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METHODS AND APPROACHES FOR IMPROVING THE FUEL ROADS AND ABSORBING ROADS NPP REACTOR CORE PROPERTIES BASED ON THE INTERVAL AND REGRESSION ANALYSIS MODELS AS COMPONENTS ARTIFICIAL INTELLIGENCE

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We will consider the prospects of using new methods and approaches for evaluating and improving the physicomechanical and physicochemical properties (indicators of microhardness, corrosion resistance, heat resistance, radiation resistance, etc.) of fuel rods zirconium cladding, component heat-releasing assemblies, hafnium absorbing roads and their clusters of NPP reactors core for Ukrainian nuclear technologies. We think such methods are more effective and correct than the well-known ones. We propose to apply them to solve the urgent problem of increasing the nuclear and radiation safety of the operation of NPP power units. These methods and approaches are based on the mathematical tools application of interval and regression analysis as components of artificial intelligence in simulation. The experiment data for evaluating the construction materials properties of the fuel pins and absorbing rods are characterized by uncertainty and ambiguity. Modelling using the methods of interval and polynomial regression analysis allows for increasing by 4…6% the accuracy of the physicomechanical and physicochemical properties estimation of fuel rods zirconium cladding and hafnium absorbing rods of a nuclear reactor core. The formalization of such methods and approaches creates a new methodology for evaluating and optimizing the properties of fuel pins and absorbing rods, their components, assemblies and clusters for the Ukrainian nuclear fuel cycle to increase the nuclear and radiation safety of NPP reactors.

INTRODUCTION

Currently, many global scientific studies are directed at improving the properties of fuel and neutron-absorbing elements of the nuclear reactor core. The basis of these various studies is a series of physical laboratory experiments to evaluate the relevant properties of nuclear construction materials, fuel rods and absorbing rods: thermophysical characteristics, indicators of corrosion resistance, radiation resistance, thermal resistance, etc. In [1], the results of studies of thermophysical properties of fuel rod cladding made of Zr1%Nb alloy with different coatings are presented. The authors showed that covering the cladding with CrN material increases its reliability in a loss-of-coolant accident (LOCA). Research on the influence of thermochemical processing parameters and regimes of zirconium alloys of fuel rod cladding showed that processing in a gas environment increases the shell's corrosion resistance [2]. The paper [3] presents the analysis of the embrittlement criteria of the shells of fuel rods made of zirconium alloys (Zr1%Nb, Zircaloy-2 (Zry-2), Zircaloy-4 (Zry-4)); these criteria are necessary to assess the possibility of safe operation of nuclear reactors under the conditions of shell depressurization during LOCA and SBO (Station Blackout) accidents. The paper [4] provides a comparative analysis of corrosion resistance indicators in a high-temperature water vapour environment of zirconium shells of fuel rods made of various alloys, which can prevent severe accidents development at NPP. The aim of the research [5] was to identify possibility of extending the life time of zirconium claddings. Zirconium surface were treated with 30 high intensity pulsed plasma beams (HIPPB). Results: Zirconium samples with modified surface layer showed the higher resistance for oxidation in simulated conditions of normal work of PWR reactor and in elevated temperatures. In [6], the authors analyzed the influence of the uncertainty of the physical experiment results on the properties evaluation and efficiency of the regulating neutron-absorbing rods of PWR reactors. The authors consider the production tolerances in the absorbing rod production and the limitation of the assessment results of these properties to be one of the uncertainty sources. In statistical analyses, typically a large number of simulations must be run. This increases the probability of failure of the simulation program due to non-convergence of the calculation, the authors of paper [7] emphasize. This results in missing data, and this could prevent the use of order statistics which are based on the sorting of observations. With missing data, the real order of the observations is unknown. This work suggests a suitable data treatment method to overcome this problem. The fission gas emission process for instant release fraction estimation is considered. A method for the determination of upper tolerance intervals for fuel assembly summary statistics, such as the mean, was developed. The investigation [8] includes a fundamental description of the use of burnable absorbing and their impacts on reactivity, absorbing depletion, self-shielding, basic thermophysical properties, and the use of burnable absorbing in next-generation nuclear applications. Neutron-physical requirements for thermophysical characteristics of absorbing roads are considered depending on the purpose of the reactor: a commercial water-cooled reactor, a research and test reactor, a next-generation advanced reactor system. In [9], an integer-coded genetic algorithm is implemented for finding the optimal arrangement of twelve absorbing rods within the core of a fast breeder reactor, satisfying and optimizing operational and safety parameters. This problem is a multi-objective, multi-constraint combinatorial optimization problem with a set of possible solutions. The paper [10] presents a physical experiment description of the assessment of critical compressive forces and bending forms of the guide channels of heat-releasing assemblies of PWR reactors during the oscillation of zirconium alloy fuel rods. The investigation [11] provides a detailed Machine Learning microstructural approach that can be utilized to understand and predict behavior in alloys with hydrides. Zirconium alloys thermo-mechanically degrade, when exposed to severe operating environments due to hydride formation. Machine Learning methodologies based on Gaussian Process Regression, random forests, and multilayer perceptrons were used to predict material fracture critical stress states. The paper [12] presents research on the influence of high temperatures on the microstructure and thermal diffusivity of the Zircaloy-4 alloy. The samples were treated in air, at temperatures between 850 and 1050 °C for 60 min. The structural areas formed on the Zircaloy-4 alloy during isothermal corrosion. The microhardness measurements in the section give the effect of oxygen on structural hardening. The hardness variation curve is well correlated with the oxygen concentration variation curve.

The analysis of the results of scientific research by the listed Ukrainian and foreign authors shows the relevance of the properties improving and optimizing task of heat-emitting and neutron-absorbing elements of the NPP reactors cores for Ukrainian nuclear technologies.

AIM

The article aims to substantiate and analyze the prospects for using new methods for evaluating and improving the physico-mechanical and physicochemical properties (indicators of microhardness, corrosion resistance, radiation resistance, etc.) of fuel rods zirconium cladding and hafnium absorbing rods in the NPP reactor core for Ukrainian nuclear technologies. It is necessary to choose more effective and correct methods than commonly known methods. We offer methods and approaches that are based on the use of mathematical models of interval [13] and regression analysis (polynomial regression [14], ridge regression [15, 16]) as components of machine learning for processing data from experiments on the assessment of the properties of structural materials of fuel pins and absorbing rods; note that the results of the experiments are characterized by considerable uncertainty and a limited amount of data.

INITIAL DATA AND TASK SETTING

According to the materials of the Energy Development Strategy of Ukraine until 2050, we can conclude that Ukraine is ready to create its nuclear fuel cycle. In addition to nuclear fuel production, a necessary element of the nuclear cycle is the fuel rod shell production, which in turn requires the extraction and processing of zirconium alloys.

One of the considerable requirements for the construction materials of the nuclear reactor core is their high corrosion resistance, which ensures the reliability and safety of the reactor plant and the entire power unit.

Today, numerous international programs are being implemented to improve nuclear fuel for new-generation WWER (PWR) reactors; works and research are directed at further increasing the operational reliability of fuel elements with fuel burn-out up to 70…75 (MW·day)/kgU and campaign length up to 6–7 years. Much attention is paid to increasing the resource characteristics of zirconium fuel rod shell and heat-dissipating assemblies.

The principal structural materials for the fuel rods shells of thermal neutron reactors with a water coolant, both in Ukraine and abroad, – are zirconium alloys. These alloys differ from other structural materials by a small thermal neutron absorption cross-section (0.18 barns). This characteristic is necessary for the use of low-enriched nuclear fuel. Such zirconium alloys used in the nuclear power industry of various countries (Ukraine, Canada, USA, France, Japan, etc.) include Zircaloy-4, E110, KTTs-110, E635, E125, M4, M5 alloys, MDA and others. Two fundamental zirconium alloys – Zircaloy-4 and Zircaloy-2, are used in the USA, Canada, and Western Europe for fuel shells, casings, and channels of light water and heavy water reactors. Moreover, the first is used mainly for PWR reactor fuel and the second – for BWR reactors.

Ensuring the corrosion resistance requirement is especially important for the structural materials of reactor fuel rods shells made of zirconium alloy Zr1%Nb. Having a minimum wall thickness (0.65 mm) for absorbing neutrons, they are in the hard operating conditions in the reactor core. That is, during operation, the material of the fuel rods can deform due to radiation damage of the nuclear fuel in the fuel rods. As a result of significant temperature differences in the shells, significant thermal stresses arise. The shell material can change its physico-mechanical properties under the neutron irradiation influence. Therefore, ensuring high corrosion resistance of fuel rods shells of nuclear power reactors is an urgent scientific and technical problem of the world nuclear energy industry.

Zirconium alloy Zr1%Nb, in which niobium Nb is an alloying element, is the basic material of fuel shells of operating reactors of nuclear power plants in Ukraine. In zirconium alloys for nuclear reactors of Ukrainian NPPs, when they are produced in the form of ingots according to domestic technology, and then - the shell of fuel rods, the content of about 20 impurities is standardized (Hf, Al, Ti, Fe, N, F, C, Si, Cl, etc.). At the same time, Al, Ti, N, and C reduce the corrosion resistance of zirconium in water at high temperatures, and Fe increases the resistance of zirconium to corrosion in water and steam environments.

These facts substantiate the relevance and scientific research aimed at improving the properties of fuel pins and absorbing rods of domestic production during the post-war modernization and development of the nuclear power industry of Ukraine. Such studies make it possible to create methodological foundations for developing new approaches and methods for evaluating and optimizing the properties of heat-emitting and neutron-absorbing elements and their components of national production for the NPP nuclear reactor core.

Scarce amount of experimental data (a short sample of a dozen pairs of observed values) often characterize studies of the properties of nuclear metals. Such experiments take places in specific conditions, in some cases are long-term, the process of conducting is complex, unique equipment is required, and often significant material costs and workforce. For example, studying zirconium alloy Zr1%Nb corrosion resistance for fuel rods shells lasts 4000 h. The results of the experiments are characterized by uncertainty and small volume (7–10 pairs of observation samples with significant data scatter when determining one property indicator) [17, 18]. Uncertainty factors include randomness, variability of variables, rounding errors, and others. The mentioned specific features significantly complicate the possibility of fundamental changes in the experiment's methods.

One of the possible ways to obtain better and more detailed information about the properties of structural materials and the indicators of the processes occurring in them is a change in the methods for assessing experimental data. Standard methods of mathematical statistics are often used to process the experiment results to establish the nature of the dependence between certain factors or to establish the presence of correlation between indicators: estimates of the mean, deviation, median, mode, confidence interval, and the method of least squares (LS-estimation) to estimate the regression parameters. But for the correct processing of experimental data by such methods for further optimization, some assumptions regarding the properties of the distribution of experimental data are necessary: the sample of measurements must be representative with a sufficient volume; the total measurement error must be probabilistic; the general probability distribution must be a Gaussian distribution; there should be no chaotic components in the measurements; errors of successive measurements must be independent.

The fulfillment of these requirements in most studies assessing the properties of fuel pins and absorbing rods is not confirmed. On the contrary, incorrect application of probabilistic approaches leads, as the preliminary analysis shows, to errors in the range of 4…6% when determining the optimal indicators of physico-mechanical and physico-chemical properties and resource characteristics of fuel rods and absorbing rods, their components, assemblies and clusters. Many experiments have been conducted, and further experiments are planned to study a wide range of NPP reactors cores' structural materials. Data processing of such studies requires new methods of modeling and forecasting. It is necessary to increase the level of reliability of the assessment and optimization results of confident indicators and resource characteristics.

Using interval analysis methods, interval statistics [19, 20], and interval polynomial regression models [21], developed based on the machine learning theory as components of artificial intelligence systems for processing and analysis of the physical laboratory experiments results can be considered a promising direction. The desire to apply this mathematical toolkit has its objective reasons. The subject of interval analysis is the solution of problems with interval uncertainties in data at the input, output or intermediate stages. In the interval analysis theory, there are methods for analyzing interval data – methods aimed at solving modeling problems with interval uncertainties in experimental data and obtaining and studying processes mathematical models with parameter estimates in the form of sets.

The experimental data on the study of the reactor core structural materials can be dissimilar and contradictory. Therefore, to make a decision, researchers often have incomplete information about the numerical values of the structural materials' characteristics or they only know the ranges of characteristics possible values. The result of an interval calculation is an interval, that is, a pair of numbers, the upper and lower boundaries of the interval. This pair of numbers guarantees an accurate answer, since the true value is in this interval. There are three sources of errors in numerical calculations: truncation errors – the result of approximation or a subjective decision to simplify the model, input errors, and rounding errors. How do we estimate the impact of all these errors on the result? Two different methods for estimating the numerical calculation error: the classical method evaluates the errors after all calculations have been completed, and the interval analysis method is based on all error estimation at each stage [22].

The interval analysis theory has been an alternative to probabilistic approaches lately. The interval model does not require that the absolute error (the value describing the uncertainty of the modeled dependence) be subject to any distribution law (probabilistic model) but only considers its limitation. This principle accepted in metrology - the assumption that the output variable value was obtained using an inaccurate instrument with a known error. And then, for an arbitrary value of the output quantity, there is an uncertainty interval with a lower and an upper boundary. The discovery of new sources of error and the ability to quantify error lead to an expansion of the uncertainty range.

The non-probabilistic approach of interval analysis also has its disadvantages. In paper [23], the authors quantified the influence of various random/uncertainty factors on the failure characteristics of a structure. They compared the main differences in models for quantifying uncertainty (probabilistic, non-probabilistic) at the fracture formulation levels. For the convex model, explicit functions that representing the relationship between uncertainties and complex physical behaviour cannot be provided, this prevents the practical implementation in structural uncertainty analysis.

The authors' references [24–33] are examples of the efficient application of interval analysis methods in the conditions of the experiments' initial data uncertainty with fuel rod structural materials. The authors proposed the application of this mathematical apparatus for assessing the safety and reliability of the systems and equipment of the NPP power unit [17], building operational and temperature characteristics of the separation system [24–26], and modeling the properties of nuclear structural materials [27–33].

The results of using interval and polynomial regression models built based on the machine learning theory in such studies show positive results. Available developments make it promising to use interval and interval regression models in future scientific research to improve up to 5% of the physico-mechanical and physicochemical properties of fuel rods and absorbing rods in the NPP reactor core. Solving this problem will open opportunities to increase the efficiency of operation, nuclear and radiation safety, and reliability of reactor plants of Ukrainian NPP in various operating conditions.

CONCLUSIONS

Interval and polynomial regression analysis methods are efficient tools for conducting a more accurate and complete analysis of experimental data in conditions of incomplete information, noise, and abnormal measurement values, which is characteristic of researching the assessment of physical-mechanical and physical-chemical properties of fuel pins and absorbing rods of NPP reactors core. Studies carried out to solve the problem of determining the dependence of the properties of alloys on various factors have shown that this approach makes it possible to increase the correctness of assessing the physico-mechanical and physicochemical properties of fuel rod zirconium cladding and hafnium rods in the reactor core by 4…6%.

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МЕТОДИ І ПІДХОДИ ДО УДОСКОНАЛЕННЯ ВЛАСТИВОСТЕЙ ТВЕЛІВ І ПЕЛІВ АКТИВНИХ ЗОН РЕАКТОРІВ АЕС НА ОСНОВІ ВИКОРИСТАННЯ МОДЕЛЕЙ ІНТЕРВАЛЬНОГО І РЕГРЕСІЙНОГО АНАЛІЗУ ЯК СКЛАДОВИХ ШТУЧНОГО ІНТЕЛЕКТУ

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Розглянуто перспективи використання нових методів і підходів, більш ефективних і коректних, як порівняти з загальновідомими, для оцінки та удосконалення фізико-механічних і фізико-хімічних властивостей цирконієвих оболонок твелів, комплектуючих тепловиділяючих збірок, гафнієвих пелів та їх кластерів активних зон реакторів АЕС для вітчизняних ядерних технологій з метою вирішення актуальної проблеми підвищення їх ядерної і радіаційної безпеки. Ці методи і підходи базуються на використанні сучасних математичних моделей інтервального і поліноміального гребеневого регресійного аналізу як складових систем штучного інтелекту, для обробки даних експериментів з оцінки властивостей конструкційних матеріалів твелів і пелів, що характеризуються значною невизначеністю та обмеженістю. Використання моделей інтервального і поліноміального регресійного аналізу дозволяє підвищити коректність оцінки фізико-механічних і фізико-хімічних властивостей цирконієвих оболонок твелів і гафнієвих пелів активних зон ядерних реакторів на 4…6%. Формалізація таких методів і підходів дозволяє створити нову методологію оцінювання та оптимізації властивостей твелів і пелів, їх комплектуючих, збірок і кластерів для вітчизняного ядерного паливного циклу з метою підвищення ядерної і радіаційної безпеки реакторів АЕС.