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Measuring the Equivalent Dose Rate Over the Shelter Object after Completion of the New Safe Confinement

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Shelter object,
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radiation mapping,
gamma radiation,
equivalent dose rate.

An experiment on measuring the equivalent dose rate over the Shelter object after the completion of the construction of the New Safe Confinement is described. Measurements of the gamma radiation were performed in the time of commissioning of the New Safe Confinement with the help of the sensor installed on its Main Cranes System. The carriage with a sensor was moved by a chaotic trajectory so the method of missing data interpolation was proposed. As a result, a cartogram of the distribution of the gamma field at the level of movement of the bogies of the Main Cranes System of the New Safe Confinement is provided in this paper.

Introduction

After completion of construction and commissioning of the New Safe Confinement (NSC), 2019 was the year of actual completion of the "Shelter Implementation Plan" (SIP) [1] project, which was funded by the international community for the implementation of phases 1 and 2 of the long-term strategy for the transformation of the Unit 4 of the Chornobyl Nuclear Power Plant (ChNPP) into an ecologically safe facility which was destroyed due to the accident in 1986 [2].

In the future, Ukraine will be faced with the task of implementing phase 3 — the direct transformation of the Shelter object (SO) facility, including the dismantling of unstable structures, radioactive waste management (RAW) and the development and implementation of technology for the extraction of fuel-containing masses (FCM) from the SO. These activities will be carried out under very difficult radiation conditions, both in respect of gamma radiation equivalent dose rate (EDR) and aerosol activity.

Thus, in order to prevent personnel over-exposure and based on the need to minimize the collective dose during the implementation of Phase 3 of SO conversion, the task of effective planning of activities based on the current radiation situation at the SO will remain relevant throughout the life cycle of the NSC. In its turn, such planning will be inefficient without development of a system for updating information on radiation situation at the SO.

The conceptual decision to dismantle the SO is based on the "top-to-down" principle [3]. It means the use of Main Crane System (MCS) under the roof of NSC to deliver mechanisms and personnel to the work areas, to extract the RAW and fragments of the SO, and to perform other necessary works. The planning of such activities requires up-to-date knowledge of the dose environment both in the work areas and at the height of the MCS movement.

To date, the most relevant published studies of EDR distribution on the roofs of the SO are dated 2002. [4].

The lack of more relevant data is due to high dose loads on the personnel required to perform these works, as well as the absence of a proven technology for remote measurement. The proposals of a number of organizations to perform such measurements with the help of commercially available drones were rejected by the ChNPP because of the justified risk of the control electronics failure and the subsequent uncontrolled drone fall on the OS.

The works on completion of the NSC project, together with the fact of creation in Ukraine the functional compatible device of the Mirion GIM204 type EDR measurement unit (which make it possible to connect it to NSC Radiation Monitoring System (RMS)) [5] has opened possibilities on placing of such device directly on the MCS and performance of remote measurements of a gamma dose distribution over the SO. As a result, the ChNPP, together with the Institute for Safety Problems of Nuclear Power Plants (ISP NPP) of the National Academy of Sciences of Ukraine (NASU) developed Decision No. 0500/14–04 of the ChNPP Radiation Protection Shop [6] on conducting such measurements in parallel with the tests on putting into operation of the MCS.

The works on this Decision were distributed as follows:

The ISP NPP of the NASU developed the methodology of the experiment and is engaged in interpretation of the result;

The Institute of Mathematical Machines and Systems Problems (IMMSP) of the NASU developed the program and technical architecture and conceptual mathematical algorithms;

The company "Digital Data Pro" developed software;

The company "Inter Atom Instrument" manufactured and delivered the experimental device;

ChNPP placed the device on the MCS and ensured an experiment with the participation of representatives of the NASU and the developers of the device.

The results of these measurements are presented in this article.

Input data for the experiment

Traditional methods of radiation situation mapping assume the division of the investigated area into a conditional coordinate grid (usually with a fixed step in both coordinates). Further, the measurements at the nodes of this grid are performed with the subsequent construction of isolines of the spatial distribution of pollution. If the grid spacing is large, then it is necessary to estimate the pollution at any point of space resort to methods of spatial interpolation. For a two-dimensional coordinate grid, these are usually the bilinear and bicubic interpolation methods. In this case, it is considered that the factors influencing the radiation situation are in a static state, i. e. the radiation situation in the investigated area is practically constant in a reasonable time interval.

According to the design criteria, the resolution of the MCS mechanisms ensures the positioning of the trolley with the installed EDR detector with an accuracy of ±35 mm. The trolley can be moved at speeds of up to 15 meters per minute. The spatial position of the trolley (and the bridge) is updated approximately once per second.

Gamma radiation detection unit itself provides measurement in the range from 0.05 μSv/h to 10 Sv/h with a relative error of ± 17 % [7]. The actual data update is carried out every 2 seconds due to the operation of microcomputer software implemented in the detection unit.

In both cases, data on trolley location coordinates and EDR readings are recorded in the NSC ICS historical database. In this case, the registration is based on the principle of "on change" recording.

The existing restrictions in the MCS commissioning test programme did not envisage the possibility of organizing the movement of MCS components along a regular grid. Moreover, the participants in the experiment could not significantly influence the trajectory and speed of the trolley movement.

Thus, the decision was made to limit the data obtained as a result of the actual movement of the trolley with the measuring instrument and to estimate the missing data by spatial interpolation.

Research progress

The detector of the instrument was placed on the "safe trolley" of the MCS with a slight offset from the centre of its movement axis, from the "north" side of the trolley under its floor at the level of the lower plane of the MCS movement, so that from above the detector shields the MCS structural elements are placed (Fig. 1). It was made to avoid potential effects of scattered gamma radiation from NSC structures.

Several series of measurements were made. In all cases the trolley movement and EDR readings were recorded by the NSC's ICS and archived on the historical server.

In order to eliminate the risk of data loss due to unstable communication with the instrument, all EDR measurements were duplicated to the internal memory of the device and were available for retrieval after communication recovery. Direct synchronization of the device operation with the NSC's ICS archive data server was

Fig. 1. Placement of the instrument on the Safe Trolley of MCS

provided by a single NTP server for the device and NSC's ICS (precise time server, with network protocol support for synchronization of the computer's internal clock using variable latency networks).

First experimental measurements

The purpose of the first experiment was to check the operation of the device under conditions of dynamic movement of MCS across the "working field" over the SO. Namely:

the influence of possible interferences from the operation of the MCS electric power equipment;

the presence of possible "dead" zones, where there is no radio communication with the device;

stability of the device interface with the NSC RMS;

stability of the device operation in high gamma fields (more than 1 R/h).

After installation of the device, the ChNPP personnel moved the safe trolley of MCS according to the planned test program. The movement trajectory and time diagram of the experiment are shown in Figs. 2 and 3, respectively.

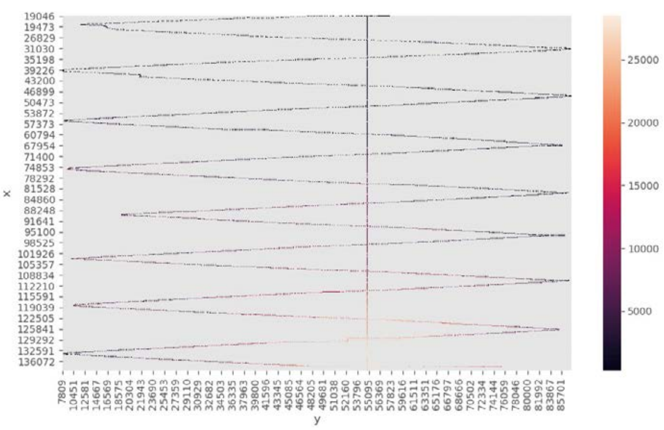

Fig. 2. Sensor trajectory over the Shelter object

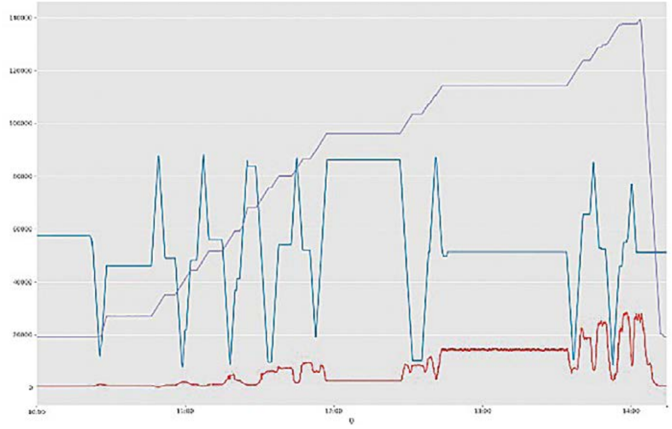

Fig. 3. Time diagram of the experiment

In the course of the experiment, a minimum value of 230 μS/hr (in the area of the northern garage of the NSC) and a maximum value of 28490 μS/hr (2.84 R/h) were recorded. Thus, the main purpose of the experiment — to check the operation of the software and hardware complex of the device and to obtain raw data for debugging mathematical algorithms — was fully achieved. As a result, it was decided to leave the device at the MCS in order to record all subsequent data on EDR values above the SO in automatic mode in the device memory and (if possible) on the NBC's IMS archive server.

On the basis of the obtained data, a software module in Python language was developed, which made it possible to build a "thermal map" of EDR density distribution over the SO. The direct visualization was performed using the Seaborn module. The data obtained in this way were processed as follows.

1. The rectangular segment in the plane under the MSC was divided into squares with the side of 1 meter. Each square was assigned coordinates *(x, y)* — corresponding to an integer number of meters from the beginning of the MCS coordinates. The obtained points are considered as nodes of a simulated EDR distribution grid over the SO.

2. If trolley was above a certain square in coordinates *(x, y)* of one or more time intervals t_i — then the EDR for this square (D_{xy}) was defined as the arithmetic mean of the detector measurements at the union of all the above time intervals. A square meter with the calculated EDR in coordinates *(x, y)* is taken as interpolation node, and pairs $((x, y), D_{xy})$ are taken as basic data point.

3. By means of bilinear interpolation methods, the values in the remaining nodes of the modeled grid are calculated from the known data base points.

As a result of the algorithm work, the following data have been obtained (Fig. 5).

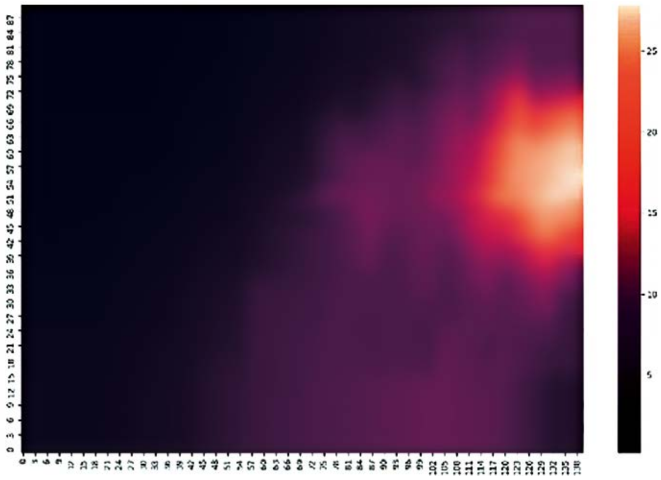

Fig. 5. Results of processing the first experimental data

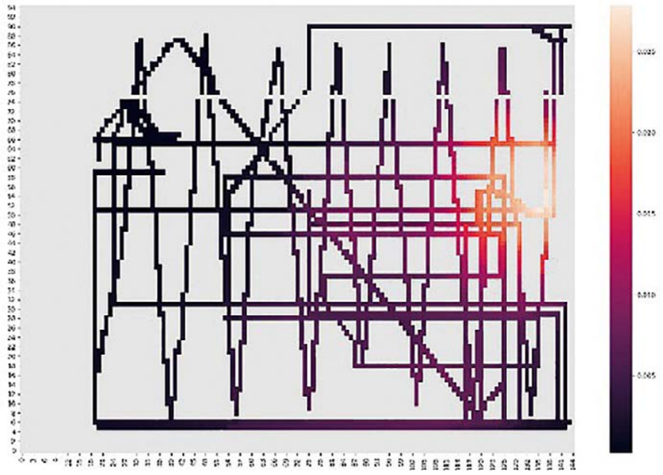

Fig. 6. Total EDR sensor trajectory for all observed time intervals

As it can be seen in the figure, the calculated distribution of EDR has a pronounced form in the form of oscillating flame, and the contours of oscillation are clearly associated with the trajectory of the trolley.

A detailed analysis of the primary results showed that there is an 8-second delay in the reading of the BDBG-09 type EDR detector. That, when the trolley moves from a "hot" place to a "cold" place, shifts the "heat" pattern to a "cold" place and vice versa. Such delay is typical for all detectors having microprocessor processing and it is caused by delays in signal processing and applied numerical filters. It should be noted here that the lag effect for the original NSC RMS detector — GIM-204 — is more significant (about 30 seconds at low activity).

Further measurements

As it was noted above, the EDR measuring device mounted on the MCS provided functional compatibility with the standard radiation monitoring instruments of the NSC RMS. Besides, the EDR readings are duplicated in the device memory. This made it possible to make a sampling of experimental data post factum, after the completion of the complex of works on testing the MCS, carried out by the ChNPP. And based on the results of long-term observations during the commissioning with the help of stationary sensors of the NSC RMS, which indicate that EDR under the NSC roof is in stable condition and its changes are related only to the shielding that occurs when the MCS is moved, it was decided to combine the results of all measurements, including the first one. The combined result of the measurements, combined with the trajectory of movement, is shown in Fig. 6.

Thus, a new dataset was selected, on which the corrected algorithm for constructing the "heat map" was applied. The essence of the algorithm changes from the one described above was reduced to the correction of the delay time of the EDR readings relative to the actual position of the cart, as well as the use of various methods for interpolating the missing data. And here it should be noted that a discussion of the "best" interpolation method is beyond the scope of this article.

Interpolation is performed by the method of iterative reconstruction of missing data with the help of the closest neighbours located at a single distance from the point under reconstruction. The essence of interpolation method is reduced to the following algorithm.

1. All the points whose values need to be reconstructed are searched for.
2. For each such point, the nearest neighbours located at a given distance are found. These neighbours form a sample, in the terminology of mathematical statistics. In this case, the distance is equal to one, and the neighbours are located along the perimeter of a square matrix of 9 cells.
3. As a value for the point to be reconstructed, some weight function is applied. In this case, if the number of neighbours is greater than or equal to 7, the median of the sample is taken as the value of the point to be reconstructed. If the number of neighbours is greater than or equal to 3, then the value of the point to be reconstructed is determined as the arithmetic mean in the sample.
4. The algorithm is repeated until all the missing points are reconstructed.
5. When all missing points are discovered a Gaussian blur filter with radius 1 is applied on the whole map.

Results and Discussion

The final calculated heat map of EDR distribution over the SO after the NSC slide is shown in the Fig. 7.

It should be noted that there are different types of interpolation available. The calculated heat map of EDR distribution over the SO after the NSC slide by the Kriging interpolation is shown in the Fig. 8. It gives probably more conservative but quite similar results by identification gamma anomalies over the SO. However, the verification of the both methods were not performed and the problem of "best" interpolation of EDR data on measurements on a chaotic monitoring network requires further study.

The obtained result was integrated with the existing 3D model of the SO-NSC system. The result of such visualization is shown in Fig. 9. As it was expected, the zone with the highest gamma rate is located close to the west side of the SO. It could be easily explained by the closest distance between the sensor and structures of the SO during measurements and the fact that while cleaning the roof of the ChNPP just after the accident, the biggest and highly contaminated (more than 1000 R/h) reactor's core parts found on the roof were dumped into the breakdown of 4 Unit exactly on this side. Here we could say that obtained results are completely corresponds to existing studies of the EDR distribution on the roofs of the SO dated in 2002 [4].

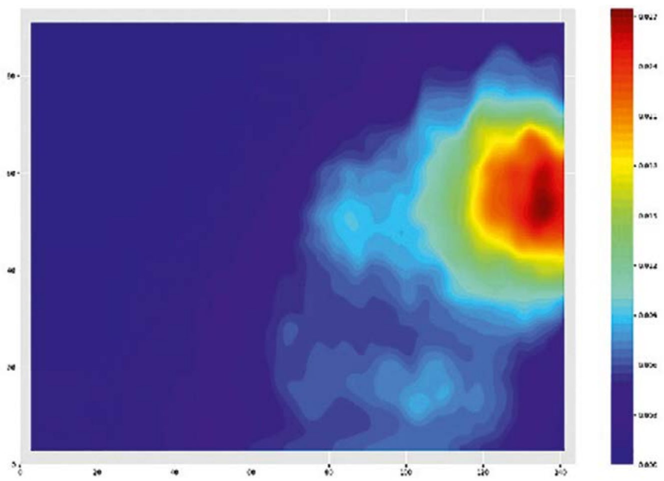

Fig. 7. Calculated "heat map" of EDR distribution over the SO after NSC slide by the algorithm above

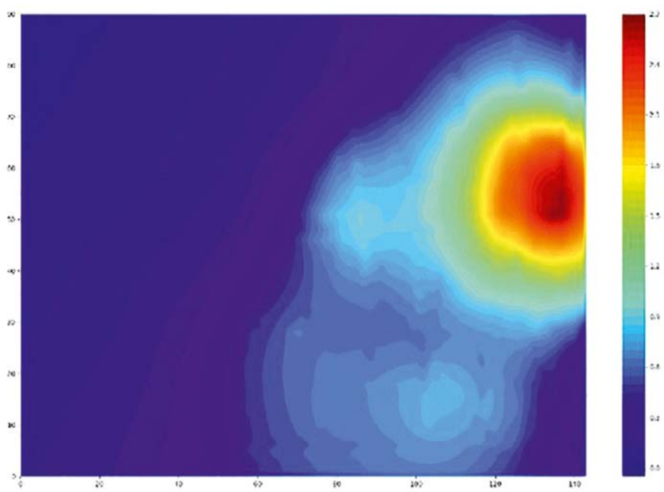

Fig. 8. Calculated "heat map" of EDR distribution over the SO after NSC slide by Kriging methods

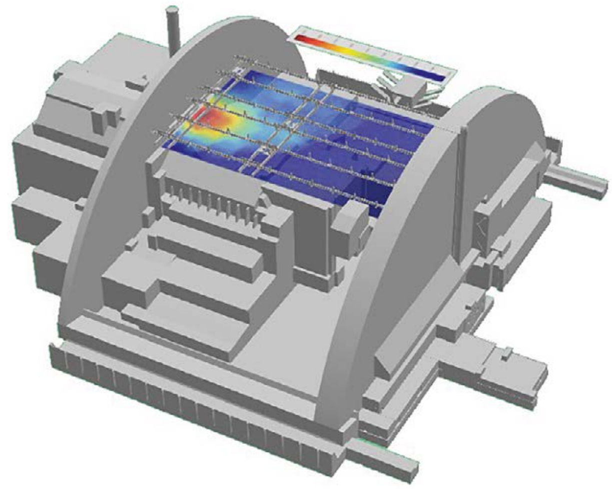

Fig. 9. Calculated "heat map" of EDR distribution over the SO superimposed on the 3D model of the SO-NSC system

The gamma anomaly on the south close to reactor hall could also be identified. However the measurements done in 2002 show 2 anomalies when measurements show only one. It will require future study and more detailed measurements in this zone.

A new measurements show also an anomaly over the reactor shaft, which are missing on the results obtained 2002 [4]. This area will need more detailed inspection in the future.

Conclusion

The work performed made it possible to create an operating technical system that ensures the actualization of data on the EDR distribution over the SO. The data obtained make it possible to continue research in the field of assessing the current state of the SO.

The problem of "best" interpolation of EDR data on measurements on a chaotic monitoring network requires further study. And a verification approach for such algorithms needs to be elaborated.

At this stage, the obtained result can be taken as a basis for calculating the collective dose when planning the maintenance of the MCS of the NSC, for example, using the tools of the ChNPP Visualization Center [8].

The obtained results of this work are planned to be used as the basis for the creation of a technical vision system to determine the radiation and technical state of the SO during the planning and carrying out work to dismantle its unstable structures.

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Вимірювання потужності еквівалентної дози над об'єктом «Укриття» після завершення будівництва нового безпечного конфаймента

Описано експеримент щодо вимірювання еквівалентної дози для об'єкта «Укриття» (ОУ) після завершення будівництва нового безпечного конфаймента (НБК). Надалі перед Україною постає завдання з демонтажу нестабільних конструкцій ОУ. Планування таких робіт вимагає актуальних знань щодо дозової обстановки як у районах виконання робіт, так і на висотах переміщення системи основних кранів (СОК). Вимірювання гамма-випромінювання проводили під час введення в експлуатацію НБК за допомогою розробленої в Україні системи, яка функціонально еквівалентна приладу Mirion GIM204 і повністю сумісна з системою радіаційного контролю НБК. Було виконано декілька серій вимірювань. Візок СОК з датчиком переміщували хаотичною траєкторією, тому було запропоновано метод інтерполяції відсутніх даних. Метод реалізовано у вигляді програмного коду, а візуалізація картограм розподілу гамма-поля виконана у вигляді «теплової карти». Під час інтерпретації результатів вимірювань відзначався ефект запізнювання вимірювань ПЕД, що під час руху візка від «гарячого» місця до «холодного» зміщує «теплову» картину в бік «холодного» місця і навпаки. Таке запізнювання характерне для всіх детекторів, що мають мікропроцесорну обробку, і це обумовлено затримками в обробці сигналу і застосовуваними числовим фільтрами. Як результат, у цій роботі подано картограму розподілу гамма-поля на рівні руху візків СОК НБК. Робота дозволила створити діючу технічну систему, що забезпечує актуалізацію даних про розподіл ПЕД над ОУ. Отриманий результат може бути взятий за основу розрахунку колективної дози під час планування технічного обслуговування СОК. У статті робиться висновок, що проблема «найкращої» інтерполяції даних ПЕД за вимірюваннями на хаотичній мережі моніторингу вимагає подальшого вивчення.

Ключові слова: об'єкт «Укриття», новий безпечний конфайнмент, радіаційне картографування, гамма-випромінювання, потужність еквівалентної дози.

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