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IMPROVEMENT OF TECHNICAL SOLUTIONS IN THE HANDLING OF SPENT NUCLEAR FUEL UNDER CONDITIONS MILITARY TIME

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For spent nuclear fuel (SNF) Ukraine built a Central Storage Facility (CSF). But now there are risks during the transportation and of the CSF's proximity to the border. The work proposes the use of an additional spend fuel pool, where SNF can be stored for more than ten years, followed by relocation to closed dry storage. The roof over the containers provides several advantages for long-term retention. For the final placement of SNF after the shutdown of the NPP, it is proposed the containment. The optimization the wall thickness ratio of the building and the ventilated container has been considered.

INTRODUCTION

Energy independence of Ukraine today largely depends on measures to improve the security level of energy facilities and to enhance design solutions for the handling of spent nuclear fuel (SNF). After operation in the reactor, spent fuel assemblies (SFA) are periodically removed from the active zone and stored in a spent fuel pool (SFP), which is located in a containment. Of course, this is only possible depending on the condition of the storage pool. When the SP is completely filled, a problem arises. Unfortunately, it is practically impossible to move the SFAs even for a short time from one pool to another block's pool. Therefore, at Ukraine's nuclear power plants, timely removal from the SP of those assemblies that have been stored for more than 3 years becomes especially urgent, as the storage pools are already unable to accept the next batch of SFA. The storage time must be more than three years for the power of the assembly to be less than 1 kW. At this power level, the residual heat release from the fuel assembly can already be removed through natural air circulation. If the power that can be removed through natural air circulation is justified, then the time to reach this power must be specified for each loading. This is because, with increased of fuel assembly burnup, the time to reach a certain power decrease. Considering the high costs and risks involved in handling nuclear waste, sufficient attention should be paid to improving these processes.

1. ANALYSIS OF THE CURRENT STATE OF THE ISSUE

According to the general scheme of project solutions for WWER-440 and WWER-1000 reactors, it was planned to systematically remove spent nuclear fuel from nuclear power plants (NPP) and timely transport it by special railway cars to specialized facilities in the RF for preliminary processing, followed by disposal. Until the deterioration of relations with the RF, Ukrainian NPP constantly engaged in timely shipments of spent fuel assemblies to RF. It seemed convenient for everyone, and dangerous accumulation in storage of spent nuclear fuel during the operation of NPP did not occur! After the collapse of the USSR, state agreements were violated, and, most importantly, project decisions regarding the NPP. Spent nuclear fuel was not being transported, and the storage pools were overflowing. Ukraine was forced to pay large sums for the shipment of SFA to RF.

The first troubles with the operation of nuclear power units in Ukraine were felt almost immediately after independence was gained. This became particularly evident after all types of documentation for the Chornobyl Nuclear Power Plant due to the accident at reactor unit 4 were lost (became unusable due to the accident), and project documentation for the construction of “Confinment-2” was needed for unit 4. In response to the Ukrainians' request to the design institutes in RF for copies of the project documentation, the answer was negative and no letters or documentation were received from Russia. This situation was understood at the time by the President of Ukraine, Kuchma, who promised to create a closed nuclear fuel cycle in Ukraine. That promise was not fulfilled. The storage pools (SP) with the spent nuclear fuel at the NPP in Ukraine soon became overcrowded because the expected special trains for the nuclear power plants were not available. The solution to this problem was the modernization of the SP and the use of two-story racks for SNA (with a capacity 1.85 times greater than the original design), manufactured at the “Skoda” plant according to the project by “Duke Engineering & Service Inc.” (Europe) together with “Sierra Nuclear Corporation” [2]. The situation that has developed was a catalyst for radical actions to improve design solutions for handling spent nuclear fuel. The next step was borrowing the experience of Holtec International in construction a dry storage facility for SFA at Zaporizhzhia Nuclear Power Plant [3].

Now a Central Storage Facility for spent nuclear fuel was built in the Chernobyl Nuclear Power Plant zone. Today, three nuclear power plants in Ukraine (besides Zaporizhzhia) already have the capabilities for sending spent nuclear fuel to the Central Storage Facility. However, it cannot be said that all problems are solved. At the SFP of NPP, the accumulation of spent nuclear fuel continues (the most active radioactive waste). It should be noted that the territory of the Central Storage

Facility is located near Belarus, which may lead to problems, especially under modern conditions.

It should also be noted that practically all energy units in Ukraine have exceeded their designed operational periods. In this condition, the number of damages to vulnerable components of the equipment in the safety systems, which were not replaced during the extension of the operational period, is increasing (primarily this concerns the spent fuel pools). There are no technologies for repairing the walls and bottoms of the pools, and removing defects from them does not seem to be a simple matter. That is, in case of an urgent need for pool repairs, several questions immediately arise: first of all, where to relocate the used nuclear fuel during the repair, especially those that have not been in holding for three years yet. The second question is: how to find defects in the walls and bottoms of the pools? How then to control the quality of the repairs? How to ensure a constant cooling mode for the temporarily relocated SFA? And so on?

Ukraine is planning today to construct a nuclear power plant with small modular reactors, where the management of spent nuclear fuel is proposed to be similar to the one considered [4]. The aim of this work is to find ways to improve the management of spent nuclear fuel through the proposal of long-term storage of SFA on the premises and near the nuclear power plant itself.

2. ENHANCED STRATEGY FOR SPENT NUCLEAR FUEL MANAGEMENT

The following strategy for the management of radioactive waste is proposed, which is based on the constant storage of spent fuel assemblies at the nuclear power plant:

1. Storage in the spent fuel pool for the time required to reduce the power to 1 kW.

2. Further storage of SFA in an additional spent fuel pool located outside the containment dome on the premises of the NPP for approximately 15 years, until the point when the activity decreases and changes very slightly.

3. Loading SFA from additional storage to containers for storage in a dry facility. The dry storage is being built as a covered structure with a roof, on which a pipe is installed to ensure more intense air circulation through the containers. The closed storage improves the storage conditions for containers with SFA. The service life of concrete structures is extended. It is advisable to install a filter at the air intake to prevent dust and fluff from entering the containers during the flowering of plants.

4. After the operation of the NPP is completed, the most acceptable option is to allow the main equipment to age in order to reduce the level of radioactivity. It is proposed to use the containment dome for the aging of spent nuclear fuel. That is, containers from closed storage are transferred to the reactor hall, where they can be stacked in several layers. The aging time may last until they are sent for processing.

Let us focus on some aspects of the proposed strategy. We will consider possible options for the location of the additional aging pool. We will first try to discuss some important issues that are expected when attempting to improve project solutions for handling spent nuclear fuel at the nuclear power plant.

It should be noted that all work on organizing and carrying out the removal of spent nuclear fuel from the reactor core and preparing it for placement in a storage facility is extremely dangerous for operational personnel, requiring strict adherence to radiation safety and labor protection regulations [5].

The procedure for removing individual spent nuclear assembly from the reactor and placing it in a spent fuel pool is especially dangerous. Subsequently, this danger increases due to the growing amount of spent nuclear fuel in the SFP. Transport technology operations are carried out using special technical means with minimal time period. This is achieved by preparing a plan taking into account the specific conditions of each work cycle: where it is possible to move the equipment from the reactor building. It may be necessary to move SFA that have not stood for the required time. How? What to use to complete the movement? These questions become important not only in the event of the need for the scheduled removal of equipment from the reactor and repairing the building, but also in anticipation of possible defects appearing in the building or in the equipment itself. The constant accumulation of equipment in the spent fuel pool leads to an increase in the amount of spent nuclear fuel and raises the risk in the containment area.

It should be noted that practically the only place for placing an additional holding pool inside the containment is the upper zone of the transport corridor. Justification for this is also the possibility of bringing a short link of the cooling system to such a pool; here, the conditions for moving and preparing nuclear fuel for the initial stage of holding are also simplified. Thus, the possibilities for improving the situation with additional pools for nuclear fuel within the containment are exhausted. Next, only locations outside the energy unit building may be considered for placing additional pool, which means there is a need to use additional means of transporting containers with nuclear fuel from the territory of the nuclear power plant.

Let's consider options for the placement of the additional SFP outside the containment:

- The first place for the additional SFP outside the energy unit premises is proposed next to the cooling system splash pool for critical consumers. In this location, it is advisable to build a separate facility. Here, it is possible to place undelayed 3-year SFA. According to this scheme, only the side wall of the SFP can be cooled. At the same time, the issues of SFA safety, the specified temperature regime with constant regulated cooling are easily resolved. When placing the additional SFP near the splash pools, the distance for transporting containers with SFA within the nuclear power plant area is short, with a short transportation time. The additional SFP can serve as a reliable emergency retention pool not only for one energy unit.
- Option two for the placement of additional SFP is a separate structure outside the nuclear power plant, where there will be special requirements for fencing (biological protection) and corresponding requirements

for the organization of cooling of the fuel assemblies, physical protection.

- The third option is to place such a SFP for several nuclear power plants at one of the nuclear power plants in Ukraine. In this case, preliminary partial holding of containers before their transportation to the Central SNF Facilities is possible. It should be noted that radioactive substances (RS) generated at NPPs during operation are mainly low-level waste with a half-life of radionuclides of less than 30 years. The amount of high-level waste accounts for less than 1% of the total amount of RS. The goal of the operations concerning spent nuclear fuel at the nuclear power plants is to maintain the possibility of processing SNF with subsequent disposal of RS. The core principle in managing SNF is that SNF and RS generated at nuclear power plants during operation must be pre-processed and stored at the NPP in such a way that throughout the entire storage period at the nuclear power plants, there is no potential danger from their action on staff, the population, or the environment. Controlled storage of SNF and RS at NPP is provided in special facilities (for example, in spent fuel pools and dry storage facilities) until their processing followed by the final disposal of RS in geological formations.

Moreover, during the operation of the spent fuel pool, damages may occur, some of which are practically extremely difficult to eliminate. For example, the loss of tightness of the SFP lining. According to the current regulations, spent nuclear fuel is maintained in the spent fuel pool after being in the reactor core. Regarding the WWER-1000, the fuel campaign has changed twice: the transition from a two-year to a three-year campaign, and the transition from a three-year to a four-year campaign. Today, after switching to American fuel, a transition to a 4.5-year fuel campaign is being discussed, meaning three periods of one and a half years each. During each of these campaigns, the fuel operating time changes, which means the amount of fission products that determine the power of residual heat release and the necessary cooling time in the SFP changes.

3. DETERMINATION OF THE NECESSARY TIME OF HOLDING UNTIL REACHING A POWER OF 1 kW DEPENDING ON THE TIME OF THE FUEL CAMPAIGN

The literature suggests the use of two formulas for determining the power of residual heat release [6]:

- Untermeier-Weils

$$N_{\beta,\gamma}/N_0 = 0.1\cdot\{[(\tau_{st}+10)^{-0.2}-(\tau_{st}+T+10)^{-0.2}] - 0.87[(\tau_{st}+2\cdot10^7)^{-0.2}-(\tau_{st}+T+2\cdot10^7)^{-0.2}]\}, \quad (1)$$

- Wigner-Way

$$N_{\beta,\gamma}/N_0 = 6.5\cdot10^{-2}[\tau_{st}^{-0.2} - (\tau_{st}+T)^{-0.2}], \quad (2)$$

where T, τ_{st} – the operating and standby time of the reactor after shutdown, s.

In [6] it is indicated that formula (1) is more accurate. It should be noted that both formulas give estimated values. In [2] it is stated that with a fuel campaign lasting three years and a holding time of three years, the power of the SFA is 1.7 kW. According to calculations, this value will be equal to: 1.43 kW for (1) and 3.43 kW for (2). That is, the Untermeier-Weils formula indeed gives an error of 15.6%, when the Wigner-Weisskopf formula gives a result that exceeds the reference value by twice. In the future, we will use formula (1). We will conduct variant calculations regarding the time required to achieve a power of 1 kW for the SFA. This power, according to [3], can be dissipated by natural circulation of air in a closed container.

Table 1 presents the results of the calculation of the necessary holding time in the SFP to achieve the residual thermal power of 1 kW for the reactor, which has operated with a different fuel campaign. The power at which the SFA operated is taken as the average for the WWER-1000 reactor: 3000/163 = 18.4 MW.

Table 1

Holding time of SFA to achieve a power of 1 kW

Nuclear fuel operating time, ef. days	Holding time in the SFP	
	Days	Years
300	810	2.22
600	1160	3.18
900	1450	3.97
1200	1680	4.6
1350	1800	4.93

From the given results, it can be concluded that the required holding time changes practically linearly depending on the operating time, and for the depth of burning corresponding to the operation of the reactor over 4.5 years, it is practically equal to five years.

The reduced radioactive emissions from groups of containers on the sites allow them to be placed (in groups of 30–50 containers) in light enclosed structures (with a roof). A possible structure scheme is shown in Fig. 1. The main component of these structures is concrete. The overall cost of the structure with containers can be reduced by decreasing the required thickness of the biological shielding wall of the container, taking into account the reduction in residual radioactive emissions from the groups of containers and the outer enclosure wall. The total thickness of the wall of the ventilated container (VC) and the outer enclosure provides biological protection for the environment. The thickness of the VC wall ensures biological protection at the safety level for the service personnel. The concrete in the walls of the light enclosed structures is no longer considered contaminated radioactive material, thereby reducing the volume for disposal. In addition, the use of these structures will allow:

a) to protect groups of containers from rain, snow, hail, fluctuations in ambient temperature, which will improve the condition of the concrete of the containers and increase their service life;

b) the use of a draft pipe on the roof over the group of containers. This will increase the natural draft in the ventilation channels and cooling systems of the containers by 3–5 times, the necessity of which for a ventilated container is emphasized in [3]. However, for one container this represents a significant increase in cost. But for a group of containers – this becomes reasonable and justified;

c) for a group of containers in light enclosed structures, it is advisable to organize rough air cleaning before supplying it to the containers for cooling.

Existing air pollutants (e.g., tree fluff during flowering) can adhere to the outer wall of the metal basket and contribute to the deterioration of heat removal from the SFA;

d) strengthening the physical protection of groups of containers;

e) light enclosed structures for containers allow the use of temporary lifting and transportation mechanisms on their supporting structures, simplifying and reducing the costs of installing and servicing the containers;

f) reducing the required thickness of the biological protection wall of the container. This will significantly reduce the weight of each container, which may allow for an increase in the number of SFA in the VC.

Thus, the possibility of continuing "wet" storage of SFA reduces radioactive radiation and heat release from each container and provides several advantages for further handling of SFA.

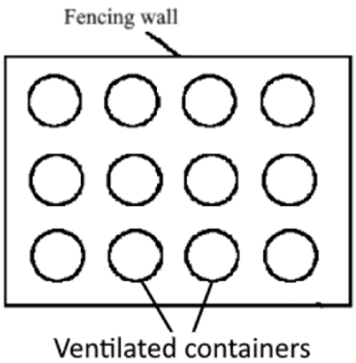

Fig. 1. Schematic diagram of the closed site for SFA dry storage

The above primarily discussed general issues related to finding rational solutions in the handling of SNF. The analysis of the overall scheme of procedures for removing the batch of fuel assemblies from the holding pond for the assembly of the next transport container revealed another issue. Fuel assemblies that had been stored in the holding pond for at least three years are removed from the pond and placed in a basket of the next transport container. The basket appears as a compact package of modules, each containing a fuel assembly.

The compactness of the fuel assembly package is so tight that the gas heat carrier can only pass along each assembly, which ensures heat exchange in the package only when it is in a vertical orientation. The transportation of the nuclear fuel assemblies to the spent fuel storage facility is planned by rail in a horizontal position. In this case, according to the transportation conditions, the heat exchange of the nuclear fuel assemblies is significantly worsened and may even stop. For heat removal from the fuel assemblies in the horizontal position of the basket, gaps between the assemblies are required (which are absent in the containers of Holtec International). During rail transportation, natural circulation will be almost nonexistent. As the train moves, air will intensively wash over the containers and enter the ventilation openings. And with stops, which should preferably be avoided, heat exchange may be worsened, so it is advisable to consider the placement of mobile fans to supply air to the storage facility. During transportation, it is necessary to ensure the entry of air into the storage facility in a horizontal position.

The absence of forced circulation of the coolant along each assembly is one of the possible causes of overheating of the central assemblies during transportation. To reduce this effect, it is proposed to leave 3–4 central cells unfilled with fuel assemblies, and instead introduce neutron-absorbing rods, which is advisable when increasing the number of cells in the basket.

Also worth noting are the issues of minimizing the volume of concrete depending on the number of fuel assemblies in the container. Let us consider the dependence of the specific volume of concrete (per fuel assembly) depending on the number of fuel assemblies in the container. The real VC consists 24 fuel assemblies (Fig. 2). The wall thickness of the container remains constant with an increase in the number of fuel assemblies and provides the allowable dose for the operating personnel.

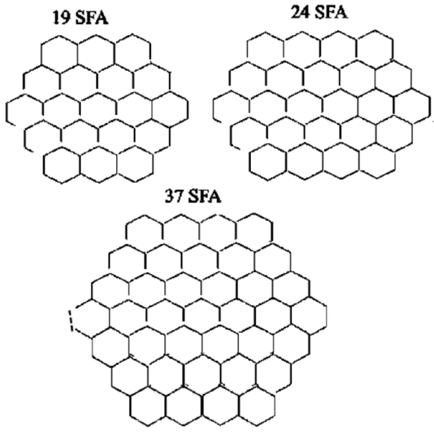

Fig. 2. Possible schemes for the arrangement of spent fuel assemblies in the storage basket

Determination of the main dimensions for a container with 24 SFA. The size of the cabinet for the cell of the SFA is 249.6 mm. The wall thickness of the "cell" is 5 mm. Thus, the grid step is h=249.6+5= =254.6 mm. From examining Fig. 2, one can determine the radius of the circumscribed circle, that is, the internal radius of the protective basket:

$$R=\sqrt{(3\cdot h)^2+(\frac{S}{2})^2}=\sqrt{(3\cdot 254.6)^2+(\frac{147}{2})^2}=769.8\text{ mm},$$

where h – the cell pitch; S is the length of a side of the hexagon:

$$S= h/(2\cdot\cos 60)=147\text{ mm}.$$

The diameter of the circumscribed circle D=1539.6 mm.

The internal diameter of the ventilated container (VC): 2007 mm. The distance to the inner surface of the concrete ring: (2007-1539.6)/2=233.7 mm.

The thickness of the concrete is 687 mm. The height of the VC is Hvc=5.809 m. The volume of concrete in the VC:

$$V_{vc} = 0.785\ (D_{external}^2-D_{internal}^2)\ H =$$
$$= 0.785\ (3.378^2 - 2.007^2)\ 5.809=33.66\text{ m}^3.$$

The specific volume of concrete per one SFA:

$$v = V_{вк}/ n_{втвз}= 33.66/24= 1.404\ m^3/SFA.$$

The results of the calculations regarding the impact of the number of installed SFA on the specific concrete consumption in VC are presented in Table 2. From the data provided, it can be seen that the outer diameter of VC when placing 70 SFA reaches the maximum value for transportation by rail. It is fundamentally possible to build a transporter with increased carrying capacity for moving VC of a new type.

Table 2

Results of concrete consumption calculation in VC depending on the number of installed SFA

Number of SFA	Inner diam. of concrete ring, m	External diam. of concrete ring, m	Volume of concrete in VC, m^3	Specific volume of concrete, m^3/SFA
19	1.754	3.126	30.53	1.607
24	2.007	3.379	33.697	1.404
37	2.261	3.633	36.871	0.996
44	2.514	3.886	40.047	0.910
61	2.769	4.141	43.226	0.709
70	3.023	4.395	46.405	0.663

The defined results shown in Table 2 allows us to conclude that with an increased amount of SFA from 24 to 70, the specific consumption of concrete decreases by 2.1 times. It should be noted that the increase in the number of SFA leads to a significant increase in its mass, which affects the transporting vehicle for the containers. The reduction of the mass of the containers is possible by using a protective structure (PS) – a building for the closed storage of containers. We will optimize the thickness of the concrete wall of the containers. The total thickness of the walls of the containers and the PS must ensure an acceptable dose of radiation for the professional personnel (group A) and remains constant, that is, equal to 687 mm. Relevant calculations were carried out for the area of closed storage of 30 containers located according to the scheme in Fig. 1. The container consists 70 SFA.

For the calculation, the following data were accepted: the distance between VC T=1.5 m, the distance from VC to the wall 1 m, height of the wall

$$Hst=Hvk+0.5=5.809+0.5=6.309\ m.$$

The volume of concrete spent on the wall is determined by the formula:

$$Vst= 2\ Hvk\ \delta st\ (Dvk+T)\ 13,\ m^3.$$

Total concrete costs for PS and VC:

$$Vcc= 30\ Vvc+Vps,\ m^3.$$

The dependence of the total volume of concrete on the enclosing structure and ventilated containers on the thickness of the VC wall is given in Table 3.

From the analysis of the given results, it can be concluded that the construction of the enclosing structure leads to a reduction in the total amount of concrete. It follows that the proposed idea is justified not only from the perspective of improving the conditions for the long-term storage of NPP waste, but also from an economic point of view.

Table 3

Calculation of the total concrete consumption for the building of enclosed storage for VC

Thickness of the VC wall, m	0.4	0.5	0.6	0.686
Volume of concrete for VC, m^3	749	964	1189	1392
Volume of concrete for the wall of PS, m^3	250	168	80.7	0
Total concrete consumption for enclosed storage, m^3	999	1132	1270	1392

CONCLUSIONS

1. The project handling of spent nuclear fuel from WWER-440 and WWER-1000 reactors involves preliminary storage of spent fuel in consideration of their systematic removal from NPPs and timely transportation by special railcars to designated facilities in the RF for preliminary processing followed by disposal. Given the deterioration of relations with the RF, a problem has arisen concerning the constant shipment of spent nuclear fuel to the RF from Ukrainian NPPs. The possibility of shipping spent fuel to the Centralized Storage Facility for Spent Nuclear Fuel does not eliminate this problem.

2. An improved strategy for handling with spent nuclear fuel has been proposed, which involves after three to four years of storage in the original spent nuclear fuel to transport the waste to a newly built additional spent nuclear fuel located on the territory of the nuclear power plant near the splash pools of responsible consumers for a period of 15–20 years. This will allow more reliable storage of radioactive waste without sending it to the central storage facility in the Chernobyl, resulting in corresponding cost savings, and the storage of radioactive waste for further use in reactors for burn-up of decommissioned radioactive fuel. After this, the spent fuel assemblies is moved to a closed dry storage facility where it can be stored until the end of the nuclear power plant's operational life. Afterward, a long-term storage site for radioactive waste may be the containment structure of the reactor compartment.

3. To improve the conditions for the dry storage of SFA containers, the use of a closed building is proposed. This requires the construction of a fencing structure, on the walls of which a roof with a ventilation pipe can be built. An air filter that will ensure the proper cleanliness of the air and more favorable conditions for cooling the concrete and VC during long-term storage is installed at the air supply to the building.

4. It is shown that with an increase in the number of SFA in the VC, the specific consumption of concrete per one SFA decreases. When placing 70 SFA in the VC, the specific consumption of concrete compared to 24 SFA decreases by more than twice. From this, it follows that increasing the number of SFA in the

container is a promising means of increasing the economic efficiency of SFA storing .

5. If we consider the possibility of reducing the thickness of the VC concrete wall by increasing the thickness of the enclosing structure wall, it is found that using the wall with the corresponding reduction in thickness is economically feasible, i.e., it allows for a reduction in the total amount of concrete.

6. With additional holding of the fissile material in the spent fuel pool and the closed storage building, the conditions for transporting the fissile material in a container for storage at the Centralized Storage Facility at Chernobyl become simpler.

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УДОСКОНАЛЕННЯ ТЕХНІЧНИХ РІШЕНЬ ПРИ ПОВОДЖЕННІ З ВІДПРАЦЬОВАНИМ ЯДЕРНИМ ПАЛИВОМ В УМОВАХ ВІЙСЬКОВОГО ЧАСУ

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За проєктом відпрацьоване ядерне паливо (ВЯП) витримується в басейні витримки (БВ) і після цього транспортується до переробного підприємства чи сховища в РФ. Після розвалу СРСР Україна побудовала сухе сховище на Запорізькій АЕС та в подальшому – Центральне сховище в зоні відчудження. Але сьогодні, коли територія країни обстрілюється, виникають велики ризики при транспортуванні. Треба також враховувати близьке розташування ЦСВЯП до кордона. Тому в роботі запропоновано використання додаткового БВ, де ВЯП може витримуватися більше десяти років, з подальшим переміщенням до розташованих за теріторією АЕС легких закритих споруд. Ці споруди є практично аналогом критого сухого сховища. Дах над контейнерами надає низку переваг для тривалого утримання. Для кінцевого утримання ВЯП після зупинки АЕС пропонується використати гермооб’єм реакторного відділення. Розглянуто можливість оптимізації кількості ТВЗ у контейнері для сухого зберігання. Наявність бетонного огородження будівлі для сухого зберігання дозволяє зменшити товщину бетону контейнера для ВЯП. Проведено оптимізацію співвідношення товщини стінки будівлі та вентильованого контейнера.

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