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THE NUCLEAR SAFETY MONITORING SYSTEM FOR FUEL-CONTAINING MATERIALS LOCATED IN DESTROYED UNIT No. 4 OF THE CHORNOBYL NPP AND PROPOSALS FOR ITS MODERNIZATION

The paper presents a brief description of the Nuclear Safety Monitoring System (NSMS), which is a part of the Integrated Automated Monitoring System of the "Shelter" object (a facility that covers the destroyed Unit No. 4 of the Chornobyl NPP). Further development of the NSMS is proposed by introducing algorithms for automatic identification of neutron anomalies with a help of fuzzy logic and statistical methods; digital filtering of specific irregular impulse interferences leading to metrological system failures; algorithms for predicting changes in neutron flux density and assessing changes in the nuclear hazard of fuel containing materials accumulations.

Keywords: Chornobyl NPP, nuclear safety, monitoring systems, fuel-containing materials, algorithm for neutron anomalies.

1. Introduction

The Chornobyl nuclear and radiation accident, also known as Chornobyl accident, occurred on Saturday 26 April 1986, at Unit No. 4 of the Chornobyl NPP (ChNPP) in the north of Ukraine. During this accident, the graphite-moderated nuclear power reactor was completely destroyed. Part of the reactor core was dispersed by the explosion while the remainder melted down, forming different clusters of lava-type and corium-type fuel-containing materials (FCM). [1].

To protect the environment and lock inside the nuclear and the highly radioactive inventory of the destroyed Unit No. 4 of ChNPP, the object "Shelter" (OS) also known as the "Sarcophagus" was erected in less than a year after the accident. In terms of nuclear safety, the OS is an object that contains spatially distributed clusters of FCM. The nuclear danger of these clusters lies in the probability of existence or conditions for the emergence of a fission chain reaction [2].

For the FCM clusters with a mass fuel fraction from 5 to 10 % calculations and experimental studies were conducted during the period 1986 - 1996. It showed that such detected FCM clusters are in a deeply subcritical state and under any circumstances (flooding with water or changes of mass and geometric parameters) cannot form a critical system [3]. However, there are several unobserved FCM clusters in sub-reactor room 305/2 and Central Hall that are not well studied yet due to a lack of access to them because of the extreme radiation environment. For such clusters, hypothetical uranium-water and uranium-graphite compositions were considered as possible fission chain reactions [2].

In 1997 the international Shelter Implementation Plan (SIP) was established to make the site of the 1986 nuclear accident safe by its conversion into safe ecological conditions. This giant program included various preparatory projects such as the completion of crucial infrastructure, roads, utilities, and other facilities, which were prerequisites for safe work at the Chornobyl site. One of the important milestones of this program was the installation of the unique system of 4 monitoring systems. These include a measurement and monitoring system for nuclear and radiation values from the FCM – Nuclear Safety Monitoring System (NSMS) and other systems that provide information on the structural integrity of the OS, measurements of seismic activities on the Chornobyl site and 30-km exclusion zone and the system that monitors the radiation safety.

The SIP program finished in 2020 with the design, construction, and putting on the operation of the giant arch-shaped structure over the OS named New Safe Confinement (NSC). This structure was constructed near the OS and was moved into a design position in November 2016 [4].

Prior to the installation of NSC in a design position in November 2016, the long-term dynamics of FCM neutron activity had a stable and predictable behavior.

A global gradual decline of neutron flux density (NFD) was registered while observing regular seasonal fluctuations associated with changes in the incoming moisture to the OS. However, from the time of installation of the NSC into the design position, the NFD values from some sensors located on the periphery of the unobserved FCM cluster in sub-reactor room 305/2 have changed their trend to growing [5]. This makes it relevant to revise the NSMS.

A set of proposals for the modernization of the NSMS is the subject of this work. It includes algorithms for the automatic identification of neutron anomalies; filtering of specific irregular impulse noise leading to metrological system failures; algorithms for predicting changes in NFD and assessing changes in the nuclear hazard of FCM accumulations.

2. NSMS of the OS overview

The NSMS of the OS is part of the integrated automated monitoring system (IAMS) of the OS, which was designed and installed within the framework of Task 17 of the SIP [6] – an international project to bring the ChNPP site into a safe state. The task for the creation of IAMS was set in 2001 [7]. In 2002, the NUTECO consortium developed requirements for the system. At the end of 2003, a tender was held for the detailed design and creation of the IAMS, including the NSMS, which won a consortium consisting of ANSALDO Energia SpA, ENEL HYDRO SpA (later CESI), LABEN SpA (later Tales Alenia Space) and the division of Ukraine National Nuclear Company “Energoatom” – “Atom Remont Service”. The system design was completed in 2005. Due to the severe radiation conditions and the complexity of the problems to be solved, the works on the creation of the system, its deployment at the OS, and commissioning were completed only in 2011, and the pilot operation began in 2012. In the year 2014, the system successfully passed metrological certification and since 2016 has received permission from the State Committee for Nuclear Regulation of Ukraine for regular industrial operation.

IAMS purpose is to perform complex informational support to Shelter personnel in a way easy to perceive and analyse. Online analysis of the received information allows us to identify the negative trends in changing the conditions of hazardous sources at the OS and foresee in advance and implement the preventive measures against the development of the above trends [8].

IAMS is a multi-level monitoring system (information and measurement system in formal terms of Ukrainian norms). The upper level of the system is the communication equipment, servers, and workstations. This level provides integration of subsystems, the presentation of information to the operator in a generalized form, and storage for up to 1 year of all data from 4 independent and capable autonomous operation systems – NSMS, described in that paper, Radiation Safety Monitoring System (SRMS), Structural Monitoring System (SSMS) and Seismic Monitoring System (SMS). Each such system has a unified architecture based on the principle of unification and represents at the middle level a data collection unit (DCU), which plays the role of both an operator console with a human-machine interface (HMI) and a server for processing and storing data from the lower level. The lower level is represented by a redundant network of data acquisition units (DAU) – the computerized devices distributed over the OS, to which the system sensors are directly connected. The difference between the lower level of the NSMS, SRMS, SSMS, and SMS is that each DAU of SMS is installed at a seismic observation facility located in the Chornobyl exclusion zone, and communication is carried out via a radio channel, except for the DAU located directly at the ChNPP site. Each DAU has its own HMI, is provided with an uninterruptible power supply, and is capable of autonomous operation for 72 h. Fig. 1 represents a schematic diagram of NSMS.

The NSMS hardware consists of the following:

- 19 sensor units (NFD and Gamma Dose Rate (GDR) detectors united in one assembly);
- normalizing amplifiers units (NAU) including preamplifier and amplifier, one per sensor unit;
- 6 DAUs;
- redundant optical fiber ring network between DAUs and the DCU;
- 1 DCU;
- operator’s console (monitor, keyboard, and trackball) for the DCU;
- interface with IAMS.

The detector of gamma radiation is an ionization chamber IG34 from Centronic, UK, and ensures radiation measurements from 10^0 mR/h to 10^4 R/h in the energy ranges from 0.1 to 4 MeV.

The neutron flux sensor is FC216A/2000/U235 highly sensitive coaxial pulsed fission chamber manufactured by Centronic, UK. It is surrounded by high-pressure polyethylene with a thickness of 23.6 mm in order to obtain the flattest frequency response in the energy range from thermal to 1 MeV. The thickness of the moderator was limited by the maximum diameter of boreholes available for the installation of sensor assemblies.

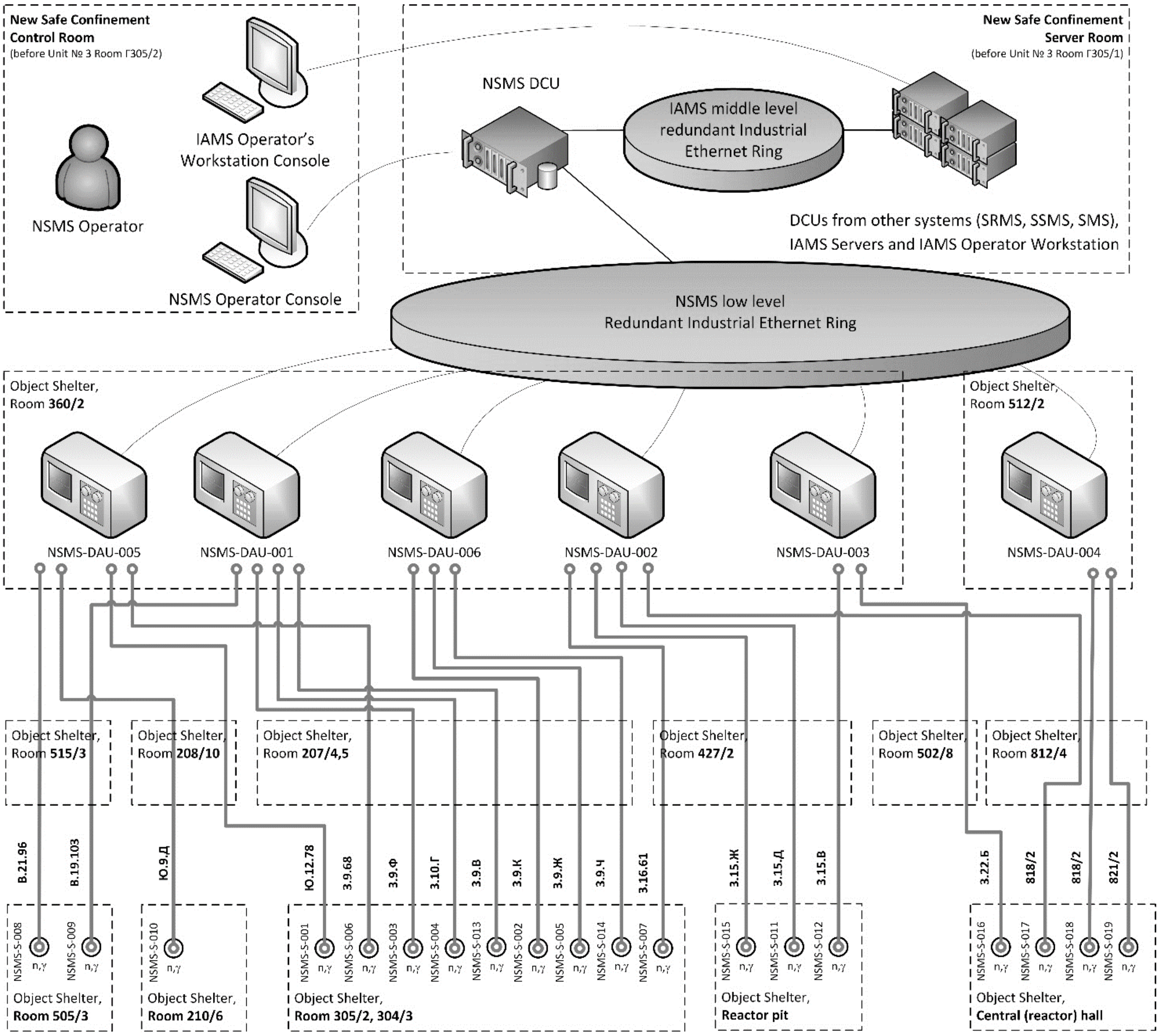

Fig. 1. Schematic diagram of NSMS (pre-amplifiers and amplifiers for nuclear sensors are not shown).

Each measuring channel for each sensor is designed as completely independent in order to exclude influence on each other.

Project coordinates (monitoring point locations) of NSMS detectors were chosen based on the condition of maximum possible approximation to FCM accumulations and maximums of count rate in NFD and GDR measurements, performed during 1989 - 1990 and updated in 2001 [9]. Sensors monitored the certain area of FCM location are connected with different DAUs. It excludes the loss of the whole scope of the monitoring area if any DAU fails [10].

3. NSMS modernization

Practical 10 years of experience in operating the system (including commissioning in 2011, when all the main equipment was deployed at the OS and minor fine-tuning of the measuring channels and software was carried out, as well as personnel training at operating equipment was in progress) has proved the correctness of the designed architectural and technical solutions. The system ensures the performance of the main functions (continuity of monitoring of the OS FCM) at single equipment failures and common cause failures. The only drawback that should be considered is the lack of temperature control in the places where the sensors are installed, however, that was laid down in the formation of design requirements.

Nevertheless, during the operation, several items were identified that required modernization of the system.

3.1. Filtering irregular impulse noise

The problem of irregular impulse interference and its identification is described in [11]. This is the most common type of metrological failure in NSMS and occurs on individual measurement channels. The main methods of solving this interference are ensuring reliable cable connections and grounding the measuring circuit. However, the solution to this issue is often associated with high personnel dose costs and, in addition, can be eliminated by upgrading the NSMS DAU software. Namely, by adding a new algorithm to the existing digital signal filtering algorithms, the essence of which is described below.

The interference observed has the form of a single pulse with a high amplitude, which when further processed by the design of digital filters (moving average over an interval of 300 s), results in a distortion of the useful signal. Such interference can be pre-filtered by selecting the median of the last 3 - 5 s of observations as the useful signal. The simulation results of the proposed algorithm compared to the existing algorithm are shown in Fig. 2.

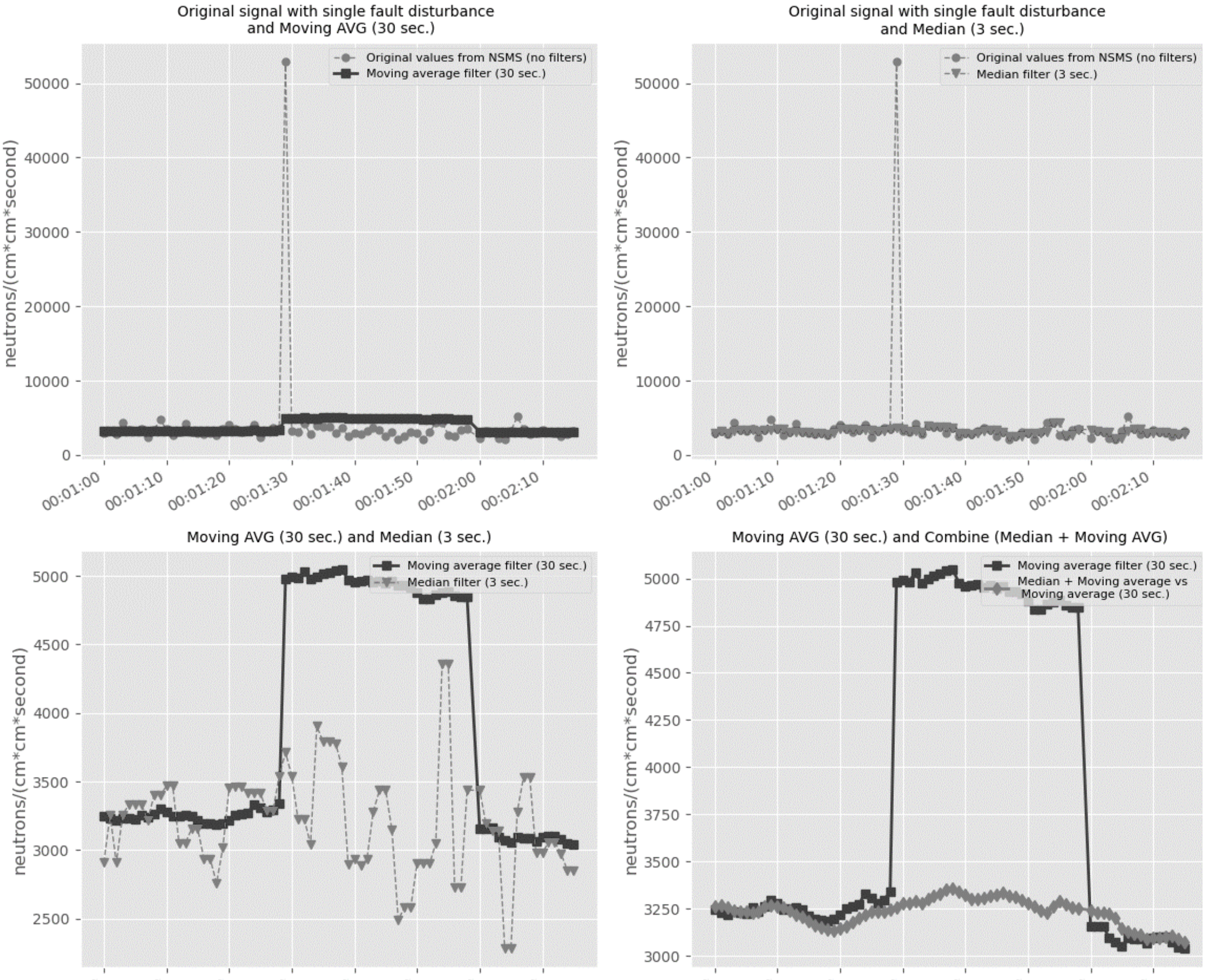

Fig. 2. Comparison of the existing and the proposed algorithm results of processing the irregular impulse interference on an NFD channel.

Such an approach may be criticized from the standpoint of detecting an instantly developing nuclear chain reaction (NCR) caused by the collapse of building structures in an OS environment with the subsequent formation of a critical component. Without going into the realism of such a scenario under the conditions of the OS-NSC system, such a theoretical NCR would be detected through an abnormal instantaneous increase in GDR readings (such data are not subjected to additional processing in NSMS), and the synchronization of information about a potential collapse from the NSMS recorded by IAMS would clearly establish the initial event.

The most realistic scenario for the occurrence of NCR at the OS assumes an increase in the growth of NFD over a significant time interval as a result of changes in the water content in the FCM accumulations [12].

Installation of the NSC in the design position eliminated the possibility of water inflow from atmospheric precipitation. However, the observed increase in NFD in the monitoring channels that monitor FCM accumulations in room 305/2 allows one to speak inconsistently about the hypothesis that these FCM accumulations are in a waterlogged state and moisture loss from them leads to an increase in the neutron multiplication factor. Estimates of existing of such a scenario are given in works [13 - 16].

In this scenario, the median filter will underestimate the absolute maximum of the registered NFD, but will not affect the dynamics of NFD changes, which is most important in this case. In fact, the use of a median filter gives the opportunity to reduce the impulse noise to an average level by treating it as a quasi-useful signal and including it in the measurement array.

3.2. Statistical identification of signal anomalies

The statistical theory of abnormal measurement estimation and identification is based on parametric methods. Their use requires two types of information: the nature of the distribution of the measured process and its parameters. The advantages of statistical methods for assessing anomalies are their simplicity, sufficient power, and a low probability of errors in the first and second types. In addition, the estimation of anomalies in a dynamic data series can be carried out both with respect to individual values in the array and for serial measurements.

Evaluation, classification, and decision-making about individual measurements can be made on the basis of an analysis of the components of a dynamic series of measurements, presented in Eq. (1)

$$Y(t_k) = S(t_k) + e(t_k) + A(t_k), \qquad (1)$$

where $Y(t_k)$ is the dynamic series of measurements; $S(t_k)$ is the useful component of the signal; $e(t_k)$ is the stochastic component of the white noise level (values of the stochastic component are uncorrelated, have zero mathematical expectation, and represent the realization of an ergodic random process); $A(t_k)$ is the anomalous component.

When assessing the abnormality of individual measurements in signals obeying an exponential distribution (for example, Poisson and Weibull), the Smolyak - Titarenko [17] and Brodsky - Bytsan - Vlasenko [18] criteria can be used. For anomalies that appear in the array of observations with a certain frequency (not single, serial anomalies), it is advisable to use the Kimber criteria [19].

The calculated value of the Smolyak - Titarenko criterion for the k-th measurement in a sample of volume *n* is determined by Eq. (2)

$$C_k = \frac{x_{k(n)}}{\bar{x}(n)}, \qquad (2)$$

where $x_{k(n)}$ – the maximum (or "suspicious of anomaly") value of the row element in the sample; $\bar{x}(n)$ – sample mean. Then the value of $x_{k(n)}$ is considered anomalous if the condition $C_k > C_{cr}(\alpha)$, where $C_{cr}(\alpha)$ – the critical value of the criterion for a given level of significance.

The Brodsky - Bitsan - Vlasenko criterion is used for an exponential distribution of form $f(x) = \lambda e^{-\lambda x}$, where λ – distribution parameter. The statistics of the criterion for abnormality checking x_k (maximum or "suspicious") value from the sample with an unknown value of λ is determined by Eq. (3)

$$z_k = \frac{x_k - x_{k-1}}{x_k - x_1}. \qquad (3)$$

To check for the abnormality of the indicator x_k the probability is calculated as follows (4):

$$P\left(z \geq z_k\right) = (n-1)!\left(1 - z_k\right)^{n-2} \prod_{j=1}^{n-2} \frac{1}{1 + j\left(1 - z_k\right)}. \qquad (4)$$

Then, if the calculated probability is greater than the accepted significance level α – the hypothesis about the abnormality of x_k is rejected.

Checking a sample in which there are several anomalous values is carried out using the Kimber test, the calculated value of which is determined by Eq. (5)

$$S_j = \frac{x_{n-j+1}}{\sum_{i=1}^{n-j+1} x_i}, \quad j = 1, 2, \ldots, n-1. \qquad (5)$$

Checking for anomalies in observation series is carried out according to the following algorithm:

1. If for $S_j(\alpha)$ – critical statistical value – for $i = 1, 2, \ldots, k$ the condition $S_j < S_j(\alpha)$ is satisfied, then, with a given significance level α the hypothesis that *k* maximum or "suspicious" values will be abnormal is rejected.
2. If condition $S_i > S_i(\alpha)$ is satisfied for $i = k, k-1, \ldots, j-1$ and $S_j > S_j(\alpha)$, then with a given level of significance α the hypothesis that *j* maximum or "suspicious" values are abnormal is accepted.
3. If $S_k > S_k(\alpha)$, then, with a given significance level α the hypothesis that *k* maximum or "suspicious" values are abnormal is accepted.

3.3. Identification of a neutron anomaly using fuzzy logic methods

With the exclusion of irregular pulse interference, one of the relevant problems will be the task of automatic identification of neutron anomalies and issuing a computer estimation of the event to the operator. One way to solve this problem is to use fuzzy set theory [20] to build a model for classifying the observed anomaly.

As is generally known, the fission of an atomic nucleus is accompanied by the release of not only neutrons but also gamma radiation, including that subsequent fission products. Thus, a change in the neutron activity of FCM will be accompanied by a change in the gamma radiation. It should be reminded that each NSMS detecting unit consists of a neutron detector and a gamma detector, placed in tandem at the monitoring point. This makes it possible to propose the construction of a hierarchical fuzzy logic inference system [21] based on the following principles:

1. For each parameter to be monitored (NFD and GDR) at a specific monitoring point and taking into account the distance from the FCM and the characteristics of the medium environment between the neutron source and detector, the FCM safe state assessments are introduced (Fig. 3):
   - not monitored, low signal failure;
   - decline;
   - normal;
   - increase;
   - attention;
   - alarm;
   - spontaneous NCR;
   - not monitored, high signal failure.
2. Each such assessment is described as a fuzzy set on the universal set of real numbers R. Where the carriers of such sets will be intervals on the set R that corresponds to the sensor readings for the entered FCM safe state estimates.
3. Then the resulting estimate of the observed anomaly can then be expressed as the following expression (6):

$$S = f\left(f_1(n), f_2(\gamma)\right), \tag{6}$$

where S – is the final assessment of the safe state of the monitored FCM, derived through the function $f(x, y)$; $f_1(n)$ – function for deriving the monitored FCM state assessment according to the NFD value; $f_2(\gamma)$ – function for deriving the monitored FCM state assessment according to the GDR value.

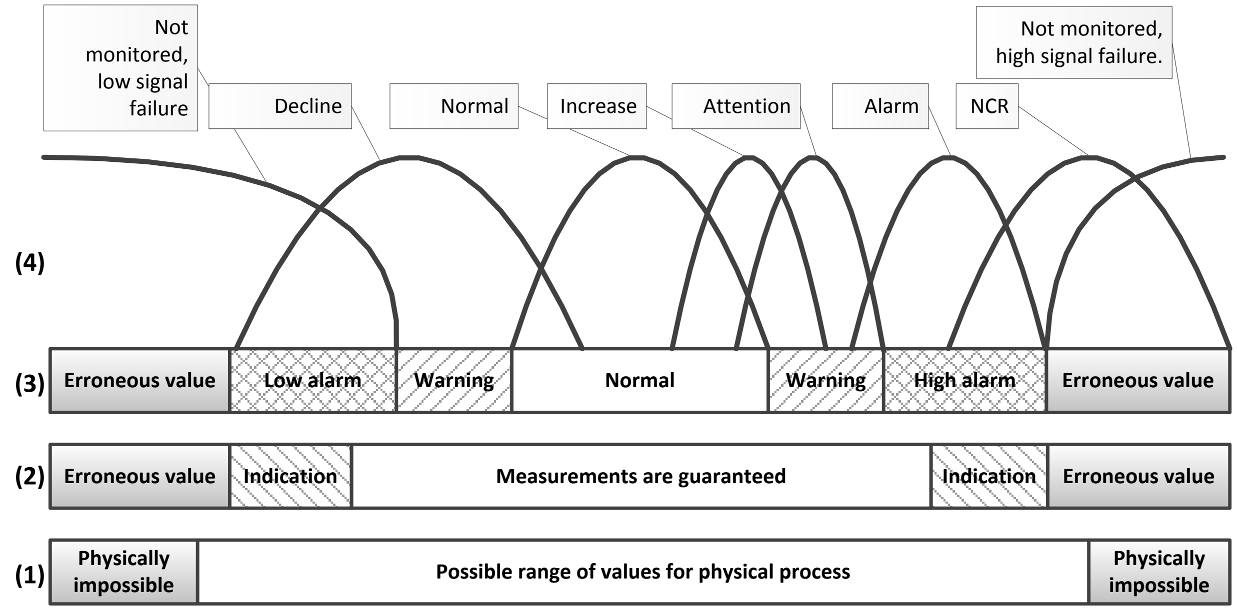

Fig. 3. General a fuzzy logic model for identifying the state of FCM by sensor’s value.

The solution to this problem by this method is beyond the scope of this article, mainly because in OS conditions, the monitoring of negative deviations from the achieved level of nuclear safety by the gamma exposure dose rate only could be ineffective. This is due to the fact that the background gamma radiation in the places where the detecting units are installed can exceed the level of gamma radiation from fission events and decay chains of fission fragments by orders of magnitude [6]. For example, for the NCR alarm systems based on GDR registration, the alarm threshold is set in μR/s units, according to Eq. (7)

$$H = \frac{2{,}7 \cdot 10^4}{R^2}, \tag{7}$$

where R – distance (in meters) from the place of the possible occurrence of SCR to detection units (in this case $R > 5$ m). That is about 4 R/h at a distance of 5 m, while the gamma radiation at some observation points is more than 1000 R/h. Therefore, it requires additional research, the results of which the authors plan to publish later.

Fig. 3 represents a general a fuzzy logic model for the identification of the state of FCM by the sensor's value. The bar marked as (1) represents the physically possible range of values for the monitored phenomenon. For example, neutron flux could not be negative and could not exceed some reasonable value for specific FCM accumulation. The bar with mark (2) represents the typical capabilities of the sensor. Any sensor normally has a range where all measurements are guaranteed with the accuracy required by the design criteria. There are also ranges where the sensor provides only quality values and where any readings will be erroneous. The bar marked as (3) represents operational thresholds. It should be noted, that in some cases alarm or warning ranges could not have operational sense. The figure area marked as (4) represents an example of possible fuzzy sets assignment to the safe state of FCM.

3.4. Monitoring of FCM by neutron-noise diagnostics methods

Another option to monitor FCM is neutron-noise diagnostic methods. These methods are based on the fact established by Feynman [22] that an increase in the multiplication factor of nuclear fission reaction can be associated with an increase in the ratio of the variance of the detector response intervals to the detected neutron to the mean value (here and after variance-mean-ratio, VMR). In subsequent works, in particular [23], the possibility of transition from the analysis of the statistics of the response intervals of the neutron detector to the statistics of the NFD values was shown. In particular, a lower bound was determined for the number of sample elements in 20,000 observations, at which the deviation of the studied parameters from theoretical values significantly decreases.

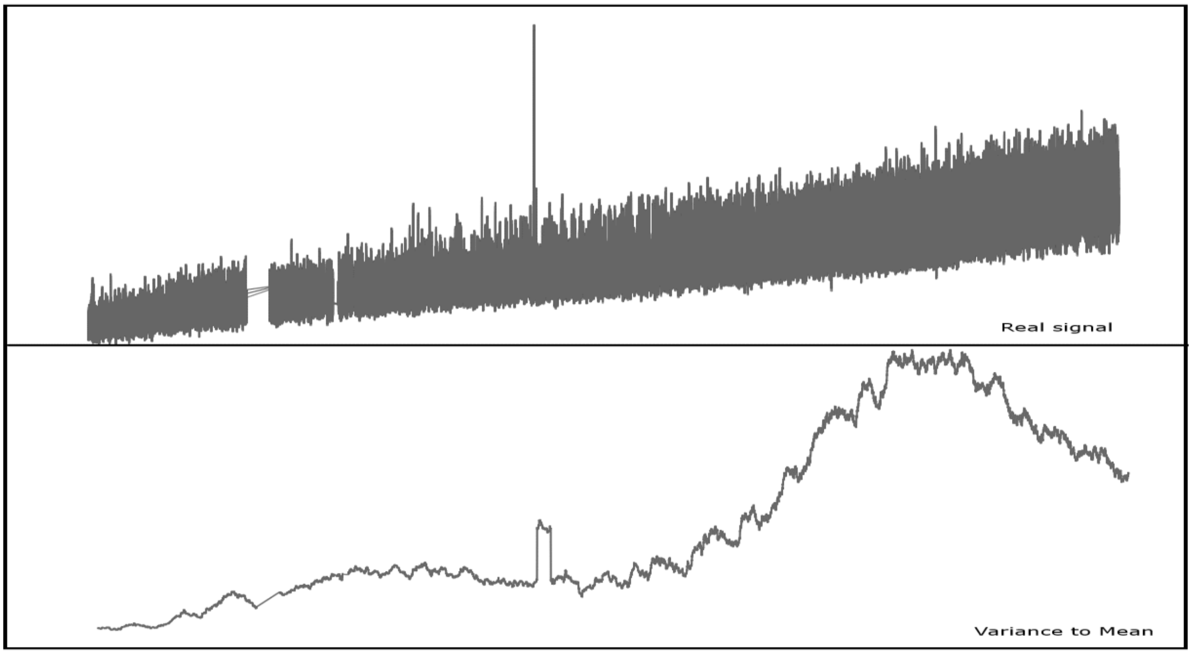

Fig. 4. Real neutron flux signal observed in the year 2019 (*top curve*) compared to its variance-to-mean ratio (*bottom curve*).

The top part of Fig. 4 illustrates the changes in readings of a NFD sensor installed inside FCM accumulation in the year 2019. It shows that neutron flux constantly grew during this period (actual values are not a subject of this work and could not be published here). Soon after the global trend of this sensor changed to the stable with the presence of season fluctuation. The bottom part of Fig. 4 illustrates the change in variance-to-mean ratio for the same signal and it shows a change in the VMR trend prior to the change of the trend of the signal. Subsequent simulation of the change in the level of subcritical according to the recorded data does not exclude such behaviour of multiplication factor of nuclear fission reaction in this cluster.

The operating experience of the ChNPP monitoring, and control system determines the following recommended intervals for the operator's historical analysis of monitored parameters: 1, 6, 12, and 24 h. This is due to the 12-hour working day of the personnel on duty. Here it should be noted that the DAU of NSMS itself stores in its internal memory a 72-hour ring-buffer archive. Taking into consideration the low computational requirements for such an algorithm, it seems appropriate to calculate the VMR on the DAU in real-time for each NFD channel for sliding time windows with the above intervals: 1, 6, 12, 24, and 72 h. Available by request to the operator, this information could be supportive for analysis in case of signal deviation from normal behaviour.

3.5. FCM monitoring by correlation analysis of sensor group signals

In [11], an approach to FCM monitoring was proposed by the correlation analysis of the signals of a group of sensors that monitor the single accumulation, when the correlation between the readings of the sensors may indicate the existence of a common cause. Such analysis is not difficult to implement in automatic mode at the level of the DCU, or an additional workstation connected to the NSMS. However, the use of classical correlation analysis to estimate the overall causal relationship between individual sensor readings is not entirely correct in terms of estimating the correlation coefficient between them.

Fig. 5 presents a correlation between pairs of NFD sensors. Some groups of sensors demonstrate good correlation. The correlation of sensors marked by black ellipses could be explained by the common cause of monitoring the same FCM accumulation. At the same time, their correlation with the sensor marked by the white ellipse has no such explanation and could be caused by an unknown factor.

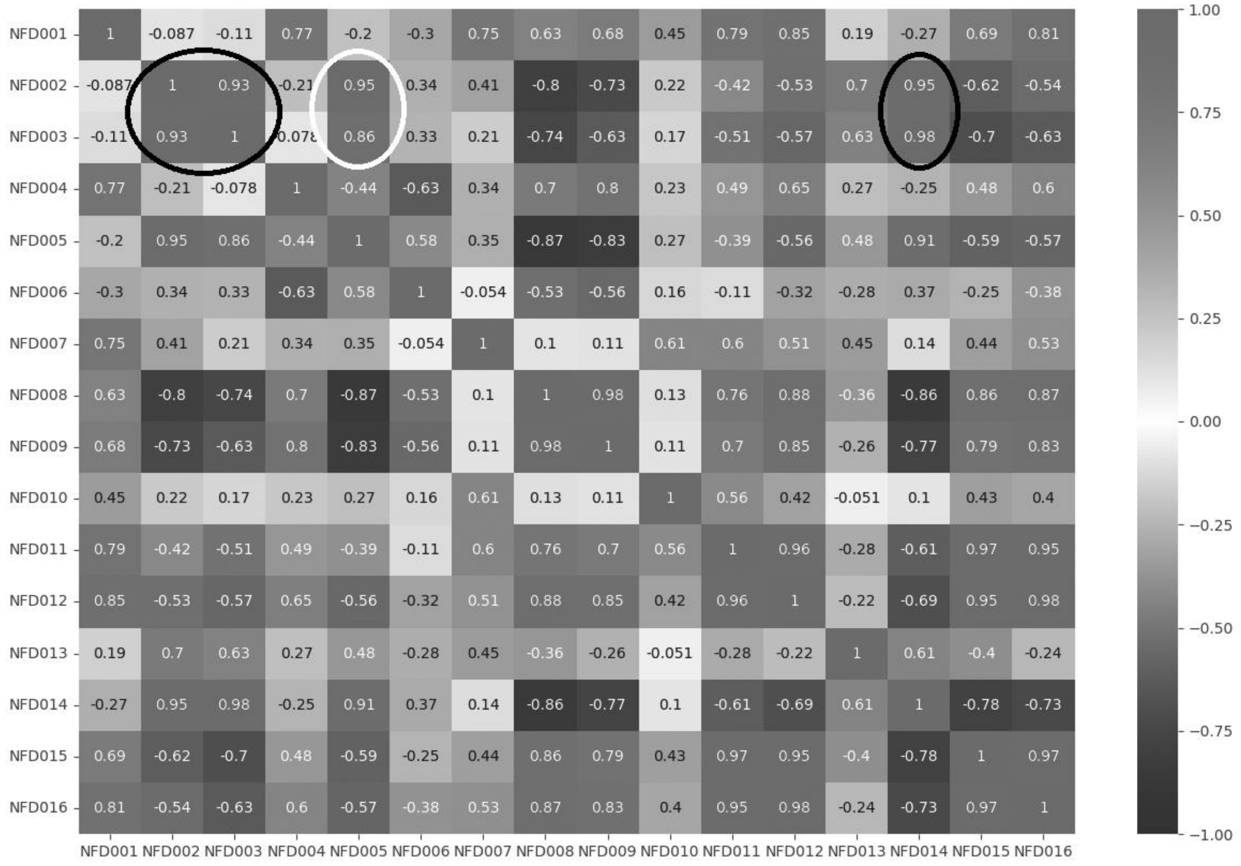

Fig. 5. Correlational heat diagram of neutron sensors observed at some period in the year 2021.

If the measurement results are presented as a relationship (8)

$$\begin{cases} Y_1 = f\left(x_1, \ldots, x_k, r_1\right) \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots, \\ Y_n = f\left(x_1, \ldots, x_k, r_n\right) \end{cases} \qquad (8)$$

where Y_i – are the results of NFD measurements by the i-th sensor located at a distance r_i from the neutron source under the influence of $x_1, \ldots, x_k$ causes, then by analogy with multivariate analysis, one can consider collinearity (multicollinearity) of the resultant signs Y_i formed by the same causes.

The test for the presence of collinearity can be conducted using the Farrar - Glober algorithm [24]

– 0 for all $Y_{i=1,n}$ (Test χ^2);

– for collinearity of individual Y_i with the remaining values $Y_{1,2,\ldots,i-1,i+1,\ldots n}$ (F-Test);

– for collinearity of each pair of values Y_i i Y_j (t-Test).

For that, hypothesis H0: “NFD measurement results have a common cause” is accepted, if the calculated values of the criteria are greater than or equal to the critical value for a given significance level α.

4. Conclusions and discussions

Undoubtedly, the NSMS system, like the IAMS as a whole, is a significant contribution to ensuring the safety of the OS and the NSC-OS system as a whole. The deployment of NSMS at the OS provided a new level of nuclear safety control and FCM behaviour. The system proved to be fully compliant with the requirements imposed on it at the stage of creation. However, the operating experience and the emergence of new knowledge of the FCM inside the OS require rethinking some design solutions and upgrading the NSMS.

Without diminishing the basic methods of dealing with metrological defects by ensuring reliable cable connections and grounding the measuring circuit, the NSMS software could be upgraded by implementing additional digital filters. For example, using the median filter presented in the work or its combination with the existing moving average filter.

In terms of neutron anomaly identification, it should be implemented additional algorithms, both at the level of individual monitoring points (DAU level) and at the level of the system as a whole (DCU level). The resulting data should be provided to NSMS operator for decision-making support. To do the same for the complexes of algorithms, the analysis of changes in the NFD, indicates a negative deviation from the achieved level of nuclear safety.

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СИСТЕМА КОНТРОЛЮ ЯДЕРНОЇ БЕЗПЕКИ ПАЛИВОВМІСНИХ МАТЕРІАЛІВ НА ЗРУЙНОВАНОМУ ЕНЕРГОБЛОЦІ № 4 ЧАЕС ТА ПРОПОЗИЦІЇ ЩОДО ЇЇ МОДЕРНІЗАЦІЇ

Наведено короткий опис системи контролю ядерної безпеки (СКЯБ), що входить до складу інтегрованої автоматизованої системи контролю об'єкта «Укриття» (об'єкта, що накриває зруйнований енергоблок № 4 Чорнобильської АЕС). Пропонується подальший розвиток СКЯБ через впровадження алгоритмів автоматичної ідентифікації нейтронних аномалій за допомогою нечіткої логіки та статистичних методів; цифрова фільтрація специфічних нерегулярних імпульсних перешкод, що призводять до збоїв у метрологічній системі; алгоритми прогнозування змін щільності потоку нейтронів та оцінки змін в ядерно-небезпечних скупченнях паливовмісних матеріалів.

Ключові слова: Чорнобильська АЕС, ядерна безпека, системи моніторингу, алгоритм нейтронних аномалій.

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