Original Article

The information system concept for thermal monitoring of a spent nuclear fuel storage container

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ABSTRACT

The paper notes that the most common way of handling spent nuclear fuel (SNF) of power reactors is its temporary long-term dry storage. At the same time, the operation of the dry spent fuel storage facilities almost never use the modern capabilities of information systems in safety control and collecting information for the next studies under implementation of aging management programs. The author proposes a structure of an information system that can be implemented in a dry spent fuel storage facility with ventilated storage containers. To control the thermal component of spent fuel storage safety, a database structure has been developed, which contains 5 tables. An algorithm for monitoring the thermal state of spent fuel was created for the proposed information system, which is based on the comparison of measured and forecast values of the safety criterion, in which the level of heating the ventilation air temperature was chosen. Predictive values of the safety criterion are obtained on the basis of previously published studies. The proposed algorithm is an implementation of the information function of the system. The proposed information system can be used for effective thermal monitoring and collecting information for the next studies under the implementation of aging management programs for spent fuel storage equipment, permanent control of spent fuel storage safety, staff training, etc.
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1. Introduction

In modern world, the information systems are gaining more and more importance in order to support the stable functioning of various spheres of human activity. The nuclear power industry is no exception, in which information and control and information systems are quite widespread [1]. The last ones are used at all stages of the nuclear fuel cycle, and are of great importance in the formation of strategies for the development of the nuclear power industry, strategies for handling radioactive waste, managing the aging of energy-generating and other equipment [2—4], etc.

Information systems are of particular importance for the spent nuclear fuel storage systems. This technology of SNF handling is quite new, and the duration of operation storage systems is usually close to, and in some cases exceeds, 100 years. It is for such systems of long-term operation that understanding the processes that take place in them, in particular the aging process of a structure or its

element, requires the analysis of a large amount of information and the collection of a sufficient amount of data [5]. Modern information systems usage in this case is the key to the development of effective strategies for ageing management and as a result the ensuring safe operation of the storage systems.

2. Literature review

Information systems are widely used in collecting, analyzing and disseminating information about events and situations related to NPP safety — one of the first such systems was launched by the IAEA in the early 80s of the last century [6]. The purpose of creating this type of system is, first of all, the collection of information on the causes of incidents and accidents, the course of the development of incidents and accidents, as well as the consequences that take place, for the further analysis of this data and the development of measures to prevent them. With the development of information technologies, such systems are becoming more complex and provide for analysis not only information directly related to the object where an extraordinary situation occurred, but also include data such as the state of the environment [7].

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Another area of the information systems usage is the collecting, saving and processing of documentation and information regarding the operation of nuclear power units. Information systems of this type, containing databases, are used to support the decommissioning process of power units [8]. Such systems provide for the collection, storage, processing and presentation of data necessary for planning, project development and decommissioning of the NPP unit, including design and construction documentation, unit operation data, results of engineering and radiation researches, results of calculation studies; and scientific support for operation of the power unit, carried out at all stages of a nuclear power plant life cycle. Unfortunately, the scope of the usage of such systems usually does not extend to facilities for long-term intermediate storage of spent nuclear fuel.

The so-called information management systems should be singled out separately among the information systems. Such systems, first of all, should include the control and protection systems of the NPP power unit, which are designed to control the power of the reactor, control and quickly extinguish the chain reaction in all modes of reactor operation, as well as support the reactor in a subcritical state [9,10]. However, such information systems have only an indirect relation to the control of the state of fuel during dry storage, namely in the part of providing information about the initial state of fuel at the time of loading it into long-term storage systems.

Another direction of application of information systems in the nuclear power industry is personnel training [11,12]. The so-called "simulators" are widely used for the training of operational and management personnel of NPPs, which include both hardware that simulates the operation of the equipment, as well as virtual programs and databases that monitor the training process and help analyze the results of completing one or another practical task. This direction of using information systems is, unfortunately, not typical on the stage of SNF storage and mentions about these systems development was not found in open literature.

Unfortunately, as mentioned above, despite the large number and variety of information systems, as well as their fairly high versatility and adaptability to the variety of processes taking place in the nuclear power industry, such systems are used quite rarely for the stage of SNF handling.

Thus, one of the first information systems should probably be considered the Research Reactor Spent Fuel Database (RRSFDB) [13], which stores information about existing SNF repositories of this type of reactors.

Another well-known database of spent nuclear fuel is the Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) [14]. UNF-ST&DARDS is a classic information system that provides technical data for various waste management systems, and also provides tools for analysis/evaluation of this data, allows for the analysis of fuel cycle systems in the framework of various types of studies (for example, to conduct thermal analysis, criticality analysis, etc.) and definition of security guarantees. The database provides access to key technical data and analysis capabilities for the characterization of SNF stocks, which creates opportunities for assessing safety, risk, and uncertainty in the waste management system.

The need to create information systems is also discussed in Ref. [15]. The authors note that for a country that widely uses nuclear energy and has to develop a strategy for handling spent nuclear fuel, it is extremely important to create information systems and use SNF databases.

Unfortunately, mentioned databases and information systems have some limitations. So, for example, they often contain only data on the quantity and quality of stored fuel, the location of the storage facility, the storage period, and do not contain the results of monitoring the state of spent fuel during storage, especially those related to the thermal state of the fuel and the main storage equipment. Known systems also lack functions that would allow them to be used during personnel training or at the stage of construction of new storage facilities. Therefore, there is a need to create an information system that would implement the above functions.

3. Problem formulation

Monitoring the thermal state of spent fuel is one of the key issues of dry storage operation safety [16,17]. Spent nuclear fuel storage facility located on the territory of the Zaporizhska NPP was chosen as the research object for the studying outer factors influence. The facility has been in operation since 2001 and has a fairly large amount of data on the thermal condition of SNF containers monitoring. In order to generalize the influence factors and identify those that can have a significant impact on the state of SNF, an analysis of the results of temperature measurement was carried out.

From the first day of the SNF storage facility operation, the temperature control of the air at the exit from the upper ventilation channels of the storage container is carried out. It is advisable to use this data to assess the degree of weather factors influence, in particular wind and outside air temperature, on the containers thermal state.

Wind is the most influential factor in the formation of temperature fields of containers, SNF stored in them and ventilation air inside the container. Further the results of temperature measurements at the outlet of the containers ventilation tracts in calm conditions and when the wind blows on them for the period from August 2001 to December 2009 are presented. The scheme of measurement markings is shown on Fig. 1. Values of ventilating air temperature in each channel ($T_{i\ out}$), ambient temperature (T_a) and wind characteristics (direction and wind velocity w) refer to the current state.

During the considered period of operation of the nuclear fuel storage facility at the Zaporizhska NPP, 33 days with no wind (calm weather conditions) were recorded on the days of temperature measurement.

It is obvious that, provided there is no wind and any external influences from nearby containers and radiation protection structures of the storage facility, the maximum and minimum
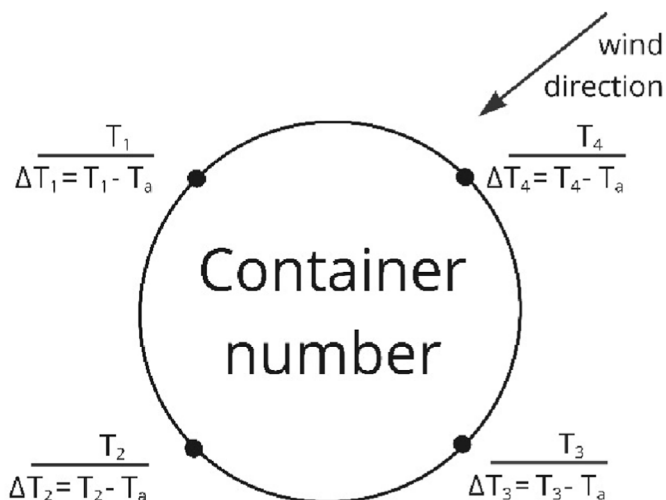
Fig. 1. Location of temperature control points in the container's ventilation ducts.

temperatures will be observed in the same channels regardless of the outside air temperature. For example, consider container No. 1, which was installed on the site on January 24, 2001. Temperature measurements in calm conditions (w = 0 m/s) are shown on Fig. 2.

Based on the temperature measurements from 14.03.2002, the maximum temperature of the ventilation air in the outlet channels of container No. 1 is observed in channel 3, the minimum in channel 2, while the difference between these values is about 7°. A similar pattern is observed during measurements on 15.05.2002 and 29.03.2003 with minor deviations that may lie within the error of the measuring equipment. The general temperature level, as can be seen from the figure, depends on the temperature of the atmospheric air.

The non-uniformity of the temperature values in the output channels is most likely caused by the different values of the decay heat of the fuel assemblies that stored in the container. That is, such a situation is possible when fuel assemblies with a higher value of decay heat are concentrated near the storage cask surface, which is cooled by ventilation air coming out of one of the ventilation channels, causing higher temperatures in it.

It should also be noted that after the storage of the SNF container at the storage site for about a year (see Fig. 2, measurements from 14.03.2002 and 29.03.2003) and with a slight difference in the ambient air temperature during the measurement, the general picture of the distribution of maximum and minimum temperatures on exits from the channels remained, but their level decreased slightly, which is due to the decrease in the heat release of spent fuel over time.

The values of air temperatures at the exit from the ventilation channels of a storage container in calm conditions sometimes are not direcly depend of ambient air temperature changes as it could be expected. So, for example, for container No. 1 on December 5, 2002, the temperatures shown on Fig. 3.

Such a change occurred, most likely, due to a local wind parameters changing (direction, velocity or both of them), which was not recorded by the meteorological station. From the data of Fig. 3, and it can be assumed that during the temperature measurements in the ventilation channels, the wind was directed into the output channel 1, as shown on Fig. 3, b. This led to the mixing of cold atmospheric and warm ventilation air, which significantly affected the measurements in channel 1 (the heating temperature decreased by approximately 16°) and somewhat affected the heating temperature in other channels (the heating temperature decreased by approximately 4°).

The different degree of the wind influence on the temperature in the channels is due to the structure of its movement around the storage container (see Fig. 3, b). A significant part of the wind flow flowing into the container enters channel 1. Channels 2 and 4 of the container are influenced by the flow moving almost parallel to the plane of the exit section of the channels, so its influence is much smaller than on channel 1. The air temperature in outlet channel 3 is not affected by the main wind flow, but by the vortex formed by it after bending the container, so its influence is also insignificant, as can be seen from the measurement results.

To confirm the conclusion about the effect of wind on the results of temperature measurements and the formation of temperature fields of the container and air, the temperature of the air coming out of the ducts on the days of measurements was analyzed. The direction of the wind relative to the upper ventilation ducts was similar to that shown in Fig. 3, b. The value of the temperature measurements when the wind flow hits a separately located container is shown on Fig. 4.

When the wind blows on the outlet channel 1 (see Fig. 4, a), there is a significant decrease in the heating temperature of the ventilation air in it (compared to calm conditions on 14° and almost 8° for both considered cases respectively) and lesser changes in the other outlet channels. The same can be said when analyzing the values of air temperatures (see Fig. 4, b) when the wind flows into channel 3. Therefore, this confirms the assumption that it is the influence of the wind that leads to the redistribution of temperatures at the exit from the ventilation channels.

The effect of wind velocity on the temperature of the heated ventilation air should be highlighted separately. As the wind speed increases, the heating temperature decreases because most of the cold atmospheric air enters the ventilation channel, preventing the exit of the container of heated ventilation air and mixing with it. This fact is confirmed in Fig. 4a and b. In the first case (Fig. 4, a), when the ambient temperature changes by 2.1° and the wind velocity changes by 1.1 m/s, the heating temperature in ventilation channel 1 changes by 8.5°. An increase in wind speed by 2.3 m/s reduces the temperature of the air leaving channel 3 by 8.5 degrees as well (Fig. 4, b) at the almost same ambient temperature. In both cases, the influence of the storage period (i.e., the decrease of decay heat over time) can be neglected, since it minor temperature reduce of the air at the exit from the channels [17].

The analysis of temperature measurements and the structure of wind flow for a stand-alone container makes it possible to reveal only the general principles of the temperature fields formation of the container and air at the outlet from the ventilation channels during dry storage of spent nuclear fuel on the open storage site. Since the location of one container at a large distance from others or from radiation protection structures is not typical for a storage
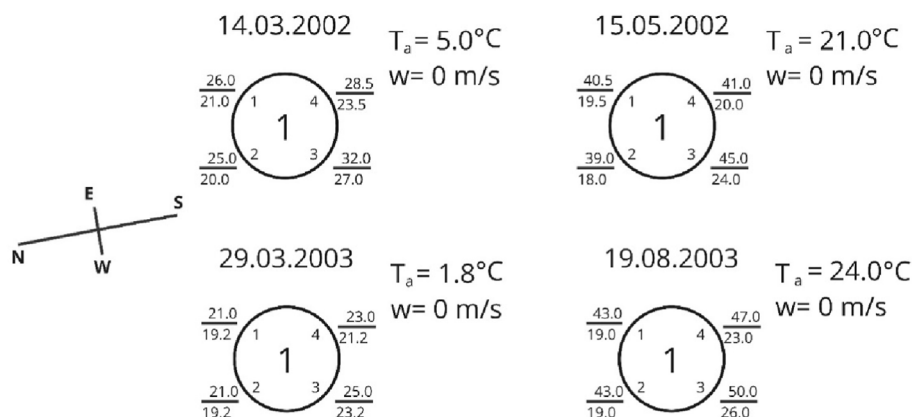

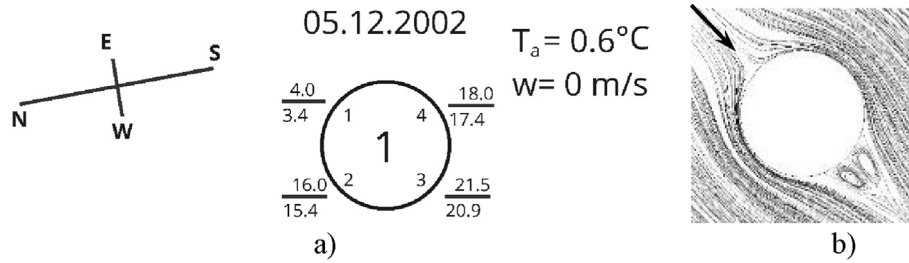**Fig. 2.** The value of air temperatures at the exit from the ventilation ducts in calm conditions.

Fig. 3. A separate container is located on the storage site: a − temperature value at the exit from the channels; b − structure of air movement around the container under wind influence.
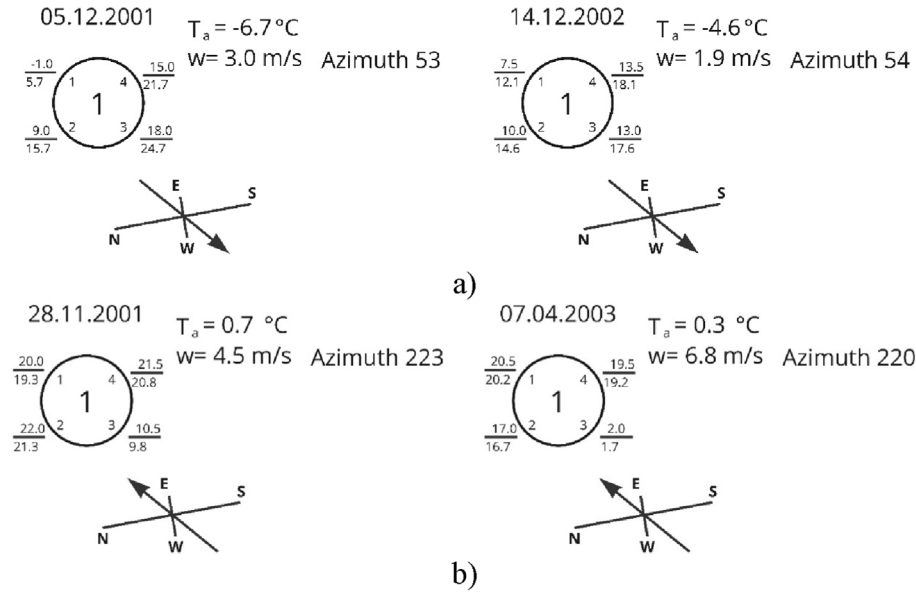

Fig. 4. Values of measurements of the temperature of the air coming out of the container channels when the wind flow hits a separately located container: a − inflow to channel 1; b - inflow to channel 3.

site, it is advisable to consider temperature measurements made in containers that are located in a group (Fig. 5).

As can be seen from Fig. 5, in calm conditions, the heating of ventilating air of each container **is** similar to the air heating for single container. It was also shown in Ref. [18]. The different degree of heating of the ventilation air during the measurements in April and August is due, most likely, to the different value of the ambient air temperature and to the decrease in the intensity of the heat release of the fuel assemblies over time.

When placing containers in a group, local short-term wind gusts may also occur, which can change the values of ventilation air temperatures at the outlet from the channels. Thus, during the measurements on 03.04.07 (see Fig. 5), container No. 12 was subjected to such an influence, in which the heating temperature of the ventilation air in channel 3 decreased to 4.5° (compared to the calm conditions 02.08.05, presented on the same figure).

Considering the effect of wind on a stand-alone container, it is advisable to analyze the temperature measurements of ventilation air for a group of containers in the presence of wind (Fig. 6).

A wind flow with a velocity of 3 m/s flows into channel 3 of container No. 9. For this container, the nature and reasons for changes in temperature measurements are the same as for a separate container. Containers located within a group are affected differently. As can be seen from Fig. 6, b the wind can carry away the warm air coming from the channels of one container and mix it

with the air coming from the channels of the neighboring container. Thus, the values of ventilation air temperature measurements can undergo significant changes depending on the direction of the wind, its velocity and the temperature of containers located nearby.

Thus, it can be concluded that when creating an information monitoring system, it is necessary, first of all, to store information about air temperature, wind speed, and wind direction and take it into account when determining the real thermal state of SNF during storage. Modern monitoring systems, unfortunately, do not have an implemented function of measuring data analysis, therefore monitoring the thermal state of spent fuel with their help is somewhat limited.

The goal of creating an information system for monitoring the state of SNF during its dry storage should be to improve the quality of control of the thermal state of SNF during the storage period, to preserve the "thermal history" of the operation of equipment and stored SNF for the development of an effective aging management strategy. However, it should be noted that when creating an information system for monitoring the state of spent fuel, it is necessary to take into account the parameters that are important in assessing the nuclear and radiation safety of the facility, but these issues are not covered in this work.
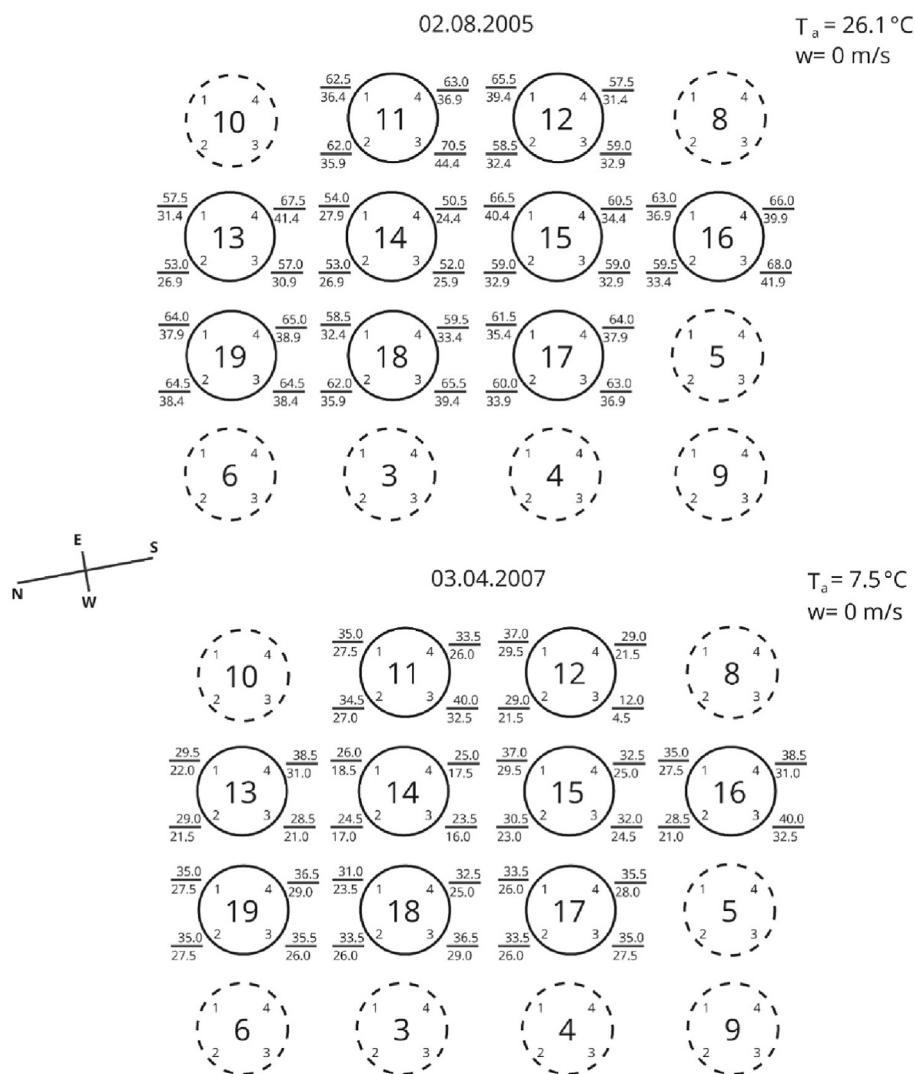
Fig. 5. The value of air temperature measurements at the outlet from the ventilation channels in a group of containers at calm conditions.

4. Monitoring information system structure

First, a conceptual model of the information system for monitoring the state of spent fuel was built (Fig. 7) for the thermal component of the complex concept of storage facility safety. The conceptual model is built in the form of an ER-model in the notation of P.Chen [19,20], entities are displayed in the form of rectangles, connections in the form of diamonds, the line shows the entity's participation in relations.

It can be seen from the conceptual model that factors affecting the thermal condition of SNF [21,22] and storage equipment and safety criteria should be taken into account when monitoring and comparing monitoring results with safety criteria. So, for example, the safety criteria are different when operating storage containers: in case of violations of normal storage conditions (for example, the influence factor is ambient air temperature), for short-term modes, the maximum temperature of the VVER-1000 fuel can reach 450 °C, in other cases, the safety criterion is not to exceed fuel temperature of 350 °C. Impact factors are also taken into account during monitoring, since the temperature of the ambient air is a directly necessary value when determining the state of spent fuel during storage [17]. And, finally, the monitoring parameters are compared with the safety criteria in order to conclude about the state of the equipment.

The information system should include external hardware, which should include means of measuring ventilation air temperature, temperature and wind speed, etc. The information received with the help of external hardware will be transferred to the database management system, which, in turn, consists of software and hardware. Software tools include an automated user workplace, software modules that convert analog information into digital and ensure its preservation in a database, etc. Hardware includes servers, monitors, etc., which ensure the functioning of software and the user's workplace. Based on this, a more detailed structural diagram of the information system will have the form shown in Fig. 8.

It can be seen from the above diagram that one of the important elements of the proposed information system is the database. The structure of the database for the information system for the SNF state monitoring is shown in Fig. 9.

It is proposed to include five tables in the database: "Monitoring", "Weather factors", "Criteria", "Container", "Fuel". Each of the tables will contains certain information that will allow to determine the thermal state of the fuel during the storage. The date
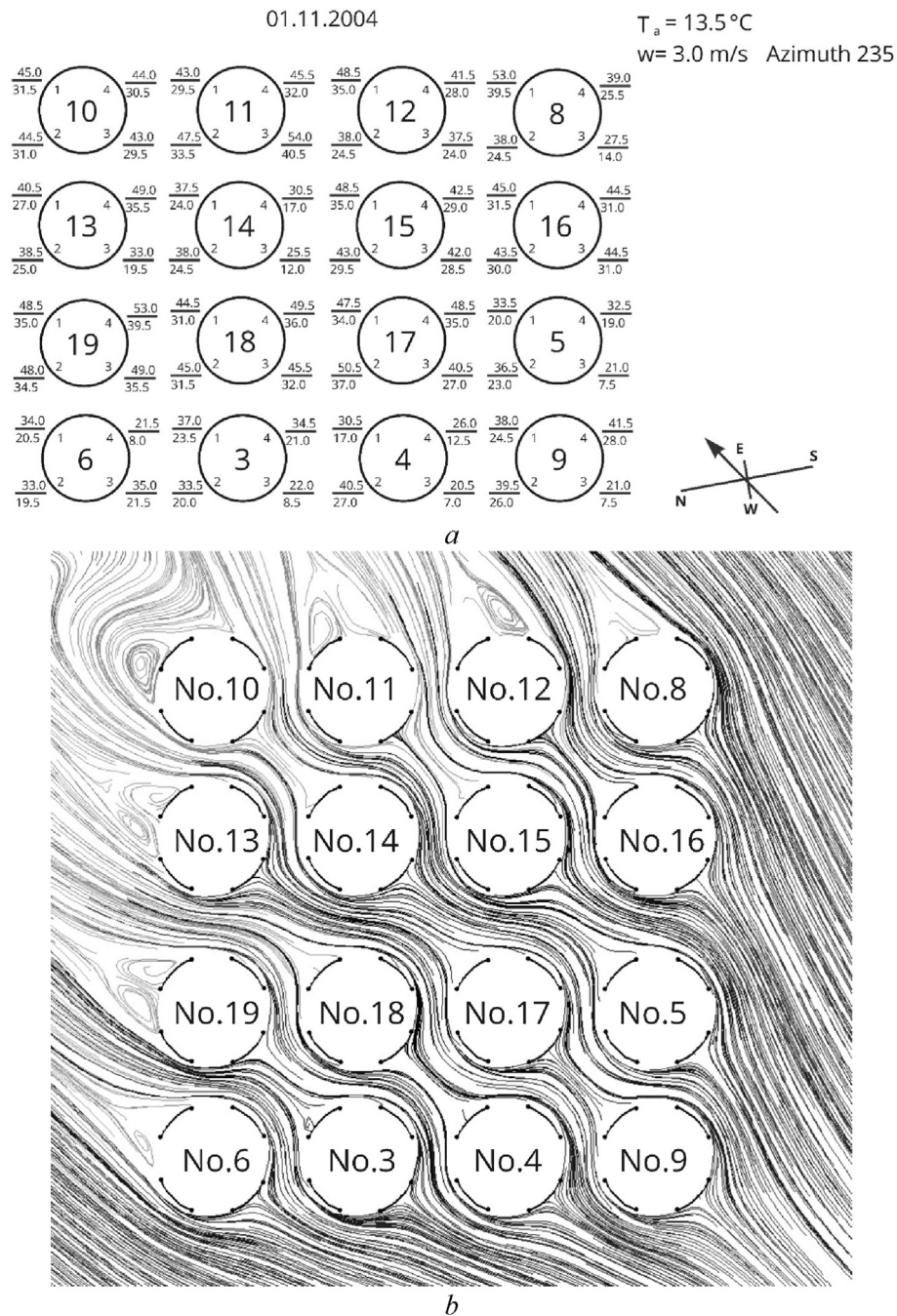
Fig. 6. A group of containers on the storage site: *a* - values of air temperatures at the outlet from the ventilation channels; *b* - the structure of the air movement around the containers at the wind conditions.

and time of the ventilation air temperature measurement, the container number and, accordingly, the ventilation air temperature in each of the channels will be stored in the "Monitoring" table. It is proposed to include data on weather factors at the storage site in the "Weather factors" table: date and time of measurements, ambient air temperature and wind flow characteristics. The "Container" table should contain data about the storage container: its number, location on the storage site, and date of installation on the site. The location of the container is important when taking into account the influence of neighboring containers on the results of

thermal monitoring and on the thermal state of SNF (the issue of mutual influence of containers is studied in detail in Ref. [18]), the date of installation - when determining the current level of decay heat release.

Each of the containers contains several spent fuel assemblies, which usually have their own characteristics when sent to storage. Thus, in order to detail the data about the fuel placed in a certain storage container, a table "Fuel" is needed, which contains the container number, the assembly number and its decay heat release. At the same time, it is not necessary to record the time of uploading
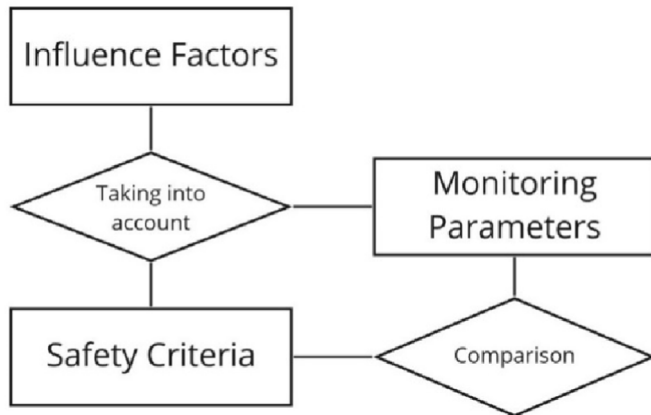
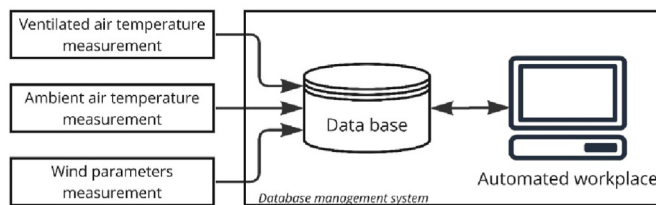**Fig. 7.** Conceptual model of the information system for monitoring the state of spent nuclear fuel.

Fig. 8. Detailed structural diagram of the information system.

into the storage container for each of the assemblies, because it is the same for all assemblies in the cask.

The database also includes the "Criteria" table, which is expected to contain calculated safety criteria, that is, calculated parameters that depend on the conditions and time of storage of the container at the storage site. These parameters can be determined according to the dependencies given in the paper [23].

All the specified tables included in the database are connected to the software module of automated workplace of the information system, where information is processed and presented in a user-friendly form.

5. Algorithm for monitoring of the spent fuel thermal state

Usually, control of the thermal state of spent fuel in storage containers is carried out by measuring the temperature of the ventilation air at the outlet of the container's ventilation channels. If the heating of the ventilation air does not exceed a certain set norm, the thermal condition of the spent fuel in the storage container is considered satisfactory and the normal operation of the equipment continues, otherwise, the hypothesis of an emergency situation is put forward. Such emergency situations may include, for example, a violation of the heat removal from the spent fuel storage cask due to the blocking of one or more ventilation channels.

As mentioned above, the thermal state of SNF significantly depends on the level of its decay heat release, which decreases with time of storage. After dry storage of spent fuel, for example, 20 years, its heat release is halved. In such a case, in case of depressurization of one or more fuel rods [24], which will be accompanied by additional heat release, the total heat release of the basket will increase slightly, but, most likely, will not exceed the permissible limit. The temperature level in such a hypothetical case in the storage basket will rise slightly, which will be reflected accordingly in the temperature of the ventilation air, but, most likely, its heating will not exceed the set limit. Therefore, the emergency situation in the container cannot be detected.

For timely detection of this kind of situation and more effective thermal monitoring, it is necessary to improve the ventilation air temperature control system.

The dependences of the temperature of the ventilation air and the maximum temperature in the storage cask, which are depend on the storage period of spent fuel were found [23].

– the temperature of the ventilation air at the outlet of the container channel

$$T_{out} = 8.13 + 0.8694 T_a + 0.002 Q - 0.00085 T_a^2 - 1.432 \cdot 10^{-8} Q^2 + 6.116 \cdot 10^{-6} T_a Q;$$

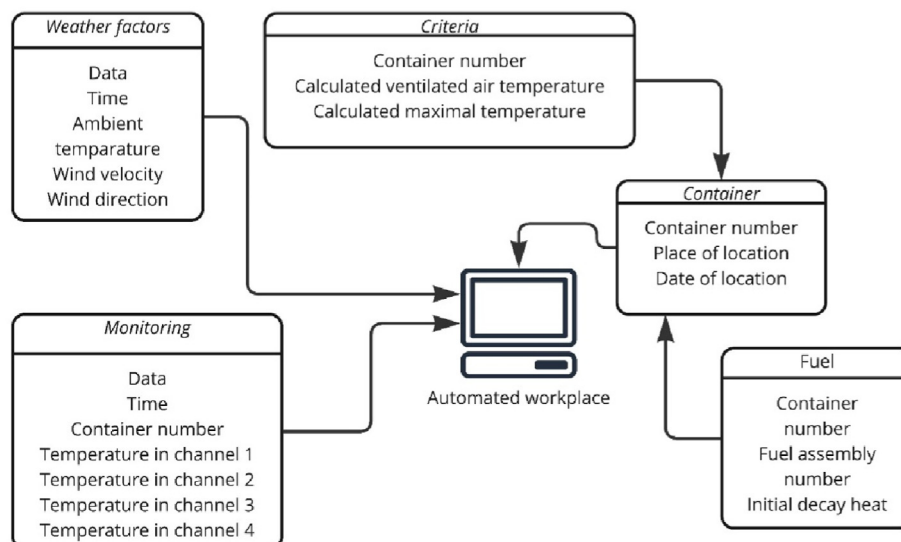– maximum fuel temperature in the storage container

Fig. 9. Database management system with detailing on database.

$$T_{max} = 26,96 + 0,74T_a + 0,014Q - 0,0036T_a^2$$
$$- 1,141 \cdot 10^{-7}Q^2 + 1,07 \cdot 10^{-5}T_aQ,$$

where T_a − ambient air temperature, Q − current decay heat of SNF (calculated on base of [25]).

The given formulas make it possible to create a new algorithm for controlling the thermal state of spent fuel in ventilated storage containers (Fig. 10).

The new monitoring algorithm is as follows. Temperatures obtained during online monitoring are compared with those obtained by calculation according to the dependence from Ref. [23]. In the case that the values coincide with sufficient accuracy, normal operation and monitoring of the thermal state of spent fuel continues. In the case that the results of calculation and measurements do not coincide, a series of measurements of the ventilation air temperature is carried out for 6 h in order to provide a sufficient amount of data for statistical processing and repeated comparison with the calculated data. In this case, the lack of coincidence of data will serve as a reason to put forward a hypothesis about a failure in the operation of the equipment and the need to check it, a coincidence − about the possibility of further normal operation of the main storage equipment.

The algorithm proposed above is an implementation of the calculation function of the information system. Other functions, such as data editing, security functions, etc., will be implemented at the software level when creating software modules of the information system user's automated workplace, or when organizing communication between database tables.

With a certain modification, the proposed information system can be used for personnel training. However, in this case, separation of certain functional elements should be ensured in order not to create prerequisites for the occurrence of emergency situations. So, for example, thermal monitoring data can be partially copied to a separate storage and used in the scientific analysis of the thermal state of containers with spent fuel.

The proposed structure and functions of the information system can be implemented, for example, into existing temperature measurement information systems [17, 26] etc., or integrated into monitoring systems that determine the maximum temperature in a storage container using neural networks for example, [27]. The mentioned and other similar information systems usually do not implement the function of forecasting monitoring parameters (for

Fig. 10. Algorithm for the thermal state monitoring of ventilated containers with SNF.

example, the heating temperature of the ventilation air of the storage container), therefore, developed approach integration to existing thermal monitoring of spent fuel is perspective.

6. Conclusions

By analyzing the data of observations on the temperature of the ventilation air of spent nuclear fuel storage containers, a significant influence of weather factors on thermal monitoring data is shown, which requires the development of new monitoring algorithms.

The need for the development and application of an information monitoring system for monitoring the SNF thermal state at the long-term temporary storage with the aim of early identification of the influence of weather factors on the results of monitoring, possible emergency situations and data collection for further detailed studies of the physical processes that take place during the SNF dry storage is indicated.

The structure of the information system and the algorithm for monitoring the thermal state of ventilated containers with SNF using forecast values of key monitoring parameters is proposed, which will allow better control of the thermal state of the fuel during the entire period of the dry storage facility operation.

Although, presented formulas, that could be included to the monitoring system, cover calm conditions and changing maximal fuel temperature with storage time, they could help to avoid situation with local short-term wind influence and improve measurements in calm conditions. For the long-term wind influence it will be usefull to find dependances for the ventilating air temperature on wind velocity and/or direction. Mentioned issues are in focus of the next author's studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] J. Kim, S. Lee, P.H. Seong, Autonomous Nuclear Power Plants with Artificial Intelligence, Springer International Publishing, Cham, 2023.
[2] W. Hoffelner, Materials for Nuclear Plants: from Safe Design to Residual Life Assessments, 2013, pp. 1−478, https://doi.org/10.1007/978-1-4471-2915-8.
[3] P.G. Tipping, Understanding and Mitigating Ageing in Nuclear Power Plants: Materials and Operational Aspects of Plant Life Management (PLIM), Elsevier, 2010.
[4] O.K. Chopra, D.R. Diercks, R.R. Fabian, Z.H. Han, Y.Y. Liu, Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel (REV. 2) (No. ANL-13/15), Argonne National Lab.(ANL), 2014.
[5] Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants, vol. 48, IAEA, 2018.
[6] IAEA Services Series No. 19, International Atomic Energy Agency, IRS Guidelines, IAEA, Vienna, 2010.
[7] V.A. Gelovany, A.A. Bashlykov, V.B. Brytkov, E.D. Vyazilov, Intelligent decision support systems in emergency situations using information about the state of the natural environment, Editorial URSS 304 (3) (2001).
[8] V.L. Tikhonovsky, B.K. Bylkin, Place and role of information technologies in decommissioning of NPP power units, Izvestiya vuzov. Nuclear energy. No. 4 (2011) 113−120.
[9] M.A. Yastrebenetsky, Y. Rozen, O. Klevtsov, NPP I&C Systems: General Provisions. Cyber Security and Safety of Nuclear Power Plant Instrumentation and Control Systems, 2020, pp. 1−26, https://doi.org/10.4018/978-1-7998-3277-5.ch001, 2020.
[10] V.V. Sklyar, YuA. Bely, S.A. Malokhatko, Assessment of the software quality of the upper level of information and control systems for nuclear power plants,
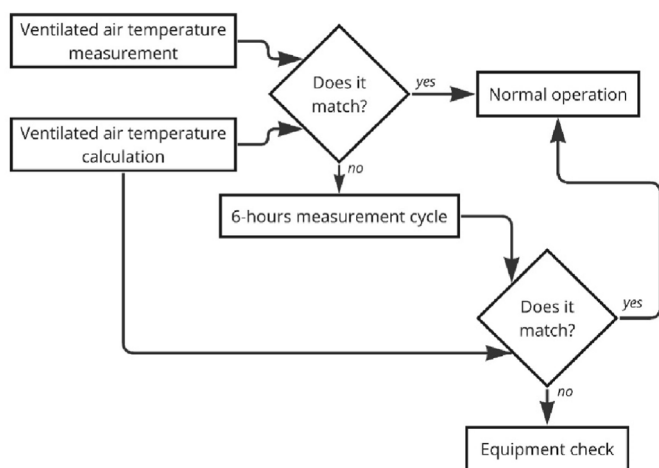
Radio electronic and computer systems, No. 6 (25) (2007) 153–158.

[11] F.J. Sánchez, The Need for Human Resources in Nuclear Power Programmes. Infrastructure and Methodologies for the Justification of Nuclear Power Pro-grammes, 2012, pp. 147–188, https://doi.org/10.1533/9780857093776.1.147.

[12] V.A. Gorbunov, A.I. Ilchenko, S.G. Andrianov, M.N. Mechtaeva, M.A. Volman, Computer technologies in the system of training specialists for the nuclear industry at ISPU, J. Phys. Conf. 1689 (1) (2020), https://doi.org/10.1088/1742-6596/1689/1/012013.

[13] International Atomic Energy Agency, Spent Fuel Management Options for Research Reactors in Latin America, IAEA, Vienna, 2006. IAEA-TECDOC-1508.

[14] J.M. Scaglione, R.A. Lefebvre, K. Banerjee, G. Radulescu, K.R. Robb, A Unified Spent Nuclear Fuel Database and Analysis System, Oak Ridge National Lab.(ORNL), 2015.

[15] D. Kook, J. Choi, J. Kim, Y. Kim, Review of spent fuel integrity evaluation for dry storage, Nucl. Eng. Technol. V. 45 (1) (2013) 115–124.

[16] S. Alyokhina, A. Kostikov, S. Kruhlov, Safety issues of the dry storage of the spent nuclear fuel, Problems of Atomic Science and Technology 108 (2) (2017) 70–74.

[17] S. Alyokhina, Thermal state of ventilated storage container with spent nuclear fuel under normal operation, Int. J. Nucl. Energy Sci. Technol. 13 (4) (2019) 381–398, https://doi.org/10.1504/IJNEST.2019.106056.

[18] S. Alyokhina, A. Kostikov, D. Lunov, O. Dybach, D. Dimitriieva, Definition of mutual thermal influence of containers with spent nuclear fuel at the open storage site, Nuclear and Radiation Safety v4 (2018) 80.

[19] E.C. Foster, S. Godbole, Database systems: a pragmatic approach, Database systems: A pragmatic approach (2016), https://doi.org/10.1007/978-1-4842-1191-5.

[20] P.P. Chen, Thirty years of ER conferences: milestones, achievements, and

future directions (2009), https://doi.org/10.1007/978-3-642-04840-1.

[21] S.V. Alyokhina, V.N. Goloshchapov, A.O. Kostikov, Y.M. Matsevity, Thermal state of ventilated concrete cask with spent nuclear fuel in the conditions of exterior airflow leaking, Nuclear Physics and Atomic Energy 10 (2) (2009) 57–63.

[22] S.V. Alyokhina, S.S. Kapuza, A.O. Kostikov, Solar radiation influence onto the spent nuclear fuel dry storage container, Problems of Atomic Science and Technology 114 (2) (2018) 57–62.

[23] S. Alyokhina, O. S., Dybach, A. Kostikov, D. Dimitrieva, Prediction of the maximum temperature inside container with spent nuclear fuel, Nuclear and Radiation Safety 2 (78) (2018) 31–35, https://doi.org/10.32918/nrs.2018.2(78).05, 2018.

[24] V.G. Rudychev, N.A. Azarenkov, I.O. Girka, Y.V. Rudychev, Change in radiation characteristics outside the SNF storage container as an indicator of fuel rod cladding destruction, Nucl. Eng. Technol. (2021), https://doi.org/10.1016/j.net.2021.05.029.

[25] V.G. Rudychev, N.A. Azarenkov, I.A. Girka, E.V. Rudychev, Irradiation dose minimization by optimizing the arrangement of radiation sources of different intensity, Atom. Energy 119 (4) (2016) 285–290, https://doi.org/10.1007/s10512-016-0061-7.

[26] G. Machin, R. Simpson, G. Sutton, W. Bond, E. Heaps, M. Hayes, J. Jowsey, Novel thermometry approaches to facilitate safe and effective monitoring of nuclear material containers, Nucl. Eng. Des. 371 (2021), https://doi.org/10.1016/j.nucengdes.2020.110939.

[27] H.C. Kim, S.H. Han, Y.J. Lee, Integrity monitoring method for dry storage casks using artificial neural network, Nucl. Eng. Des. 366 (2020), https://doi.org/10.1016/j.nucengdes.2020.110741.