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Shelter Implementation Plan at the Stage of Radiation Risks Elimination for Public

In this article, efficiency of the SIP projects, which already have been implemented at the Shelter, are analyzed in the context of the staged elimination of radiation risks for public. It starts with the analysis of the Shelter state in 1998 before SIP implementation compared with the state after implementation of stabilization and other measures and finally with the state which is reached after construction of the New Safe Confinement (NSC). For the analysis a probabilistic approach has been used. Measures to be implemented in the future are mentioned in conclusions.

Keywords: Chornobyl Nuclear Power Plant Accident, Shelter Object, Shelter Implementation Plan (SIP), Risks.

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План здійснення заходів на об'єкті «Укриття» (ПЗЗ) на етапі ліквідації радіаційних ризиків для населення

Аналізується ефективність проектів ПЗЗ, які реалізовано на об'єкті «Укриття», в контексті поетапного усунення радіаційних ризиків для населення. Стаття розпочинається з аналізу стану об'єкта «Укриття» в 1998 році до початку реалізації ПЗЗ у порівнянні з його станом після виконання стабілізаційних та інших заходів та, в довершення, зі станом, досягнутим після будівництва нового безпечного конфайнмента (НБК). Для аналізу застосовано імовірнісний підхід. У висновках наведено заходи, які треба здійснити в майбутньому.

Ключові слова: аварія на Чорнобильській атомній електростанції, об'єкт «Укриття», План здійснення заходів на об'єкті «Укриття» (ПЗЗ), ризики.

On 26 April 1986, a beyond design accident occurred at the Chornobyl (Chernobyl) nuclear power plant (ChNPP) Unit 4. This was the most severe nuclear accident in the history of the use of nuclear energy for peaceful purposes. This accident destroyed the reactor core and damaged the reactor hall, the deaerator building, the turbine hall and other adjacent buildings. Barriers and safety systems protecting the environment from the release of radioactive materials from the reactor and its irradiated fuel content were destroyed. The main release of about 10^{16} Bq per day lasted 10 days. Activity releases decreased by several orders of magnitude after this period of time.

To create barriers to prevent further radioactivity spread and to protect the destroyed reactor from environmental impacts, a steel/concrete structure — the so called the Shelter Object — was built within six months after the accident. The remaining structures of the ChNPP Unit 4 are partially included within the Shelter Object (hereinafter referred to as "Shelter"). Because of the high radiation fields near the destroyed unit, it was necessary to apply remote methods for installing structures. As a result, the constructed Shelter has acquired certain drawbacks.

The Shelter hazards have been identified by the following main factors [1]:

radioactive materials with total activity about 10^{18} Bq remain in the unit, including long-lived radionuclides without reliable barriers to limit spreading of radioactivity into the environment;

the Shelter structures that function as the main physical barriers against spreading of the radioactivity do not meet regulatory requirements for mechanical strength and structural integrity;

accidental cases like the collapse of the Shelter structures, or large scale fire in the areas with high level of radioactive contamination could lead to significant releases of radioactive material into the environment;

nuclear material (by conservative estimation, about 200 tons) is located in agglomerations of fissionable material within the Shelter, thus providing the potential for a Sustained Fission Chain Reaction (SFCR). Water infiltration into agglomerations of the fissionable material could lead to an increase in effective neutron multiplication factor and, potentially, to a SFCR.

The Shelter implementation Plan (SIP) [2] was approved at the highest levels by Ukraine and a broad association of countries under aegis of the G-7 in 1997. The SIP contains both short-term and long-term actions on the Shelter safety enhancement.

The following actions are considered as the short-term ones:

stabilization of the Shelter structures;

equipping the Shelter with required systems, like a modernized dust suppression system, an integrated automated monitoring system, fire protection systems, modernized physical protection system, a management system for contaminated water of the Shelter;

improvement of programs and plans on safety assurance of personnel working at the Shelter and on the ChNPP industrial site;

improvement of the infrastructure required for the Shelter operation, implementation of various activities at the Shelter, radioactive waste management.

The long-term actions are:

construction of the New Safe Confinement (NSC);

determination of the fuel containing materials (FCM) management strategy.

The implementation of the short-term actions (projects) has been almost completed at the present time.

The construction of the NSC including auxiliary systems and supporting infrastructure is also close to finalization. This is the so-called first start-up complex of the NSC. The detailed design of the project for the dismantling of the Shelter unstable structures (the second start-up complex) and the design of the equipment and the NSC infrastructure have not been developed so far.

The FCM management strategy is developed only on a conceptual level and has to be further elaborated.

In this article, efficiency of the SIP projects, which already have been implemented at the Shelter, are analyzed in the context of the staged elimination of radiation risks for public.

1. APPROACH TO ASSESS EFFICIENCY OF THE SIP PROJECTS

The objective of the Shelter transformation into an environmental safe system is to ensure the protection of personnel, population, including future generations, and the environment from radiological hazards [3].

The safety objective will be considered as achieved, if the probability and the effect of the radiation impact on personnel, population and the environment will be reduced to reasonably achievable levels taking into account economic and social factors and which will be considered as acceptable ones in the long-term perspective.

The following correlation can be considered as an efficiency indicator for achieving the objective on safety assurance of the public:

$$W/W_p \to <1,$$

where W — the estimated probability of such CE (Critical Event); W_p — the permissible (reference) probability of a CE, which can lead to accidents with contamination of populated territory.

In accordance with the "Design Criteria of Potential Exposure Limitation for NSC" [4], the probabilities have to be assessed and compared with W_p reference levels separately for different density ranges of territory contamination σ. W_p values depending on territory contamination level (consequences category C1-C4) are given in Table 1.

Table 1. Design Criteria of Potential Exposure Limitation for NSC

Consequences category	σ, kBq/m^2		W_p, year^{-1}
	^{137}Cs	$^{239+240}$Pu	
C1	< 0,7	< 0,06	$1{\cdot}10^{-2}$
C2	0,7 — 7	0,06 — 0,5	$2{\cdot}10^{-4}$
C3	7 — 50	0,5 — 4	$2{\cdot}10^{-5}$
C4	> 50	> 4	$1{\cdot}10^{-7}$

The criteria on limitation of contamination density of territory presented in Table 1 have been calculated for a conservative scenario of "typical mixture" of radionuclides expected in 100 years (NSC operation lifetime). At the same time, the existing assessments of radiation consequences have been made for dust and "typical mixture" radionuclides activity for present time. The half-life period of ^{137}Cs is considerably lower than for $^{239+240}$Pu. Therefore, it would be more correct to compare assessments of radiation consequences with the contaminated territory limitation criteria $^{239+240}$Pu. According to [4], the contribution of $^{239+240}$Pu to activity of "typical mixture" constitutes 0,005 at present.

Assessments of probability of CE initiation in the result of individual central interim events (CIE), W_k, and respective radiation consequences are given below, CIE is an event directly leading to initiation of a CE [4].

The main CIE associated with the Shelter state of the following types are probable:

CIE-1. Destruction of roof or other localizing structure (LS) constructions or internal Shelter structures.

CIE-2. Fire.

CIE-3. SFCR.

The assessments are based on data presented in the Report on the Shelter safety state dated 2008 (RSSS-2008) [5], and in the documents [6, 7].

2. CIE-1. DESTRUCTION OF THE SHELTER STRUCTURES

2.1. Assessments of hazards associated with destruction of structures performed to assess the Shelter state in 1998 before SIP implementation

Contamination level of territories outside the Chernobyl Exclusion Zone (CEZ) depends on a scenario of roof and other Shelter structures destruction as well as spreading of radioactive dust into the air.

2.1.1. Shelter LS destruction by tornado class 3.0, drawing in and transfer of dust by tornado vortex funnel. The probability of such a destruction amounts to 10^{-6}/year [6].

Maximum contamination with α-emitting nuclides outside CEZ is assessed as 18 kBq/m^2 [5, Table 10.2—44]. According to [4], contribution of $^{239+240}$Pu constitutes 38 % from the α-emitters mixture. Thus, $\sigma(^{239+240}\text{Pu}) \approx 0{,}38{\cdot}18$ kBq/m^2=7 kBq/m^2. Consequences category is C4.

2.1.2. Shelter LS roof destruction by tornado class 1,5, drawing in and transfer of dust by tornado vortex funnel. The probability of such a CE amounts to 10^{-6}/year [6].

Density of contamination by α-emitters on the EZ border is estimated as 0,24 kBq/m^2 [7]. Thus, $\sigma(^{239+240}\text{Pu}) \approx$ $\approx 0{,}38{\cdot}0{,}24$ kBq/m^2=0,09 kBq/m^2. Consequences category is C2.

2.1.3. Shelter LS roof destruction by earthquake and dust spreading by wind.

The probability of such a CE amounts to $1{,}6{\cdot}10^{-1}$/year according to [5, Table 9.1—2].

Density of territory contamination outside the CEZ is assessed in the range from 10 to 180 kBq/m^2 (depending on models used and input data on conditions of aerosols spreading) [5, Table 10.2—50]. Contribution of $^{239+240}$Pu in activity of "typical mixture" constitutes 0,005 (see above). Thus, $\sigma(^{239+240}\text{Pu}) \approx 0{,}005{\cdot}(10...180)$ kBq/m^2 = (0,05...0,9) kBq/m^2. Consequences category is C2.

2.1.4. Destruction of the Shelter LS separate constructions by wind and dust spreading by wind. The probability of such a CE amounts to $1{,}3{\cdot}10^{-1}$/year[5, Table 9.1—2].

Consequences under partial roof destruction and drop in the Shelter of the roofing structures (not bearing ones) only will be considerably lower than the consequences indicated above in item 3). Consequences category is C1.

2.1.5. Destruction of internal structures where FCM are accumulated, or which will fall on accumulations of FCM may lead to the release of radioactive materials from the Shelter beyond the established limits.

Most probably is that the destruction of internal structures may occur in the result of additional impacts during an earthquake. Taking into account the high probability of the Shelter roofing LS destruction due to an earthquake (see above) for the Shelter state in 1998, we can assume that destruction of LS roofing and the Shelter internal structures take place simultaneously.

The probability of the destruction of the Shelter internal structures can be assumed tentatively on the same level as given for the probability of a design basis earthquake, which amounts to about 10^{-2}/year.

2.2. Prevention of hazards associated with destruction of the Shelter structures due to SIP projects implementation

2.2.1. Implementation of urgent stabilization measures ensured the reduction of the probability of a CE on destruction of the Shelter LS structures. At that, according to [7]:

stabilization project did not lead to reduction of probability of the Shelter LS destruction by tornado class 1.5 and 3.0 since the stabilization measures were not designed for tornado loads;

destruction probability of the Shelter LS constructions affected by an earthquake reduced to 10^{-3}/year;

destruction probability of the Shelter LS constructions affected by wind reduced to $4{\cdot}10^{-4}$/year.

2.2.2. Implementation of the project on dust suppression system modernization (DSSM) ensured reduction of dust release and air contamination by the creation of a protective film in the area under the roof of the Shelter.

At the same time, the consequences of the destruction of the Shelter LS by tornado will not be reduced significantly since the protective film cannot prevent drawing in dust into tornado vortex.

The consequences of the destruction of structures by an earthquake or wind can be reduced by about 2 times. However, such reduction of consequences will not lead to considerable redistribution of consequences categories for the public.

The stabilization projects and DSSM do not have substantial effects neither on probability nor on consequences for the Shelter internal structures destruction.

2.2.3. Implementation of the NSC project ensures:

personnel, public and environment protection against impact of sources of hazards located in the Shelter, with probability once every 10,000 years (safe shutdown earthquake, extreme wind, snow, shower rain, temperature) and a tornado of class F3.0 with the probability of passing through NSC once every million years;

creation of required conditions for practical activity on nuclear and radioactive materials management, in a first line for the dismantling of unstable Shelter structures.

The probability of the Shelter LS destruction will be reduced to an acceptable low value only after the dismantling of unstable constructions of the Shelter upper part, at the same time, carrying out of additional stabilization measures is possible for individual structures.

The implementation of the NSC project has no influence on reduction of destruction probability of the Shelter internal structures, since their destruction is the most probable under an earthquake only. The NSC protective structure will just ensure reduction of consequences of such event. Consequences category is C1.

3. CIE-2. FIRE

3.1. Assessment of hazards associated with large fire for the Shelter state in 1998 before SIP implementation

A large fire in non-serviced premises with high level of radioactive contamination can lead to release from the Shelter beyond the established limits.

According to [5, Table 12.4–1], the following initiating events can lead to a large fire: lightning, fire at unit 3, water radiolysis, and small fire progression. The latter can be regarded as the most probable initiating event. A small fire in non-serviced Shelter premises can be initiated primarily as a result of an initiating event associated with power supply.

Referring to initiating events which led to actual fires at the Shelter (basing on which general assessment of fire probability at the Shelter was made — 0,2/year), and also taking into account that scope of power supply in non-serviced premises is considerably lower than in premises serviced on a permanent or periodical basis, it can be assumed with certain level of conservatism, that probability of small fire in non-serviced premises is approximately 10 times lower of general probability, and, respectively, is assessed as 0,02/year. Taking into account insufficient level of control after fire initiation in non-serviced premises, it can be assumed that the probability of small fire development into large fire is high (50 %). Thus, it can be considered with certain level of conservatism, that probability of large fire in non-serviced premises is 10^{-2}/year.

Release from the Shelter under fire in the Shelter premises compared to release in case of the roof destruction is considerably lower.

The exception is the fire with propagation in the Shelter sub-roofing space. For this case we will assume that probability of large fire spreading in the sub-roofing space is high (50 %). Thus, let's assess consequences of a large fire conservatively: C2 — with probability of about $0{,}5{\cdot}10^{-2}$/year$=5{\cdot}10^{-3}$/year, C1 — with probability of about $0{,}5{\cdot}10^{-2}$/year$=5{\cdot}10^{-3}$/ year.

3.2. Reduction of the hazard associated with large fire in the result of SIP implementation

3.2.1. The implementation of the Fire Protection System project (FPS) ensured: reduction of fire loads; fire detection at its early stage; limitation of fire spreading to other premises; fire extinguishing; limitation of impact of fire dangerous factors on personnel. FPS project covers the premises of the deaerator stack only, and does not cover the most contaminated premises including premises, destroyed reactor vault and premises included in the sub-reactor space.

Thus, probability of fire initiation in the deaerator stack is reduced to a low value, but probability of large fire in the other Shelter components remains at the same level.

3.2.2. Implementation of the NSC project does not have significant impact on reduction of the large fire probability $1{\cdot}10^{-2}$/year in the Shelter. Fire detection and extinguishing systems in the NSC design are provided only for deaerator stack roof and turbine hall containing large amounts of combustible materials, as well as for areas around the Shelter.

NSC protective structure ensures significant reduction of an emergency release. Consequences category is C1.

4. CIE-3. SFCR

4.1. Assessment of the hazard associated with SFCR for Shelter state in 1998 before SIP implementation

According to [5, Vol. 3, items 9.1.5.8 and 10.2.2.10] SFCR is hypothetically possible under the following conditions: presence of hypothetical composition in FCM accumulation in which SFCR is possible under availability and distribution of the necessary water amount within the volume of this composition; ingress and distribution of the required water amount in this FCM accumulation.

It is necessary to assess conservatively the probability of composition flooding with the required water amount. Within the period from 1998 to 2008, the monitoring systems of FCM state did not register anomalies indicating changes in the state of accumulation sub-criticality. Water amount in the rooms where SFCR was hypothetically possible was not directly monitored, but indirect factors (including leaks in boreholes) show that significant water ingress into these rooms did not occur. SFCR requires forming compositions with a size of more than 1.3 m [5, Table 10.2–51].

Thus, it may be assumed that for a considerable risk of SFCR of FCM accumulation the water ingress must be increased by at least an order of magnitude.

According to [5, Vol. 1, item 3.3.3.7] the maximum rainfall within 1998—2008 was in July 2000: 172 mm. Taking into account uneven precipitations (factor 2) during the month, day rainfall may be evaluated (172/30) 2 mm/day≈10 mm/day.

One may conservatively assume SFCR probability as of 1998 equal to the probability of 100 mm/day rainfall. Day maximum rainfall with a probability of 10^{-2}/year is 105 mm/day and with a probability of 10^{-4}/year is 190 mm/day [6].

Then conservatively evaluated probability of SFCR is 10^{-2}/year (according to [5, Vol. 3, item 10.2.2.10.4]). Radiation consequences of SFCR were evaluated as local within the Shelter site.

The above assessment does not consider risks from the water ingress from the technological systems (i.e. under fire extinguishing), assuming that such risks should be excluded.

4.2. Reduction of hazards associated with SFCR due to SIP implementation

4.2.1. Within the stabilization project, light roof was repaired to decrease rainfall ingress inside the Shelter, in particular to places with FCM accumulations. One assumes that the probability of SFCR resulting from this measure is decreased by at least 10 times, i.e. to 10^{-3}/year.

4.2.2. Implementation of the integrated automated monitoring system (hereinafter — IAMS), which includes, in particular nuclear safety control system (monitoring of neutron flux and gamma-radiation dose rate), allows timely detection of criticality increase in FCM accumulation and injection of neutron absorbing solutions. Due to this, SFCR probability is decreased. Taking into account limited possibility for injection of neutron absorbing solution only on the surface of FCM accumulations, one may assume that SFCR probability is decreased by about 2 times, i.e. that considering light roof repair to $5 \cdot 10^{-4}$/year.

4.2.3. Due to the NSC project implementation, ingress of rain and melted snow will be stopped and there will be no further ingress of water to FCM accumulations from these sources. Therefore, the SFCR probability will decrease.

5. ANALYSIS OF INDEX DECREASE FOLLOWING THE SIP PROJECT IMPLEMENTATION

Probabilities of W_k divided by W_p were assessed below in Table 2. Total values of W/W_p were also assessed. The assessments are presented for each next SIP project taking into account decrease of W_k and W due to the implementation of previous projects.

Table 2. Index decrease of hazard following the SIP project implementation

Project	Category of consequences	W_p, year^{-1}	W_k / W_p				W/W_p
			Destruction of Shelter LS structures	Destruction of internal structures	Fire	SFCR	
Initial state	C1	$1 \cdot 10^{-2}$	13		0.5	1	15
	C2	$2 \cdot 10^{-4}$	800		25	-	825
	C4	$1 \cdot 10^{-7}$	10				10
STAB	C1	$1 \cdot 10^{-2}$	0.04	1	0.5	0.1	2
	C2	$2 \cdot 10^{-4}$	5	-	25	-	30
	C4	$1 \cdot 10^{-7}$	10	-	-	-	10
MDSS (Modernized Dust Suppression System)	C1	$1 \cdot 10^{-2}$	0.04	1	0.5	0.1	2
	C2	$2 \cdot 10^{-4}$	5	-	25	-	30
	C4	$1 \cdot 10^{-7}$	10	-	-	-	10
IAMS	C1	$1 \cdot 10^{-2}$	0.04	1	0.5	0.05	2
	C2	$2 \cdot 10^{-4}$	5	-	25	-	30
	C4	$1 \cdot 10^{-7}$	10	-	-	-	10
FPS (Fire Protection System)	C1	$1 \cdot 10^{-2}$	0.04	1	0.5	0.05	2
	C2	$2 \cdot 10^{-4}$	5	-	25	-	30
	C4	$1 \cdot 10^{-7}$	10	-	-	-	10
NSC	C1	$1 \cdot 10^{-2}$	insignificant	1	1	insignificant	2
	C2	$2 \cdot 10^{-4}$	insignificant	-	-	insignificant	insignificant
	C4	$1 \cdot 10^{-7}$	insignificant	-	-	insignificant	insignificant

As of 1998, the risks of potential public exposure exceeded permissible values by 800 times. This was caused mainly by the hazard of destruction of Shelter LS structures.

The analysis results show that taking into account implementation of the stabilization and MDSS projects for the public:

1. Hazard associated with destruction of Shelter LS structures was decreased by several dozens of times but remains above the reference values: by 5 times for C1 (destruction under earthquake) and by 10 times for C4 (destruction under class 3.0 tornado).

2. Hazard associated with destruction of Shelter internal structures that was not eliminated by implementation of these projects became noticeable compared to the hazard of destruction of Shelter LS structures.

3. Hazard associated with potential large-scale fire in roof void became the highest. According to conservative assessment, this hazard may exceed the reference values (approximately by 25 times).

NSC project implementation will ensure W/W_p decrease to insignificant value for a critical event with average and significant consequences (C2 and C4), under assessing sufficient tightness of the NSC main protective structure. However, there is the hazard of destruction of Shelter internal structures and large-scale fire in unattended Shelter rooms and areas (especially with FCM accumulations). Critical events caused by these events will have insignificant consequences for the public (C1), but due to high probability of these events conservative assessment of $W/W_p \approx 2$, i.e. the reference values may be exceeded. A detailed analysis of the specified hazards shall be performed and if necessary measures to reduce them shall be provided. These hazards will be essentially reduced in case of FCM removal.

Conclusions

The implemented projects within the SIP efficiently ensured protection of the public. However it must be stated that these projects did and do not eliminate hazards entirely like the hazards of destruction of internal structures and large-scale fire in the places of FCM accumulations. The NSC project ensured essential provisions for the mitigation of the consequences of these events for the public.

Today, the degree of these hazards is assessed only approximately. It is necessary to perform a detailed analysis of these hazards and, where appropriate, to define the measures to reduce them. To these measures must be assigned the dismantling and/or further stabilization of instable Shelter structures.

The above assessments were made based on the current state of FCM accumulations and other radioactive materials located in the Shelter. Degradation of this state (for example FCM destruction, formation of additional radioactive dust) will cause correspondingly level increase of the remained hazards.

Important measures are the monitoring of FCM physical state and the prevention of their further degradation. These measures are also important in view of safety assurance of FCM long-term storage within the NSC. The selection of FCM removal strategy depends on observed changes of the FCM physical state and therefore such monitoring shall be provided at all stages of the Shelter transformation.

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