Current conditions of the nuclear safety ensuring of Shelter object
THE STATE OF 4TH UNIT OF CHNPP AFTER THE ACCIDENT

Destroyed building structures

Destroyed 4-th unit of ChNPP in 1986

Fragments of the reactor core
STAGES FOR CONVERSION OF DESTROYED CHERNOBYL NPP UNIT 4 INTO AN ECOLOGICALLY SAFE SYSTEM

- Temporary (15 years) localization of radioactive materials - construction of protective facility “Shelter object”
- Destruction of Unit 4 Chernobyl NPP - generation of high-level radioactive materials
- Strengthening of unstable building structures
- Construction of New Safe Confinement
- New Safe Confinement
STAGES OF ERECTION OF ARCH STEEL STRUCTURES
New Safe Confinement

NSC performs the following main functions:

- Restriction of radiation impact on public, personnel and environment
- Restriction of ionizing exposure and radioactive substances dissemination
- Technological support
- Monitoring of the facility status parameters
- Prevention of unauthorized access to fcm and raw
- EXCLUDING OF WATER ENTERING FROM PRECIPITATIONS
Air temperature in NSC depends on environmental temperature from 5.4 °C to 30.7 °C. On bottom marks - from 8.5 °C to 18.4 °C.

- **Air humidity** under NSC depends so far on environmental conditions. On bottom marks, high humidity is permanently preserved (up to 100%).

- **Dew point** in NSC under which the condensate produces was not observed. On SO bottom marks, mist and condensate up to 5 mm are frequently observed.

- **Airflow velocities** in NSC did not exceed 1.7 m/s. Direction is Western, in SS (sub-roofing space) is Western and Northwest.
When the LRW clusters dry out, bottom sediments with a high relative content of $^{244}$Cm are formed, which is the main source of spontaneous fission neutrons.
Computer model of SO and NSC takes into account physical phenomena and processes occurring inside SO and NSC:
- Carry-over of heat between individual parts of SO, NSC and environment (processes of heat conductivity, convection and radiation heat exchange);
- Occurrence and spread of radioactive dust (RA) inside SO and NSC and its escape into environment together with airflows; evaporation, condensation and accumulation of moisture on SO and NSC surfaces, and its distribution in air of NSC basic volume by airflows and diffusion;
- Airflow movement in SO and NSC due to flowing around NSC external envelope by exterior wind airflows with different intensity, ventilation of NSC basic volume and natural heat convection in SO and NSC;
- External weather conditions – environmental temperature and humidity, wind force and direction, solar radiation; permeability of SO light roofing and structures, and of internal and external NSC envelopes for air, moisture and RA;
- Heat generation by heat sources in fuel-containing materials, heating and ventilation systems in SO and NSC, which can influence heat-moisture state and RA spread in SO and NSC.

Based on consideration of physical processes occurring between these constituents and objects, the model enables obtaining detailed information on distribution of temperature, velocity, airflow direction, radioactive aerosol concentration and temperature-moisture condition from the moment, when the NSC was installed in its design position and before operation start.
<table>
<thead>
<tr>
<th>Name of rooms</th>
<th>FCM modifications</th>
<th>Fuel, t (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Hall (914/2)</td>
<td>ACF, LFCM</td>
<td>more 22</td>
</tr>
<tr>
<td>Southern exposition pool (505/3)</td>
<td>129 cassettes with SNF</td>
<td>14.8</td>
</tr>
<tr>
<td>All upper rooms, including CH (mark +24.000 and above)</td>
<td>Fuel dust</td>
<td>4 - 5 in sub-roofing space, ~10 total</td>
</tr>
<tr>
<td>All upper rooms, including CH (mark +24.000 and above)</td>
<td>SNF</td>
<td>20 – 110</td>
</tr>
<tr>
<td>304/3</td>
<td>LFCM</td>
<td>6 ± 2</td>
</tr>
<tr>
<td>301/5+301/6+303/3</td>
<td>LFCM</td>
<td>5 ± 2.5</td>
</tr>
<tr>
<td>217/2</td>
<td>LFCM</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>Sub-reactor 305/2 and 504/2 to mark +24.000</td>
<td>ACF, LFCM, dust</td>
<td>80 ± 30</td>
</tr>
<tr>
<td>SDC (210/5+210/6+210/7)</td>
<td>LFCM</td>
<td>12 ± 6</td>
</tr>
<tr>
<td>PSP-2 -(012/14+012/15+012/16)</td>
<td>LFCM</td>
<td>minimum - 3, maximum - 12</td>
</tr>
<tr>
<td>PSP-1 -(012/5+012/6+012/7)</td>
<td>LFCM</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>Fuel under cascade wall</td>
<td>ACF, dust</td>
<td>(0.9 ± 0.3) ?</td>
</tr>
<tr>
<td>Water in all rooms of reactor department</td>
<td>soluble uranium salts, slurry.</td>
<td>~4 kg</td>
</tr>
<tr>
<td>Fuel at “Shelter” object site</td>
<td>ACF, dust</td>
<td>0.75 ± 0.25</td>
</tr>
</tbody>
</table>

At the accident moment, mass of fuel loaded in AC made 190.2 t. Estimate of fuel remained in the SO on the basis of researches of radioactivity releases at territories of USSR and foreign countries – not less than 95 % fuel of initial reactor loading, approximately 180 t.

The estimates show that at the elevations below +24.000, from 115 45 t SNF on uranium can be located. Above the mark +24.000 may be locate from 20 to 110 t fuel of initial reactor loading with considering the dust present in SO.
At least 95% of the initial reactor loading (about 180 tons of irradiated nuclear fuel) is remain inside the NSC-SO. 77±25 tons of nuclear fuel are located in room 305/2.

Fig. Cross-section of the 4th unit of the Chernobyl NPP on the axis 46 + 2500 with a dedicated room 305/2

Fig. The robot scout, equipped with cameras, lighting and other devices, moving on special rails moved into room 305/2

Fig. The results of the external inspection of the area of localization of the cluster with a high concentration of FM (southeastern quadrant of the room 305/2)
**Cluster 1.** It is the place for formation of main LFCM mass. In this part, southeast sector of "OR" plate was located and melted during the active accident stage. This part of LFCM solid contains, mainly, black lavas. The cluster contains one area with high uranium concentration (from 30 to 50 %). On are bottom part, there is a metal layer. Maximum fuel amount in a cluster ~ 50 t.

**Cluster 2.** It is the place for formation of brown LFCM. From this field during the active accident stage lavas were coming out, which later formed a large vertical flow.

The SP concrete was destroyed under thermal impact. This cluster contains, mainly, brown lavas. Maximum fuel amount in cluster may reach 30 t.

**Cluster 3.** It is an obstruction along southern wall of room 305/2, produced as a result of metal structure collapse. Assumed FCM type – fuel rod fragments, black and brown LFCM.

Obstruction volume makes ~ 60 m³. Approximately, the obstruction includes from 1 to 5 t fuel on uranium (mainly – fuel rod fragments), which is, mainly, concentrated in obstruction bottom part at LFCM solid boundary.

**Cluster 4.** Semicircular wall of loose FCM produced during meltdown of southeast «OR» sector and lava batch. The FCM have rusty-red, sometimes grey. It is supposed that these FCM have produced at the very beginning of melting process of materials located in southeast part of room.

The data of visual survey assess the volume at ~ 40 – 60 m³. The density of loose FCM can be assessed at the level of 1–1,5 g/cm³, uranium content at 4 – 6 % (mass). This cluster can contain from 1,6 to 5,4 g uranium.

**Cluster 5.** Scheme "OR" and obstruction on it.

In the cluster, there are fuel rods in amount of 50 – 100 pcs. (fuel mass from 3 to 6 t). Presumably, at upper plate of remained "OR" part during the interaction of core fragments with structural materials, LFCM layer with integrated in it non-melted fuel may be produced. A part of these FCM could penetrate inside the «OR» scheme through visually observable thermal damage of its upper plate. Total FCM volume in cluster 5 makes 70 - 100 m³, fuel mass- (12 ± 5) t.

**Cluster 6.** Polychromatic FCM. It is a FCM build-up ("stalagmite"). New formation colour – sealing wax-brown with bright-blue streaks, surface – shiny, glossy, non-subject to degradation or flaking-off. Earlier, the "stalagmite" represented a LFCM column, as if holding the upper end of concret plate. Uranium content in samples is blue ~ 5,7 %, in yellow and brown samples ~ 7 and 7,6 %. Total volume of "stalagmite" and "stalactite" ~ 0,7 m³. Average density of "stalagmite" material ~ 2,8 g/cm³. Fuel mass in cluster makes 100 – 300 kg on uranium.
**THE NEUTRON ANOMALY, REGISTERED AT THE PERIPHERY OF ZONE OF THE MCCI PRODUCT’S LOCALIZATION**

The dynamics of the counting rate (CR, impulses/sec) of neutron detectors during the emergence and self-extinguishing of the neutron anomaly in 1990

The dependence of the effective coefficient (Kef) on filling by water of available porosity

The evidence of a high temperature in 1990 at zone of localization of FCM

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This neutron anomaly can be interpreted in three ways:

1. **When water was entering into FCM cluster (which temperature was about 100 °C)** the sub-criticality level was gradually decreased (accordingly there was the temperature increasing, steam generation, and pressure/stress increasing), that led to the destruction of system's structure and to eliminating of conditions, that were necessary for maintaining or developing of SSCR.

2. **When water was entering into the FCM cluster with high temperature the system achieved the critical state (second zone) and then the self-sustained chain reaction was quenched due to over-moisten of breeding system (it reached the third zone).** This processes were indicated by decreasing of count rate of neutron detectors This option of interpretation is conservative approach.

3. **The measuring equipment failed,** but this option was excluded after careful subsequent rechecking of the equipment.
THE STATE SYSTEM (NSMS IAMS) OF MONITORING OF NUCLEAR SAFETY AT NSC-SO

Allocation of the research boreholes (RBH) with neutron detectors

Allocation of research boreholes with neutron detectors at elev. +9.0

The potentially nuclear dangerous cluster of FCM

The implementation of procedure of the metrological certification of NSMS IAMS and drilling of RBH
THE RESULTS OF MONITORING OF NEUTRON FLUX DENSITY (NFD) AND TEMPERATURE, THE GRADIENTS OF WHICH CONFIRM THE PRESENCE OF A HIDDEN FM CLUSTER IN ROOM 305/2

Fig. Precipitation intensity (L) and relative NFD dynamics ($\varphi(t)/\varphi$), registered at periphery of FM clusters by measuring channels of state system of nuclear control

Fig. Functional dependence of concrete temperature of sub-reactor slab depending on the distance to the boundary of fissile materials cluster

Fig. Dynamics of temperature recorded (in 2018) by detectors of measuring channels at periphery of FM clusters
The "Bui" device, installed in the collapse of the central hall of the ChNPP unit 4

The thermometric probe, used in measurements of heat flux and temperature

The temperature (results of measurements in research boreholes and by portable instruments) at zone of localization of nuclear dangerous cluster (room 305/2)

The determination of volume of the zone with high concentration of nuclear fuel, localized in under-reactor slab
Regardless of the approaches used in estimating the total amount of fuel in room 305/2, quite similar results were obtained:

- According to the results of estimating the amount of fuel by Cs-137 balance were amounted to $90 \pm 27$ t, by magnesium balance - $80 \pm 25$ t.
- According to the results of experimental thermometric studies in this room $75 \pm 25$ t of SNF.
- According to the results of the visual-analytical method (division into separate clusters, averaged data of analyzes of samples taken from room 305/2) – $85 \pm 25$ t by uranium.
- According to the results of analytical work, the amount of fuel in room 305/2 is equal to $80 \pm 30$ t by uranium.

According to the current Technological Regulations of the OS there is $75 \pm 25$ t of SNF in the FCM clusters localized in the sub-reactor room with an average content of NDFM of about 26% (as the maximum concentration of FM taken 100%) and an average burnout of 10.8 MW days/kg of U (and the minimum value is 4.5 MW days/kg of U).
ESTIMATES OF FM CONCENTRATION BASED ON EXPERIMENTAL-ANALYTICAL ASSESSMENTS OF MASS AND VOLUME OF THIS FCM CLUSTER
Fig. Probable intersection of FM clusters, localized in the concrete of the sub-reactor plate, where 1 – structural blockages in the room 305/2, 2 – concrete slab, 3 – lava-like FCM, 4 – clusters with high FM concentration.

Fig. Scheme of formation of multilayer structure of material environment of FCM, formed as a result of interaction of corium with concrete (modeling by means of the integrated ASTEC code).

Fig. Cross-section of products of interaction of corium with concrete (experiments COMET L2 and L3).

Fig. Results of VULCANO experiments on the study of the products of the interaction of corium with concrete.
NEUTRON INCIDENT IN 1990 AND DETERMINING THE CAUSES OF THE NFD GROWTH ON THE FM PERIPHERY. FEATURES OF LOW-ENRICHED BREEDING SYSTEMS

where 1 is brown lava-like FCM with density ($\gamma$) = 2.7 g/cm$^3$, U share = 8%; 2 - lava-like FCM with $\gamma$ = 2.5 g/cm$^3$, U share = 8%; 3 - black, $\gamma$ = 2.5 g/cm$^3$, U share = 5%; 4 - black, $\gamma$ = 1.15 g/cm$^3$, U share = 5%.

Experimental curves were obtained for samples taken from the depth of lava-like FCM flows at the lower marks of the OS.

The curves are constructed for the physical model in the form of a flat cylinder $2 \times 0.9$ m with a uranium mass of up to 20 t with an enrichment of $^{235}$U = 1.15% and a porosity of 52% by volume. The calculations were performed with the following variations of the simulation lattice step: 0.5 cm (I curve), 3 cm (II), 4 cm (III) and 5 cm (IV).
The calculations were performed using a MNCP code. Estimation of FCM PNDC parameters was performed on the basis of modeling and variational calculations of critical assemblies with input data corresponding to available experimental data.

**Material characteristics of the proposed model**

**Structure:** heterogeneous with a porosity of up to 52% of the cluster volume and a density of wetted assembly of about 4.3 g/cm³

**Composition:** 52% U (with 1.15% enrichment by 235U), light nuclei (O, Mg, Al, Na) and other elements corresponding to the samples taken on the periphery of PNDC

The range of PNDC parameters, which ensures the occurrence of SSCR at "recurrent" criticality

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of nuclear fuel (U), t</td>
<td>15 ÷ 20</td>
</tr>
<tr>
<td>Mass fraction of fuel in FCM, %</td>
<td>46 ÷ 60</td>
</tr>
<tr>
<td>The volume of the concrete slab penetration, m³</td>
<td>14 ÷ 18</td>
</tr>
<tr>
<td>The maximum volume of FCM cluster, m³</td>
<td>9 ÷ 11,3</td>
</tr>
<tr>
<td>FCM density, g/cm³</td>
<td>6,3 ÷ 7,9</td>
</tr>
<tr>
<td>FCM density taking into account the porosity filled with water (up to 52%), g/cm³</td>
<td>3,6 ÷ 4,4</td>
</tr>
<tr>
<td>Heterogeneity of the environment, cm</td>
<td>0,5 ÷ 5</td>
</tr>
</tbody>
</table>

In the case of FCM PNDC overwetting, the main factors that can affect the dynamics of the "recurrent" criticality (achieving the optimal uranium-water ratio by reducing the water concentration in the system) are the rate of water introduction, change in structure (change in spectrum/porosity range) and increase in breeding medium temperature.
MATHEMATICAL MODELING OF THE NFD DYNAMICS IN THE CLUSTER WITH HIGH FM CONCENTRATION. MODEL VALIDATION AND FORECAST ESTIMATES

The system of differential equations that connect the basic parameters of the multiplication system:

\[ \frac{dn}{dt} = \frac{\rho t}{\gamma} + S = \left[ \frac{St_{eq}}{\rho} \right] \frac{d\rho}{dt} \]

\[ \frac{dm}{dt} = v(t) - \theta (T - T_{eq}) \left( \frac{dm}{dt} \right)_{eq} \]

\[ (MC_{FCM} + mC_{H_2O}) \frac{dT}{dt} + \lambda (T - T_{eq}) \left( \frac{dm}{dt} \right)_{eq} + v(\lambda)C_{H_2O}(T - T_i) + \chi(T - T_i) = \sum v \cdot T \]

**Fig. Comparison of the results of modeling the NFD dynamics (right) and experimental data (left) obtained within a neutron anomaly in 1990**

**Fig. Examples of the dynamics of NFD dependence on the change of one parameter in a mathematical model (in this case evaporation rate)**
The effective monitoring of NFD at localization zone of potentially nuclear dangerous cluster of FCM (in room 305/2) is provided by only three measuring channels of NSMS IAMS: NFD 01, NFD 03 and NFD 04.

The nearest (to FCM cluster) detector is located at a distance of about 2.5m (1.5m of which is concrete), therefore the registered NFD's power must be lower by several orders of magnitude then the real one. In addition, the knowledge regarding the spectrum of neutron radiation at the control point is insufficient.

The concentration of neutron absorber at zone of MCCI products localization after filling it by gadolinium solution through/from dust suppression system of NSC-SO.
CONCLUSIONS ON ENSURING OF THE NSC NUCLEAR SAFETY

1. In the sub-reactor room 305/2 (the epicenter of the formation and spreading of lava-like flows of "fuel-containing materials", FCM) localized a cluster with an increased concentration of nuclear-dangerous fissile materials (FM), direct access to which is absent. Experimental data obtained at the periphery (in particular, the gradients of neutron flux density – NFD – and the temperature) confirm the presence of this hidden FCM cluster.

2. According to the results of experimental and analytical estimates of the mass of spent nuclear fuel in room 305/2 and the results of the construction of the material balance in only one ("southern") cluster is about 20 tons of FCM (more than 200 kg of NDFM). Based on estimates of the mass and volume of this cluster, it is assumed that the mass fraction of uranium in its lower part may exceed 40% (at least 30%).

3. According to the basic principles of neutron-noise diagnostics, the recorded increase of ratio of the variance to the average value in the results of NFD measurements is evidence of growth of the effective neutron multiplication factor (Keff) in this FCM cluster. Under NSC conditions (decrease in water concentration), the growth of Kef is evidence of the over-moisten state of these FCM.

4. Mathematical modeling of the NFD dynamics in FM cluster was performed and verified, and the parameters that will affect on the characteristics of possible "reverse" criticality (occurrence of self-sustained chain reaction, SCR, due to the decrease in water concentration in the system) were estimated.

5. After the NSC installation into design position, the storage conditions of the FCM clusters changes and potentially dangerous processes are observed, respectively, the problem of reassessing the effectiveness ensuring of the level of nuclear safety becomes relevant. Within the framework of a conservative approach to nuclear safety and taking into account the peculiarities of low-enriched breeding systems, as well as the interpretation of the neutron incident on June 1990 (i.e. the probability of the critical composition's existence) there is a potential risk of SCR occurrence.
Thank you for attention!