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PROBLEMS OF CREATING SCIENTIFIC AND METHODOLOGICAL BASES OF SPENT NUCLEAR FUEL DRY CASK STORAGE THERMAL SAFETY IN UKRAINE

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An analytical review of modern researches into spent nuclear fuel (SNF) dry cask storage, or dry storage thermal processes is presented and problems of creating scientific and methodological foundations for SNF dry storage thermal safety are discussed. The results of researches into normal and emergency operating conditions for SNF storage facilities (SF), as well as those of scientific achievements aimed at increasing the efficiency of the main equipment and general safety level of SFs are considered. Advantages and disadvantages of modern approaches to thermal research during SNF storage are presented. In numerical studies, computational resources are the main limiting factor, which is why within the framework of the conservative approach that dominate in safety analysis, use geometric simplifications, equivalent thermal properties of individual components, or simplify the task, considering part of the object under the most probable operating conditions. When highlighting the state of the problem of thermal research into emergency storage regimes, it is shown that there are no researches into a number of emergency situations, no attention is paid to the generalization of the results of existing researches and, as a rule, the fuel temperatures directly in storage containers are not determined, which significantly limits the value of such results. This paper highlights directions for carrying out optimization researches into the dry storage of SNF from nuclear power reactors, substantiates the need for research in predicting SNF thermal state and works aimed at creating special protective structures whose main function will be to improve the thermal state of both fuel and basic equipment. The need to formalize the thermal processes that take place during SNF storage and inclusion of the results into the scientific and methodological bases for SNFSFs operation safety are indicated.

Keywords: *thermal safety, spent nuclear fuel, thermal processes, emergency situations, normal operating conditions, dry storage, dry modular storage.*

Topicality

The problem of storing SNF in the world, and in particular in Ukraine, has recently become increasingly important [1–3]. Since the share of nuclear energy in the total amount of electricity produced here is traditionally high and exceeds 50%, each year the power reactors of the four operating nuclear power plants (NPP) generate a significant amount of high-level radioactive waste, which includes SNF.

The problem of handling SNF from power reactors in Ukraine is regulated, in particular, by the order of the Ministry of Energy and Coal Industry of Ukraine dated June 19, 2015, No. 386 'On Approval of Strategic Directions for the Treatment of Spent Nuclear Fuel from Nuclear Power Plants of Ukraine with WWER Type Reactors for the period up to 2030 and Action Plans for their implementation' [4]. It provides for SNF long-term storage at the Zaporizhzhya NPP (ZNPP) SF, fuel of other domestic reactors – in the repositories of the Chernobyl Exclusion Zone.

SNF long-term storage on the territory of Ukraine today is actually carried out only at the largest NPP – ZNPP. Its SNFSF is designed to store more than 9 thousand spent fuel assemblies of ZNPP six WWER -1000 reactors and provides for its operation for about 50 years, that is, during NPP predicted lifetime [5].

In addition to ZNPP SNFSF, two other SNFSFs are planned to be commissioned in Ukraine. These are the SNFSFs for the fuel of the Chornobyl NPP RBMK-1000 reactors (SNFSF-2) and a centralized storage facility (CSFFSP) for other existing reactors in Ukraine's NPPs [6]. Both of these SFs will implement the so-called 'dry' storage method, that is, without using water as SNF coolant.

A dry storage method for SNF is a fairly widespread waste management strategy for countries with an open nuclear fuel cycle. There are several types of dry SFs, two of which will be used in SFs in Ukraine – cask storage facility (at ZNPP SNFSF and CSFFSP) and modular one (at SNFSF-2). Despite the difference in the design of the main storage equipment, SFs have common scientific and technological safety issues of operation, which should be addressed and their scientific support should be directed.

The safety of the operation of any SNFSF is a complex concept [6] and, in addition to nuclear and radiation safety measures, it includes the creation of appropriate conditions for thermal regimes throughout SF life, that is, it requires compliance with the rules of thermal safety. Since SFs are usually planned for several decades, their storage conditions, thermophysical properties of basic equipment materials and SNF, as well as its energy characteristics are changing significantly. Therefore, problems arise in the area of thermal monitoring and management of aging equipment and SNF, which is impossible without a detailed study and synthesis of the nature of heat processes.

The purpose of this paper is to analytically review modern researches into the thermal processes for SNFDS and coverage of the problems of creating scientific and methodological bases of thermal safety of SNFDSFs.

Approaches to thermal research during SNF storage

There are a lot of research papers by leading domestic and foreign scientists that highlight the problems of determining the level of radiation and its impact on personnel and the environment, adhering to the required level of criticality and preventing the emergence of an uncontrolled nuclear reaction, creation of additional radiation protection structures, etc. Unfortunately, the thermal component of the integrated concept of safety of SNFDSFs is not given much attention.

A traditional approach in the analysis of thermal safety usually involves using separate thermal calculations at the stage of designing the main SF with a large number of assumptions and a high degree of overstatement of the basic parameters so that the so-called 'safety margin' be put into the construction. However, such an approach, although justifying itself in a number of extraordinary situations during its lifetime, can not be considered to be fully effective. There is always a need for a full understanding of SNF processes in one or another situation to develop effective measures to counteract the emergence of emergencies and further increase the equipment operation safety level or modernize it, which may be caused by commercial competition on SNF handling market.

An effective methodology for determining SNF detailed thermal state is to solve the problems of computational fluid dynamics (CFD). This methodology can be implemented in commercial or open source CFD software. Unfortunately, all known studies of SNF thermal state during storage, which uses the CFD methodology, have some disadvantages. For example, in [7, 8], the motion of a cooling medium is not considered, or a certain problem is solved in a two-dimensional setting [9, 10]. Some researchers use a simplified geometric model of the main storage equipment and equivalent thermophysical properties of materials during the analysis of SNF storage safety [11, 12]. However, this approach does not make it possible to obtain a detailed information on SNF thermal state during storage, even when using the CFD-methodology, since part of the storage equipment is considered to be a solid body.

It should be noted that the use of SNF equivalent thermophysical properties is a fairly widespread approach with a number of advantages. Thus, when part of a computational domain is replaced with a homogeneous body having equivalent thermophysical properties, computing resources are spared significantly. If the equivalent thermophysical properties are chosen properly, the 'safety margin' is guaranteed in the calculations, which is, of course, an advantage during the operation of most dangerous facilities.

There are several key researches concerning the determination of the equivalent thermal conductivity of fuel assemblies for different reactors. There are two models for calculating equivalent thermal conductivity, which are mainly used by foreign scientists to assess the thermal state of SNF assemblies. The first of them is the study [13] based on bi-regional and one-dimensional analytical model of thermal conductivity. Another model [14] is based on the finite elemental thermal analysis of various SNF assemblies stored in different environments. The difference between these two models is that the beam and conductive components in the bi-regional model are presented as a nonlinear temperature dependence in the second one.

In the study [15], the author proposes to consider fuel assemblies as homogeneous rods with constant thermal conductivity and an internal heat source. The method was based on the numerical simulation and selection of equivalent thermal conductivity. The value was found for different parts of SNF assemblies, compared with the experimental data, and calculated as the average for the whole assembly.

Models of equivalent thermal conductivity were tested and compared in [11] to calculate the maximum temperature in a fuel assembly using a two-dimensional finite element model. As a result, the necessity of using the uneven temperature of a storage basket wall was noted.

Another numerical approach to solving two-dimensional CFD problems was considered in [16] to simulate the thermal state of the baskets with SNF assemblies for PWR reactors. This allowed taking into account the convective gas flow and radiation heat exchange through the fuel zone and its influence on the processes of thermal conductivity in solids.

All of these techniques for calculating equivalent thermal conduction are aimed at determining it for SNF assemblies, rather than for a group of assemblies in a sealed container, as well as for four-column assemblies for different types of reactors. This creates a number of limitations and prevents the use of the results obtained for thermal process simulations in large SNFSFs and those that store hexagonal assemblies for WWER reactors. Consequently, there is a need for extending the methodology of using equivalent thermal conductivity for it to be used in the analysis of the thermal safety of large SNFSFs, in particular in Ukraine.

A peculiarity of many thermal researches is analyzing the processes taking place during SNF storage, in the stationary setting. Unfortunately, very often the research of non-stationary heat exchange for SNF is performed for the conditions of its location in the reactor [for example, 17, 18]. Such results are important, but the thermal processes during dry storage are somewhat different from those that occur in the reactor. However, in open sources, there are studies on the unsteady thermal state of objects at the final stage of a nuclear fuel cycle [19, 20]. However, they relate either to underground SFs or a short period of SNF transportation and can not be used to analyze the thermal safety of intermediate SFs.

Some authors consider the problem of changing SNF thermal state during the storage period in a quasi-stationary setting [21, 22], but this approach does not fully reflect the transitional processes in the main storage equipment and fuel, and can therefore not be applied to the analysis of thermal safety.

Non-stationary researches using CFD-methods are used primarily for storage container components [20], or for simulating either special storage conditions [23, 24] or unventilated containers [25]. Unfortunately, such results can not be used during the thermal analysis of other types of repositories.

For some problems of thermal analysis, open literature sources, in general, contain no results regarding the prediction of the thermal state of SNF and basic equipment. A similar situation has also occurred with protective structures, which are mainly designed to reduce radiation level, and not to localize the influence of external factors, which can lead to an increase in the stored fuel temperature.

Investigation of emergency modes

Research into the emergency modes of SNF main storage equipment operation is an essential component of the safety analysis of any repository. There are usually a lot of researches in this area, but they are devoted to a narrow list of emergencies that are most likely to occur. These emergency situations include the extreme temperatures of atmospheric air for the region where SNFSF is operated [25], fire [26, 27], and coolant loss (for wet storage facilities – loss of water, for dry ventilated storage ones – lack of cooling air flow) [8, 28]. Such emergency situations are analyzed, as a rule, using a conservative approach with a large number of assumptions and do not answer the question of what SNF temperatures will be achieved and what temperature fields the elements of the main storage equipment will have.

Thus, [8] considers a ventilated container whose basket is assumed to be a solid body with equivalent thermal conductivity, and the temperature of the basket surface is determined under full and partial cooling losses. The problem is considered in a quasi-stationary setting. However, results regarding fuel temperatures inside the storage basket are not given, so it is impossible to determine whether the criteria for thermal safety are met. Several standard emergency situations are considered in papers [26, 27], but there the approach, in which the calculated area is simplified to reduce the design time and save computer resources, is also used. None of the above researches indicate what temperatures SF assemblies will have, since a fuel basket in accordance with the conservative approach is considered as a solid body with equivalent thermal conductivity.

Another disadvantage in the thermal analysis of emergencies can be a significant limitation of the list of possible situations. For example, the options for the partial overlapping of channels are not considered, but only those with full and 50% overlap [8, 29]. Therefore, in this case, an additional thermal analysis of emergency situations is necessary to assess the safety of the operation of SNFSFs.

As the literature review showed, such design failures as container rollover, storage basket shift, etc., attention is only given to the analysis of storage equipment integrity [for example, 30, 31]. Typically, research results show the reliability of equipment and absence of mechanical damage to SNF being stored, but the question of how storage thermal regimes will change as a result of an accident remains open. A limited list of emergencies is also considered for the single Ukraine's dry storage facility at ZNPP, the safety analysis report of which does not contain any data on the level of possible temperatures of SF under the conditions of certain design-base accidents [32].

Optimization studies

While storing SNF, there often arise challenges of conducting optimization studies on equipment in which storage is carried out [33, 34] or in relation to technological processes [35, 36], in order to increase the overall SF safety level. For example, in relation to SNFSF-2, work was carried out to reduce the amount of radioactive wastes and an optimal scheme for handling them was proposed [37]. However, works of this type, although of considerable practical importance, do not solve the problems of SNF storage safety in their entirety and, in particular, the problems of creating appropriate thermal storage regimes.

Reducing the overall temperature of the main storage equipment and SNF and, consequently, increasing SF thermal safety level during its entire operation period is possible, for example, by such actions as an optimal placement of fuel assemblies in storage baskets and containers on a storage site, optimization of cooling system parameters, etc. Unfortunately, there are very few works in this direction; they mainly contain a list of design or technological solutions, the results of solving individual application problems or are of an exploratory nature. Thus, [38] describes the operation principle of a number of systems for dry storage of SNF, and describes the systems of heat transfer together with an analysis of the modes of their operation in different operating conditions. The results of the study show the most optimal operating modes in terms of reducing the overall temperature of the main equipment and stored fuel. In contrast to [38], [39] analyzes the influence of several factors on the thermal state of SNF and identifies the most important issues in the analysis of thermal safety. However, there are no clear recommendations with regard to changing the characteristics of storage equipment, operating conditions, or SNF loading method. Neither the possibility of distributing the obtained results to the equipment of another type is identified.

An operational analysis of SNFDS systems, their comparative analysis and coverage of the ways of modernizing the main storage equipment is a widespread approach among domestic and foreign researchers. For example, in [40], the stages of the development of cooling systems during SNF storage are highlighted, and new ways of allocating the residual heat of SNF during the whole period of its storage are proposed. The study [41] is also of a survey-analytical nature and has a further development with regard to the operation principle of cooling systems, which is included in a number of inventions patented by the authors. These and other researches, although not of a clear optimizing nature, can, however, be classified as belonging to this class. They are usually aimed at a more efficient 'organization' of thermal processes that take place in storage equipment, that is, optimize the operation of cooling systems, increasing their efficiency.

In the case of research aimed at optimizing the loading of containers (baskets) with SNF and placing them in storage facilities to reduce their temperature level and increase their thermal safety level, an almost complete absence of results should be noted. For example, for modular repositories, which are planned for use in SNFSF-2, research of this type in open sources has not been found. For the equipment that is planned to be used in CSFFSP, there are separate results of thermal research (for example, in [39]), which only partially highlight thermal problems and have no recommendations on the installation of containers or loading of fuel assemblies. For the already existing SNFSF at ZNPP, such researches were partly carried out in [42], but they have some limitations too, that is, they have several options for loading SF assemblies into a storage basket without a common algorithm, which should be followed throughout SF life.

Conclusions

Investigation of thermal processes during dry storage of SNF in container or modular repositories is an essential component of the safety analysis of their operation. In this aspect, a number of tasks arise, in particular, those of studying normal and emergency operating conditions, and those aimed at improving safety and performance of the main equipment. Among these types of researches, numerical calculations, in comparison with field experiments, are dominated, which is primarily due to the increased risk of radioactive material handling.

In the analysis of normal operating conditions, the main problem is the limited computing power, which is why they use simplification of geometry, equivalent to thermophysical properties or solve the problem only for part of the object. In all these cases, tasks are usually solved at the stage of the initial assessment of SNFSF safety, the results relate to specific, clearly described situations and there is no generalization of data on heat processes in SNF. In view of this, there is a need for additional research, especially for those types of dry storage facilities used in Ukraine, the synthesis of their results and creation of scientific and methodological bases for the analysis of thermal safety of objects of this type.

As the analysis of modern researches has shown, emergency situations during SNF storage in a dry manner are considered only partially, processes occurring in the accident are not generalized, and, as a consequence, recommendations for improving the design characteristics of the main storage equipment are not put forward. Further research and generalization of the results in this area is a necessary component of the creation of scientific and methodological bases for the operational safety of dry storage facilities for SNF.

Unfortunately, all known researches that can be classified as belonging to an optimization class, have a number of disadvantages. This is, in particular, the absence of a generalization of the factors affecting the level of thermal safety during SNF storage, the uniqueness of the results and their practical value for storage equipment of different manufacturers, dependence on storage and operation of SFs, etc. Consequently, the formalization of the processes occurring during SNF storage, and the search for optimum equipment parameters and storage conditions are important components in the analysis of thermal safety and should be included in the scientific and methodological bases of safety of exploitation of SNFSFs.

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Проблеми створення науково-методологічних основ теплової безпеки сухого зберігання відпрацьованого ядерного палива в Україні

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Подано аналітичний огляд сучасних досліджень теплових процесів за сухого зберігання відпрацьованого ядерного палива (ВЯП) та висвітлено проблеми створення науково-методологічних основ теплової безпеки сухих сховищ відпрацьованого ядерного палива. Розглянуто результати досліджень нормальних та аварійних умов експлуатації сховищ ВЯП, а також результати наукових доробок, що спрямовані на підвищення ефективності роботи основного обладнання та загального рівня безпеки сховищ. Наведені переваги та недоліки сучасних підходів до теплових досліджень під час зберігання відпрацьованого ядерного палива. За чисельних досліджень основним лімітуючим фактором є обчислювальні ресурси. Отже, у рамках консервативного підходу, що домінує під час аналізу безпеки, використовують геометричні спрощення, еквівалентні теплофізичні властивості окремих компонентів або спрощують задачу, розглядаючи частину об'єкта в найбільш вірогідних умовах експлуатації. Висвітлюючи стан проблеми теплового дослідження аварійних режимів зберігання, показано, що відсутні дослідження ряду аварійних ситуацій, не приділено уваги узагальненню результатів існуючих досліджень та, зазвичай, не визначаються температури безпосередньо палива в контейнерах зберігання, що значно обмежує цінність таких результатів. У роботі висвітлені напрями проведення оптимізаційних досліджень за сухого зберігання відпрацьованого ядерного палива енергетичних реакторів, обґрунтована необхідність проведення досліджень щодо прогнозування теплового стану ВЯП та робіт, що направлені на створення спеціальних захисних конструкцій, основною функцією яких буде поліпшення теплового стану палива та основного обладнання. Зазначена необхідність формалізації теплових процесів, що мають місце під час зберігання ВЯП, та включення результатів до науково-методологічних основ безпеки експлуатації сховищ відпрацьованого ядерного палива.

Ключові слова: *теплова безпека, відпрацьоване ядерне паливо, теплові процеси, аварійні ситуації, нормальні умови експлуатації, сухе контейнерне сховище, сухе модульне сховище.*

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