation of changeable containers with large-sized fragments, as well as granular and mixed materials; 2) casks with high protective level for transportation of changeable containers with FCM.

Taking into account the specifics of FCM and associated RAW when removing them in the CH, there are sites (Fig. 6.24), for which it is necessary to develop individual technical designs: the new fuel assembly transfer station and conning bridges of the CH; coatings and rooms of the steam drums; radioactively contaminated metal structures, bridge crane of the CH, trusses and other massive metal structures; northern and southern cooling ponds, other premises, to which there is an access from the CH; scheme “E”; blockages of the CH.

The following general sequencing of work on FCM and associated RAW retrieval from the upper marks of the Shelter object is recommended:

- 1) Fragmentation and removal of the CH bridge crane, radioactively contaminated and other overall metal structures, which block further retrieval of FCM and associated RAW.
- 2) Dismantling of blockages from laps of the steam drums rooms.
- 3) Dismantling of laps of rooms of southern and northern steam drums.
- 4) Removal of steam drums, if FCM accumulations will be found in them and under them.
- 5) Removal of the core fragments and fresh fuel from bridges of the new fuel assembly transfer station.
- 6) Dismantling of the new fuel assembly transfer station and preparation of the site for RCU work in the CH.

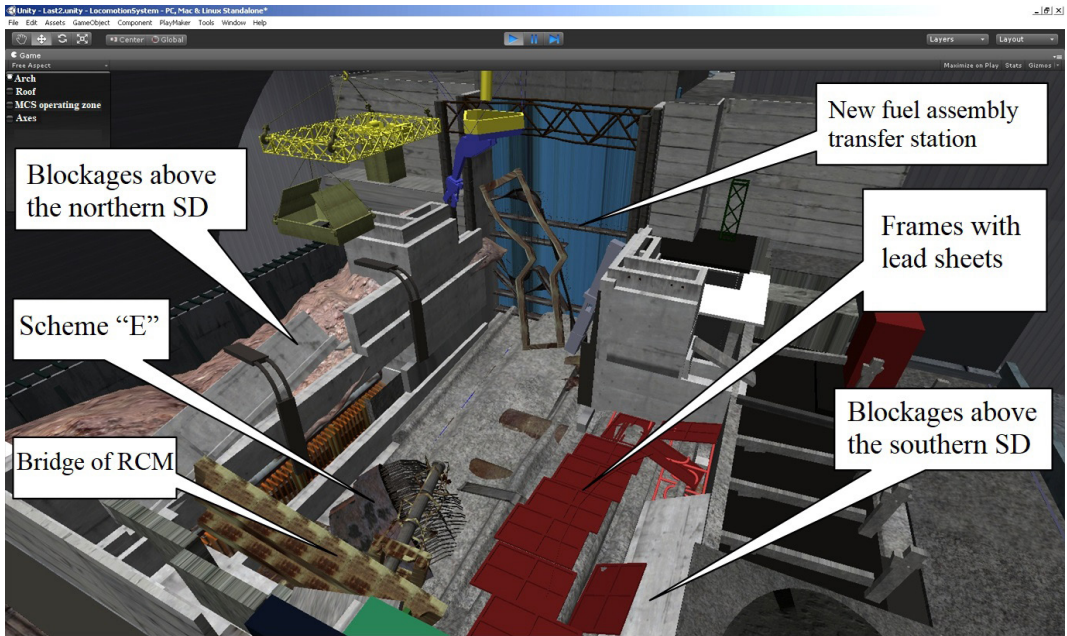


Fig. 6.24 — Model of the work site in the central hall before the retrieval fuel containing materials

A place without hatches in the floor should be chosen as a pioneer site for the RCU placement and hinged equipment since metal structures of some of them could be damaged during the accident. Moreover, the “pioneer” site for the RCU operation must be able to supply power and/or a refueling system for the RCU with internal combustion engines. Such a site can be a place near the control point of the CH (room 1005/2), which is applicable for the power supply and maintenance of the RCU.

7) Decontamination of the CH using RCU, starting from the eastern wall towards the cooling pond and farther towards the scheme “E”; retrieval of other intensive radiation sources that affect the radiation situation in the CH, open-lying fragments of FE, graphite blocks.

Since hatches of most of the CH pits were torn from their regular places during the accident, it is necessary to carefully approach the choice of the RCU type taking into account its dimension so it can move freely through the CH. Open pits orifices in the CH should be protected by metal shields capable of carrying the load from the working RCU and close them during dismantling. In the future, when dismantling blockages and clearing the access to rooms connected to the CH, the presence of FCM in them and the possibility of their

retrieval (in case of detection) are studied. After clearing rooms, the issue on their use for loading short-lived LLW and ILW (primarily large-size fragments of equipment and reinforced concrete and metal structures) is resolved.

8) Stabilization of the scheme “E” for removal of fragments of technological channels with FA using RCU and/or MIP.

It is possible to stabilize the scheme “E” using a four-sided metal-framed structure, which will be assembled separately and erected above the Shelter object reactor pit using the NSC MCS. The metal structure of the scheme “E” will be attached to the framed structure using jacks and grips. To prepare the places for the installation of the framed structure, works on the partial dismantling of blockages using RCU will be conducted. Complete dismantling is carried out after the scheme “E” stabilization using RCU and/or MIP.

Stabilization of the scheme “E” can be carried out also in other ways, for example, supply to the reactor pit of additional support beams, installation and fixing on the shell of the scheme “E” of the bracket-“ears” and even filling the reactor pit with porous concrete.

9) Removal of technological channels fragments with FA from the scheme “E” using RCU and/or MIP.

Clearing the scheme “E” from the technological channels fragments with FA in the future will allow cutting its metal structures, remove backfill from the serpentinite and carry out its step-by-step dismantling. The used framed structure can be the skeleton of the shielded structure above the destroyed reactor pit of the Shelter object for the further mothballing of the Shelter object rooms or controlled access to them.

10) Removal of the suspended FA from the southern CP, FCM retrieval from the bottom of the southern and northern CP (Fig. 6.25).

The inspection of the southern CP using an optical device through inclined wells revealed that hatches in the CP above the wells were not broken, and canisters with spent FA were suspended in the regular position. Today, there is no reliable information on the state of spent FA in the southern CP, but we can assume that some of them are damaged. The inspection of the CH showed that hatches of the northern CP were torn from their places, and FCM accumulation was found at its bottom.

11) Refinement of the radiation situation in the CH, search and retrieval of the remaining FCM.

The retrieval of FCM from zones 2 and 3. FCM retrieval from the medium and lower marks has certain features, and first of all, is accompanied by some problems in case of use of vertical method using MCS, such as:

by the necessity to dismantle a considerable part of the massive reinforced concrete structures located above FCM accumulations for access to the zone of FCM retrieval;

by low productivity of the NSC cranes when removing loads from the medium and lower marks and limited capabilities of MIP on these marks;

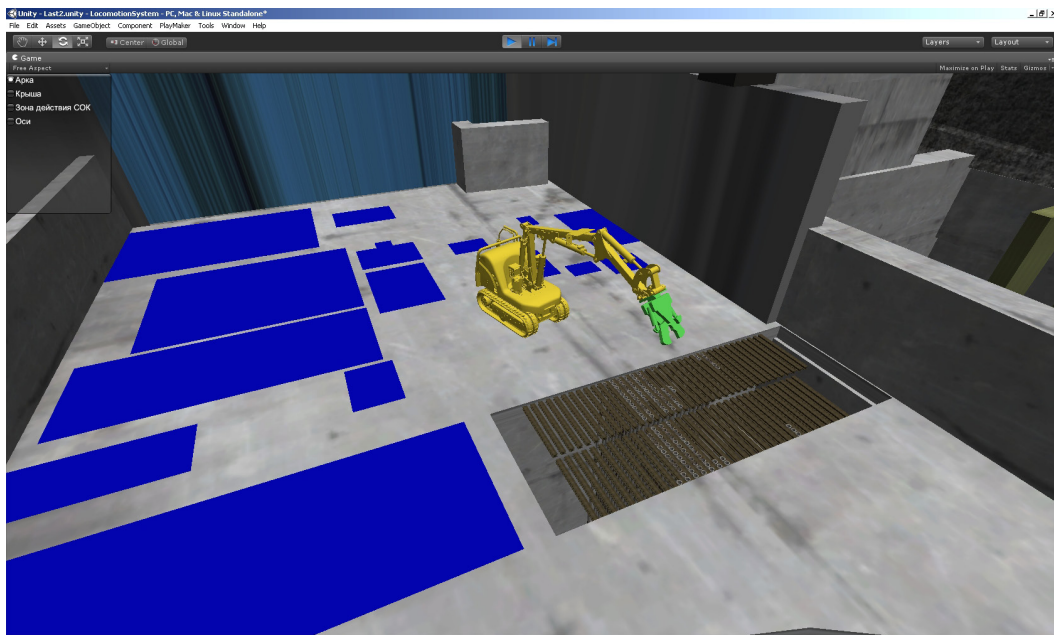


Fig. 6.25 — Work of the remotely controlled unit on the retrieval of spent fuel assemblies from the southern cooling pond

by the long duration of FCM retrieval from the upper marks; it can significantly postpone the start of works on the medium and lower marks that potentially create a danger to the complete end of FCM retrieval on these marks during the NSC life-cycle.

Therefore, the prospective variant is to organize work on FCM retrieval at the medium and lower marks by the horizontal access method.

To demonstrate the organization of the horizontal access to FCM accumulations at the lower marks, we present a three-dimensional model of the Shelter object fragment (Fig. 6.26). As we can see, the creation of the access paths to places of FCM localization is complicated by the existing walls, sags of concrete and slabs at different levels. The walls and slabs to be dismantled are highlighted in white. Concrete sags, blockages from metal structures and equipment located on the access paths and are RAW, are also subject to dismantling.

The general view of the access paths to FCM localization places after the partial dismantling of structures, removal of concrete sags and blockages, as well as erection of lifting mechanism (freight elevator) to move necessary working equipment (including remotely controlled units) and primary packages with FCM is shown in Fig. 6.27.



Fig. 6.26 — The Shelter object fragment model



Fig. 6.27 — Access paths to fuel containing materials accumulations

To deliver mechanisms to the working zones, as well as to organize the completed scheme of FCM retrieval and other RAW management, including their transfer to other sites for further treatment, it is proposed to construct an external closed trestle equipped with a load lifting mechanism (Fig. 6.28).

Casks with FCM will be transported to the edge of the closed trestle and with the help of the roller mechanism — to the slinging site located at the end of the trestle (Fig. 6.29). From this site, using the NSC crane, FCM in the protective casks will be transported for further treatment.

In the general view of the transport and technological scheme of FCM retrieval from the lower marks includes the following stages:

- creation of access paths to FCM accumulations;
- dismantling, cutting, loosening to separate FCM from the Shelter object structures and FCM fragmentation in places of accumulation;
- containerization of FCM into the primary package (barrels);
- transportation to the loading elevator;
- loading of the primary packages (barrels) into the transportation cask;
- lifting of the transportation cask with barrels to the edge of trestle;
- radiation control;

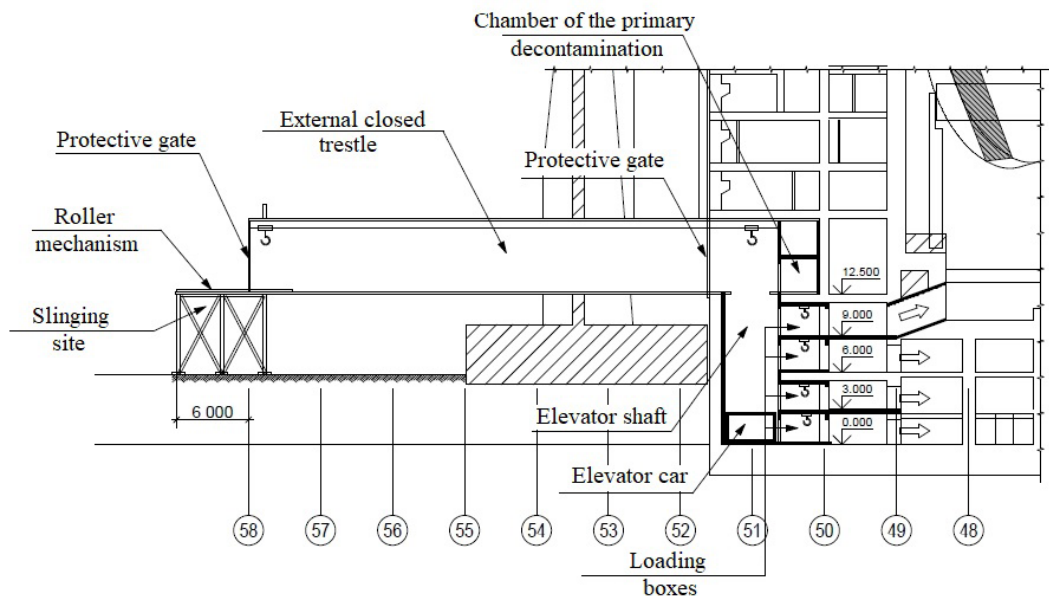


Fig. 6.28 — General scheme of the external closed trestle

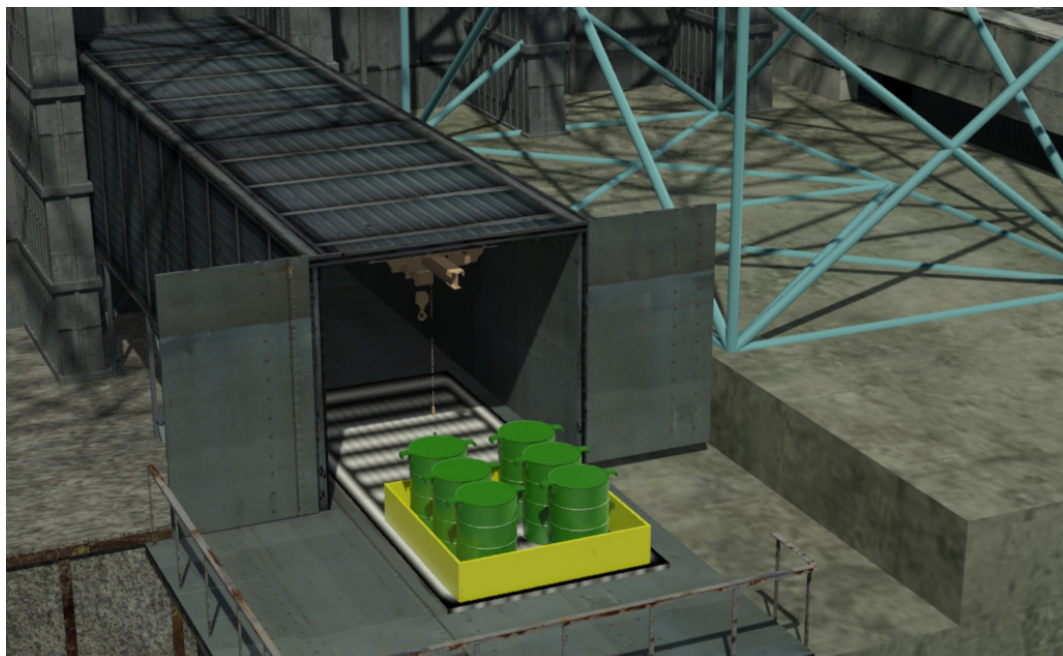


Fig. 6.29 — General view of the trestle with slinging site

decontamination of the transportation cask (if necessary) in the chamber of primary decontamination;

loading the transportation cask with barrels into the protective cask by the beam-crane;

transportation of the protective cask to the slinging site;

slinging of the protective cask and its transportation using MCS of the NSC or other lifting mechanism for further FCM treatment.

The large volume and extreme complexity of work on FCM retrieval from the lower marks significantly affect the possibility of their completion during the NSC lifecycle. Therefore, the variant of the delayed FCM retrieval from lower marks of the Shelter object after the NSC decommissioning can not be dismissed. The following circumstances speak in favor of this scenario:

building structures of rooms at the lower marks has a satisfactory condition, i.e. can effectively fulfill the function of physical barriers comparatively long time;

when organizing horizontal access to the rooms at the lower marks, there is a possibility to equip the self-reacting mechanized scheme for supplying necessary mechanisms and equipment in the working zones, as well as to retrieve FCM and other RAW in the protective casks without using the NSC systems outside the Shelter object, including MCS.

Thus, the proposed variant of the work organization based on the method of horizontal access solves the problem of FCM retrieval from the lower marks of the Shelter object in the short-term (during the NSC lifecycle), as well as delayed retrieval after the NSC decommissioning.

The NSC infrastructure should be used as much as possible in the transport and technological scheme of FCM retrieval from the Shelter object rooms. When analyzing the existing NSC infrastructure, the following preliminary conclusions can be drawn as to whether the requirements for technical and technological support of works at the stage of FCM retrieval meet:

the main cranes system and other transport of the NSC (forklift, self-propelled cars) — yes;

sizes of the temporary storage site (placement of the necessary technological sites) — yes;

RAW management systems contained in the technological building — no;

systems of the technological building for decontamination, technical maintenance and repair of the changeable operating tools of RCU and MIP — yes;

the NSC systems for decontamination, technical maintenance and repair of RCU and MIP — no.

An international and domestic experience in the management of high level IRS, which includes FCM, indicates the necessity to create “hot” chambers. Therefore, in the preparatory period before the NSC retrieval in the space under the NSC, it is necessary to build a new structure — “hot” chambers unit with the decontamination sites and all other necessary sites and life support systems (ventilation, power supply, industrial television, etc.). Taking into account the space-planning decisions and the NSC infrastructure, it is possible to create a “hot” chambers unit on the temporary storage site, which will be free after the unstable structures dismantling. The technological line of the WEP factory in the United Kingdom may be considered as a prototype of a “hot” chambers unit [192] (Fig. 6.30). Following works should be carried out in the “hot” chambers unit:

additional fragmentation;

sorting (separation of FCM from other RAW); it is extremely important operation, taking into account high costs for the future FCM storage and disposal;

FCM placement in the primary packages (barrels) and certification;

loading barrels with FCM into the protective cask and its transfer for temporary storage.

Since retrieved from the Shelter object FCM according to the classification of NRB-97/D-2000 is long-term waste and subject to the disposal only in the storage facilities, located in the stable geological formations, and there are no such storage facilities in Ukraine (their creation is possible only in the remote prospect), it is necessary to solve the problem of temporary (long-term) storage of FCM. Therefore, it is necessary to organize the interim FCM storage facility.

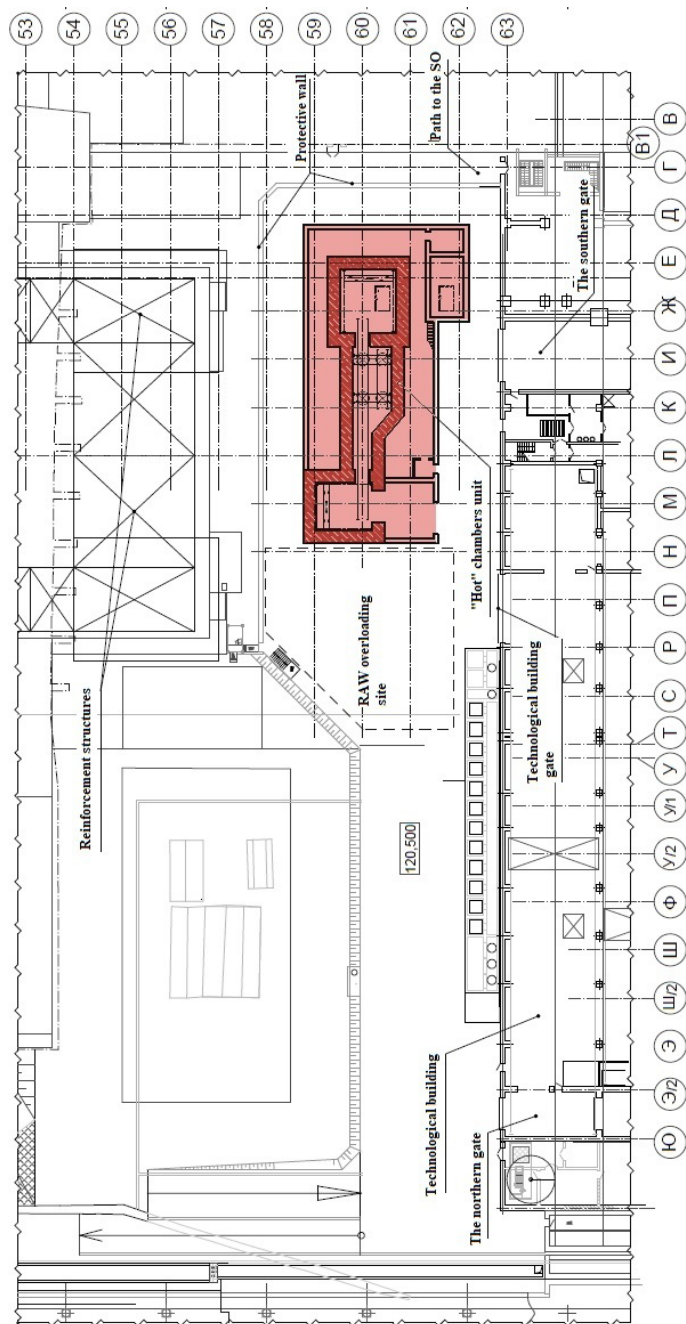


Fig. 6.30 — Location of the building of "hot" chambers unit and existing objects of the NSC infrastructure

As a foreign and domestic experience demonstrates, for the long-term container storage of the spent nuclear fuel and HLW, open sites can be used, provided with systems of physical protection and other systems, in which the storage of protective casks is safe. This scheme of long-term storage is also quite acceptable for FCM retrieved from the Shelter object.

The site for the interim FCM storage facility can be used as an available concrete platform for assembling the arch metal structures, located at a distance of about 300 m from the NSC. This platform has effective lightning leads, a foul water system with settling ponds, enclosure, the infrastructure of the physical protection and access control [8]. The enclosure can be additionally modernized according to the specific safety requirements of such type of RAW storage facilities.

The area of the site between the southern and northern foundations of the arch is over 22,000 m². It is located in front of the NSC, outside the organized access and pedestrian paths to the NSC. Therefore, the site of the concrete platform for the NSC arch assembling is suitable for the arrangement on its territory of the storage facility for the long-term storage of canisters with FCM.

GENERAL CONCLUSIONS

Finishing the construction and commissioning of the NSC became the most important result of the multi-year activity on the Shelter object transformation into an ecologically safe system. The scientific, technical and social significance of such activity is in achieving a drastic reduction of the risk of negative impact on the environment of nuclear and radiation sources, concentrated in the Shelter object. Thus, the NSC is not only a protective structure around the Shelter object but also a complex of modern systems of safety, control and life support, as well as the developed infrastructure, necessary for current NSC operation and further activity on the Shelter object transformation into an ecologically safe system.

As 35 years ago, the most important sources of the Shelter object hazard are materials, which contain irradiated fuel. After installation of the NSC, the moisture-temperature conditions of FCM presence have changed. With the change of the moistening level of nuclear hazardous accumulations, the NFD gradually increases, and this process will last until drying of critical composition, i.e. for at least another two years. During this period, it is important to permanently control specified parameters and to prevent the increase of criticality to dangerous levels.

The time, environmental conditions and peculiarities of physical and chemical characteristics of FCM affect the change of their strength, which leads to the formation and accumulation of fine, dust-like particles with high radioactivity. Now an increase in the intensity of degradation processes takes place. According to the created model of FCM evolution, which takes into account the available rates of their oxidation, the destruction of nuclear materials can occur in 25—50 years. It is necessary to study how the NSC construction over the NSC will impact these processes.

Thus, it is already clear that the NSC significantly affected the radiation safety state at the site. Exposure dose rates at the adjacent territory decreased more than ten times after setting the NSC into design position. There are also drastic changes in the behavior of RA, which with air flows emitted from the Shelter object into the environment; the total activity of the emission into the space under the arch decreased almost three times. At the same time, due to the lack of capability to disperse in space for long distances, radioactive dust is accumulated on the inner surfaces of the NSC and Shelter object. As compared to the period before the NSC construction, the density of radionuclide fallouts on the inner surfaces increased twice.

Preventing precipitation from entering the Shelter object has significantly changed the state and characteristics of radioactive waters. Some water accumulations disappeared, and the volume of some of them is about several cubic meters and ranges depending on the season. The volumetric activity of radionuclides in these accumulations has increased many times. The only accumulation of RW that remained unchanged is located in room 012/13; it is necessary to determine the source of water intake.

At the place of dried RW accumulations, finely dispersed bottom sediments with a high content of radionuclides are formed. They can become new sources of RA. The ability of these components to affect the radiation safety state needs additional study.

Thus, with the construction of the NSC, the state of components and parameters, which determine the radiation safety of the Shelter object, has undergone significant changes. At the same time, with an improvement of conditions, there are negative manifestations, the significance of which must be studied.

Construction of the NSC is an extremely important stage in the implementation of the strategy of the Shelter object transformation, but not the final solution to the problem. FCM accumulations, formed as a consequence of the beyond design-basis accident at the fourth power unit, continue to be the main source of hazard. Taking into account that the guaranteed lifetime of the NSC is only 100 years, and the half-lives of nuclear materials in it are many orders of magnitude higher, the hazard to the environment will exist for millennia. Therefore, it is extremely important to transfer them into the controlled state and to retrieve FCM before their destruction can become large-scale. The problem of further Shelter object transformation into an ecologically safe system remains urgent even after the NSC is put into operation.

The prior task after the NSC commissioning is dismantling of the Shelter object unstable structures. Implemented in 2004—2008 urgent stabilization measures provide an admissible safety level for the Shelter object for a 15-year operation time of stabilized structures, i.e. only until the end of 2023. But the question naturally arises: why is it necessary to dismantle the Shelter object structures after the NSC construction, as it fulfills the function of protective structure over the Shelter object? Of course, the NSC plays an important role in the minimization of negative impact on the environment in case of the potential collapse of the Shelter object structures. However, the collapse will be accompanied by an intensive rise of radioactive dust and aerosols, due to which the NSC structures and technological systems are subject to radioactive contamination; it will worsen the radiation situation, lead to the additional exposure of operating personnel and decontamination works. The fall of unstable structures on the damaged building structures of the power unit can provoke the collapse of the latter and destroy the existing engineering barriers around FCM accumulations, which will have negative consequences for the level of nuclear and radiation safety. In addition, the collapse of unstable structures will create some problems in the future activity on the Shelter object transformation, since it will make it difficult to access FCM to transfer them in the controlled state, in particular for retrieval.

According to the results of probability assessment of structures collapse and radiation consequences of the implementation of such scenario, the list of the Shelter object unstable structures subject to the “early” or “delayed” dismantling is formed. “Early” dismantling, as the first stage of prior works on the unstable structures dismantling, should begin immediately after the NSC commissioning; the second stage, i.e. “delayed” dismantling is a continuation of the “early” one, it should begin immediately after the first stage.

In the developed concept decisions on the Shelter object unstable structures dismantling, the volume and sequence of dismantling were determined, basic technological schemes of treatment with different types of radioactive waste were proposed, as well as it is foreseen: 1) creation of the infrastructure of the unstable structures dismantling inside the NSC; 2) enhancement and modernization of the infrastructure of the RAW management at the Chornobyl NPP site for treatment with all types of radioactive waste, especially with high level ones, formation of which is forecasted during blockages dismantling at the upper marks of the Shelter object; 3) the possibility of the temporary storage of those RAW, which do not meet the criteria of acceptance for the disposal at the located inside the NSC special site.

The first in the list of projects on the dismantling of the unstable structures relates to a metal truss installed during the stabilization of the Shelter object southern roof. One of the purposes of the development and implementation of this project is to demonstrate the possibility and efficiency of the infrastructure use, developed within the NSC, as well as substantiate the need for additional equipment of the NSC sites and systems for dismantling of the object unstable structures. The dismantling of the metal truss is scheduled for 2022.

After the construction of the NSC EP and the installation of the arch in the design position, the part of the Chornobyl NPP, which is a part of the Shelter object, was out outside the NSC. Studies of the technical state of the structures of these parts have shown that they do not meet the requirements for the structures of the NSC, and must be reinforced or dismantled. Based on the results of the analysis of the options for the reconstruction of the PS of the Shelter object the Technical decision “On the choice of the reconstruction variants of parts of the deaerator stack and turbine island of the Shelter object protruding outside the NSC enclosing perimeter” has been adopted. It provides: 1) reconstruction of the eastern and western parts of the Shelter object DS should be performed by the reinforcement of the structures; 2) reconstruction of the western part of the Shelter object turbine island should be performed by the structures dismantling; 3) the storage site of the dismantled structures of the turbine island western part should be organized in the Shelter object turbine island rooms with further installation of a new roof; 4) reconstruction of the Shelter object turbine island eastern part should be performed by the structure’s reinforcement.

After dismantling of the Shelter object unstable structures and reconstruction of the parts protruding outside the NSC, it is necessary to move further in the direction of the

Shelter object transformation into an ecologically safe system. Currently, there are three main strategies of further Shelter object transformation into an ecologically safe system: in situ disposal by filling with concrete or other mixes; temporary isolation with the purpose of delayed FCM retrieval; step-by-step FCM retrieval.

The variant of “in situ disposal” was proposed in different variations long before deciding to construct the NSC. At the first sight, the variant is acceptable taking into account the relatively quick solution to the problem of the Shelter object transformation. But it has serious disadvantages, among them:

filling with concrete of the Shelter object rooms will lead to the significant overload and settlement of the ground base, and consequently to the significant deformations of the damaged building structures of the fourth power unit, as well as mutual structures of the third power unit with their possible destruction; it will negatively impact on the structures state, which function as the NSC enclosing perimeter (Fig. 6.20), as well on the NSC foundations. This, in turn, may decrease indicators of the operational reliability of the NSC (in particular make the operation of the main cranes impossible), and at worst to the NSC arch destruction;

concreting of FCM accumulations make it impossible to reliably control the state of nuclear materials, which does not meet requirements for nuclear safety;

even in the case of successful implementation of the “in situ disposal” variant, the Shelter object safety problem is solved only in the short term. Such a structure is not durable even with quality concreting of premises, which is practically impossible in the conditions of the Shelter object;

the “in situ disposal” variant does not allow achieving the final state of the Shelter object as an ecologically safe system, since it does not provide reliable isolation of FCM and other long-lived RAW for the whole period of their hazard to the environment, and therefore does not meet requirements of the normative legal acts in the field of radiation and environmental safety.

The variant of “temporary isolation” also involves filling the Shelter object rooms with concrete or other mixes, but to a much lesser extent due to the need in FCM isolation only for a certain period. As compared to the variant of “in situ disposal”, this variant provides the creation of additional barriers around FCM accumulations and their further retrieval. It is the variant of the delayed solving the Shelter object problem, but with aggravating circumstances, because the additional circumstances in the future activity arise (the complexity and scope of work on the Shelter object dismantling increase significantly after its concreting, and volumes of formed RAW also increase accordingly, etc.).

The variant of “step-by-step retrieval” provides the prior retrieval of the most hazardous FCM accumulations during the NSC life cycle. The part of less hazardous FCM can be retrieved during the NSC lifecycle, as well as after its decommissioning. Taking into account the compliance with the requirements of nuclear, radiation, environmental and general

industrial safety, as well as the possibility of practical implementation (taking into account the NSC existence), the strategy of “step-by-step retrieval” has significant advantages and is considered as prior.

The Shelter object transformation into an ecologically safe system according to the strategy of “step-by-step retrieval of FCM” can be implemented in several potential scenarios. The scenario, which involves FCM retrieval during the NSC lifecycle (except for FCM localized in the technogenic soil, because they are located under the NSC structures), is the most ambitious, and it is necessary to try to implement it. However, it is recommended to consider other scenarios taking into account real possibilities of such a large-scale and complex activity as retrieval of FCM and their further treatment. Delayed retrieval of individual nuclear safe accumulations of FCM, located in rooms with a satisfactory state of building structures and their effective performance of the engineering barrier function, is possible even after the NSC decommissioning (i.e. in 100 years and longer). The final conclusion on the best scenario of the transfer to the controlled state and FCM retrieval can be made after a detailed study of several potential scenarios and their comparison based on multi-criteria analysis. Such work is currently underway.

Future activity on the Shelter object transformation into an ecologically safe system will be carried out at the object, which has no analogs in world practice, — it is unique and needs appropriate regulatory support. According to the results of analysis of requirements of normative legal acts and international norms, rules and standards, there are several issues.

In particular, currently the Shelter object status without taking into account the NSC is determined in NRBU-97/D-2000 as “place of the surface storage of unorganized RAW (temporary storage of unorganized RAW that is at the stage of stabilization and reconstruction)”. The reason for the Shelter object qualification as a temporary storage facility of RAW was the assumption that fuel containing materials could not be used today or ever in the future. In our opinion, this status is not correct since FCM contained in the Shelter object is included in the inventory list of nuclear materials and is subject to the IAEA safeguards. Moreover, taking into account that FCM is the main source of the Shelter object hazard, as well as its kind of “visiting card”, it would be logical in the determination of the Shelter object status to say about the presence of fuel containing materials. After the NSC commissioning, the Shelter object will be integrated into the NSC complex, which requires determination of the status of this new formation.

From the very beginning of the IAEA safeguards application regarding the Shelter object nuclear materials, there were difficulties concerning their placement under the safeguards. First of all, it was related to the inability to use standard registration procedures applied to non-emergency nuclear materials at the Chornobyl NPP, as well as the inability to identify declared nuclear materials. Therefore, during the IAEA safeguarding of the Shelter object nuclear materials, a compromise decision was taken on the stated amount of nuclear materials

at the moment before the accident, i.e. as of April 25, 1986. Therefore, before retrieval of the Shelter object FCM, the normative legal and normative-technical documentation on the treatment with emergency waste containing nuclear materials should be developed and agreed upon by the IAEA.

Ensuring nuclear safety in Ukraine in the process of the treatment with nuclear materials is regulated by several normative documents, which establish general requirements, criteria and principles for safety ensuring during the treatment with nuclear fuel of nuclear power plants, research reactors, critical and subcritical assemblies, and spent nuclear fuel storage facilities. Requirements to the criticality at every stage of their lifecycle, as well as requirements to the safe geometry of their accumulations have been established for these nuclear materials.

At the Shelter object, we are dealing with unorganized, chaotic accumulations of nuclear hazardous materials in the form of FCM, for which there is a risk of criticality. The problem of uncontrolled intake of precipitations, which created a risk of criticality, after the NSC installation has lost its relevance. Thus, due to the destruction of FCM accumulations in the NSC conditions under the impact of the external factors and hazard of the collapse of the Shelter object building structures, the possibility of an uncontrolled change of FCM accumulations geometry with dust release into the space under the NSC is not excluded. Therefore, to regulate FCM retrieval and containerization, there should be an appropriate legal and regulatory framework, a normative document to ensure nuclear safety directly at the Shelter object in the NSC condition — a document, which includes all stages of FCM treatment: retrieval, containerization, organization of places for temporary storage or disposal, transport-technological procedures, as well as (if necessary) requirements for long-term mothballing of individual FCM accumulations, the retrieval of which is not an urgent task.

One of the key issues concerning ensuring the further Shelter object transformation is a determination of clear criteria of long-term storage and disposal of FCM and other RAW after their retrieval. In recent years, in Ukraine, some steps were taken to optimize the RAW management system and improve their classification system. With the support of the European Commission under the Program of International Cooperation on Nuclear Safety, experts from the consortium DBE TECHNOLOGY GmbH (Germany), ANDRA (France), COVRA (Netherlands), ENRESA (Spain) and SKB International AB (Sweden), with the broad involvement of Ukrainian specialists, implemented the project “Improvement of the RAW classification system in Ukraine”, which resulted in the proposed modified RAW classification system, which includes VLLW, LLW, ILW and HLW. The introduction of VLLW class has already been reflected in the adopted Law of Ukraine “On amendments to some Ukrainian laws on improvement of legislation in the field of radioactive waste management”, which will come into force 11.07.2021.

VLLW includes RAW, in which radionuclides activity exceeds the levels of retrieval or liberation from the regulatory control (lower limit of classification of waste as VLLW), but

according to their radiological characteristics, they can be transferred for disposal in the simplest surface storage facilities. The introduction of this class will have a positive impact on the Shelter object transformation activity since it will include some of the RAW, formed during the works. First of all, it is secondary waste, represented by contaminated personal protection equipment, tools and other equipment not eligible for decontamination.

LLW are waste, in case of disposal of which in the near-surface storage facilities equipped with a multi-barrier protection system, safety goals can be achieved with a duration of administrative control of not more than 300 years. According to the IAEA recommendations, the maximum permissible total specific activity of α -emitting radionuclides of 4,000 kBq/kg (in the separate package) at the end of the management control under 400 kBq/kg in the average in the storage facility is taken as the upper limit of LLW. ILW are waste subject to be disposed for the storage facility at the interim or greater depths with HLW. It is recommended to take the specific activity of α -emitting radionuclides (at least 4,000 kBq/kg) as the lower limit of ILW. The upper limit is determined by the heat release level lower than 2 kW/m³. According to this classification system, ILW will include a significant part of the Shelter object waste.

HLW are waste, which can be disposed only in deep storage facilities. They are characterized by high specific activity (10^4 — 10^6 TBq · m⁻³), heat release higher than 2 kW/m³, and high content of long-lived radionuclides.

Preliminary results of calculations have shown that the energy release of FCM in 2060 will be 0.36 kW/m³, in 2120 — 0.12 kW/m³. It means that at the time when FCM retrieval is most likely to be carried out, according to the proposed modified classification, there will be no HLW in the Shelter object that will require disposal in the stable deep geological formations, i.e. FCM can be classified as ILW and disposed in storage facilities at the interim depths (several tens — hundreds of meters from the ground).

The implementation of a modified classification system of RAW will have a positive impact on the further Shelter object transformation activity since it will significantly reduce the costs of RAW disposal due to the use of more economical variants for isolation from the biosphere.

The most important task in the Shelter object transformation into an ecologically safe system, in the short-term future, is the dismantling of unstable structures. However, the success in the implementation of next steps, such as substantiation and development of FCM retrieval technologies, creation of infrastructure for their treatment at the Chornobyl NPP site and further disposal in the special storage facility, will require long-term concentration of scientific, technical and financial resources. Taking into account the scale of tasks, it becomes clear that for their implementation it is extremely important at the present moment, in the conditions after 35 years from the accident, to involve international scientific, political, and financial institutions to unite efforts in the creation of the special fund of support for such activity. The experience of the Chornobyl NPP Implementation Project has shown that such an international assistance mechanism is effective, and the NSC construction and commissioning is a clear confirmation of this.

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У монографії, підготовленій за результатами багаторічних наукових досліджень з нагоди 35-х роковин Чорнобильської катастрофи, наведено опис нового безпечного конфайнмента (НБК), огорожувального контуру, технологічних і допоміжних будівель та комунікацій, системи основних кранів, системи життєзабезпечення, безпеки та контролю. Розглянуто питання ядерної та радіаційної безпеки в умовах НБК, наведено динаміку нейтронної активності й температури паливовмісних матеріалів у процесі змін волого-температурного режиму, які відбулись після накриття об'єкта «Укриття» аркою. Показано напрямки підвищення ефективності забезпечення ядерної безпеки. Зроблено оцінку зміни полів гамма-випромінювання після встановлення НБК в проєктне положення, активності радіоактивних аерозолів та водних скупчень у приміщеннях об'єкта. Проаналізовано вплив об'єкта «Укриття» в умовах конфайнмента на довкілля, розглянуто програми науково-технічного супроводу діяльності з перетворення об'єкта на екологічно безпечну систему. Описано подальші роботи з демонтажу нестабільних конструкцій об'єкта «Укриття», реконструкції будівельних частин, що виступають за межі огорожувального контуру, а також потенційні сценарії перетворення об'єкта «Укриття».

Видання рекомендовано спеціалістам атомних електричних станцій, науковим та інженерно-технічним працівникам служб з ядерної безпеки та радіаційного захисту, протиаварійного реагування та надзвичайних ситуацій, студентам вищих навчальних закладів, може бути корисним для широкого кола читачів, які бажають отримати та систематизувати свої знання з розглянутих питань.