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PROBLEM OF EVALUATION FOR STRUCTURAL MATERIALS OPERABILITY IN ELEMENTS OF NUCLEAR POWER PLANTS EQUIPMENTS

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It is presented the review of published data about different dangerous damaging of critical equipment at a nuclear power unit during industrial operation, which indicate the urgency of the problem of evaluation of structural materials operability in elements of nuclear power plants equipment. Limited opportunities of experimental approaches are noted, and in connection with this circumstance, based on mathematical modelling evaluation for structural materials operability in elements of equipment of nuclear power plants is discussed. The general approach, in which evaluation for structural materials operability in elements of nuclear power plants equipment is reduced to a system of several related initial-boundary-value problems, is proposed. The correspondences rules between the mathematical objects and relationships of the proposed approach and the processes in equipment and structural materials of elements of nuclear power plants equipment are considered.

INTRODUCTION

The main ways of improvement of nuclear power plants are currently connected with the intensification of technological processes by increasing their operating parameters. For example, for the steam generators PGV-1000 the specific steam capacity exceeds the same index in steam generators PGV-440 more than the old design by 37% due to increased coolant flow rate more than 3 times, water temperatures – by 6.7%, and its pressure – by 28% [1, 2]. High operating parameters of modern nuclear power plants lead to operating conditions of equipment components that are close to the limit the possibilities of modern construction materials. This complicates the development of nuclear power plants, and, in particular, causes the significantly increase the overall dimensions of the unit to increase the capacity, such as in prospective projects of steam generators and nuclear reactors for nuclear power plants [1, 2]. Thus, the further development of nuclear power plants requires the solution of a number of materials science problems, as well as some of the problems of optimum design of equipment for the most efficient use of structural materials properties. Actuality of the theme of this work stems from the fact that it discusses the problem of evaluating of materials operability in structural elements of nuclear power plants, a decision which has an important role for ensuring durability parameters of the equipment in the design and during operation clarifying, including taking into accounts the possible emergency conditions [3].

DAMAGES OF THE NUCLEAR POWER PLANT EQUIPMENT

Currently, the problem of operability evaluation of equipment of nuclear power plants has not been solved fully. This is confirmed, for example, by the damage of equipment elements which periodically occur during the NPP units operation, at that the causes of many of these lesions is not well established. We consider further some examples of the most dangerous equipment elements damaged nuclear power plant nuclear power plants. We will consider some examples of the most dangerous damages of the equipment elements of NPP reactor installations. Causes of bending of the fuel assemblies guide tubes, which are observed on many WWER-1000 reactor installations since 1992, consist in a loss of stability due to excessive longitudinal compressive force [4], which is consistent with approximate estimates of the critical compressive force [5]. Although the measures to reduce the longitudinal compressive forces resulted to a positive effect [4], causes of excessive these longitudinal compressive forces is not exactly established and, apparently, is the effect of a complex series of internal and external influencing factors.

During operating of reactor units WWER the cladding in some of fuel elements may be damaged and it is may develop leaks of fission materials [4]. These leakage emergencies are difficult to predict due to the complex set of internal and external influencing factors causing thermo-elastic deformation, corrosion damage, creep properties of materials degradation and other processes. The intensities of external influencing factors herewith are themselves the result of mutually influencing complex processes. For example, the interaction between the nuclear fuel and cladding is determined by the thermal conductivity, heat transfer, emission of gaseous fission products, diffusion etc. and can be reduced to the high internal pressure or to the mechanical contact with the fuel and cladding [6]. Moreover, the order of permutation of the fuel assemblies acts on the external influencing factors due to the unevenness of the neutron flux at least [7]. The probabilistic nature of nuclear reactions and other difficult-to-account factors leads to uncertainties in the input data to assess the durability of cladding that makes consider the probability of fuel elements failure.

Damage output collectors that showed up at the 25 steam generators PGV-1000 in 1986 after several years of operation are caused by the combined action of the set of damaging factors [1]. Reducing the residual stresses due to the implementation of a number of decisions allow to exclude such damage in the future [1]. Nevertheless, the study of damage process of steam generator collectors and, especially, the fact that damage was observed only on the output collectors that have a temperature lower than the input collectors is of considerable interest.

Damages made of stainless steel of heat exchange pipes of steam generators of WWER reactors installations are due to the stress corrosion cracking [1, 8], which occurs only when occur the combined effect of an aggressive corrosion medium and the tensile stresses [9]. At the present time there are no approaches that can precisely predict the damage of heat exchange pipes of steam generators, and so the industrial exploitation of steam generators of NPP with WWER is possible only thanks to the available relatively efficient diagnostics tools of the current state of defects in the heat-exchange pipes [1, 8].

Occurring equipment failures during the NPP units operation in some cases creates a potential danger of severe accidents that with increasing safety requirements makes it necessary to ensure the high reliability of equipment components of NPP units. Most of the known dangerous of NPP equipment damages are connected with disadvantages of modern approaches to the justification of structural materials operability in the elements of equipment, including those, that represented in the form of standards, for example [10]. These disadvantages are due to primarily neglect between mutual influence of several factors (e. g., creep and corrosion) that could lead to the destruction, as well as a simplified representation of the external factors that can actually depend significantly on the current state and operating conditions of equipment.

EXPERIMENTAL AND THEORETICAL RESEARCHES

Operability of structural materials is mainly ensured by their properties: physical, mechanical and others. The study of properties of structural materials in principle cannot be implemented without conducting appropriate experiments. The experimentally determined values of yield strength and long-term strength, the critical brittle point and modulus of elasticity, coefficient of thermal expansion, and other important characteristics that provide operability of structural materials in elements of equipment of nuclear power plants.

It is natural that shape and size of the samples, the external influencing factors created on testing machines for studying the properties of materials considerably different from the actual inherent to elements of the equipment of nuclear power plants. For a more accurate assessment of operability of structural materials in elements of equipment of nuclear power plants in recent years resorted to unconventional experiments. For example, in [3] for research of high-temperature creep in fuel elements cladding research is performed testing using annular tensile specimens that loaded inside by means of a special device to create an effect close to internal pressure in cladding, instead the standard testing. The adopted in [3] testing scheme corresponds to the actual geometric shape and size, as well as simulates operating conditions of fuel elements cladding at the emergency shutdown of the reactor cooling. Thus, in [3] test conditions as close as possible to the conditions of operation that allows the experimentally evaluate the operability of the zirconium alloy in the cladding of the fuel element.

Operating conditions of equipment components of nuclear power plants are inherent a variety of external influencing factors, including mechanical and thermal loads, various internals of radiations, that produces the various processes of damage in structural materials, leading to changes in the properties of the materials, the accumulation of irreversible deformation and destruction. Evaluation of the effect of the combination of several external factors impacting on the operability of structural materials is not always obvious and is not always can be reduced to the summation of the effects of each of the factors separately. Accounting for all the multitude of external influencing factors in the experimental study of operability of structural materials of equipment elements of nuclear power plants requires a very labour-intensive and costly of multifactor experiments. This limits the possibility of experimentally researching of the operability of structural materials in equipment elements of nuclear power plants. In view of the noted circumstances for assessing the operability of structural materials in equipment elements of nuclear power plants seem promising theoretical researches based on mathematical modelling of equipment elements of nuclear power plants, taking into account the experimental data on the properties of their structural materials. Mathematical modelling allows the explore the operability of structural materials in the equipment elements taking into account the combinations of external influencing factors, which are difficult to reproduce in physical experiments.

MATHEMATICAL MODELS FOR EVALUATION OF OPERABILITY OF STRUCTURAL MATERIALS IN EQUIPMENT ELEMENTS

Mathematical models of the state of equipment elements, which take into account the impact of various external factors and experimentally established laws of behaviour of structural materials, are required for theoretical research and study of operability of structural materials in equipment elements of nuclear power plants. Next, we will consider a common approach to the construction of mathematical models, which is a generalization of the ideas and the results of [6, 9, 11–13].

We consider the equipment elements of nuclear power plants from the standpoint of continuum mechanics, as a set of points, which occupies an area Ω with boundary Γ in the three-dimensional Euclidean space, in which the coordinate system is introduced, so that the position of the points in space can be defined by a vector $\mathbf{x}$ composed from spatial coordinates. State of the equipment elements may change at each theirs point $\mathbf{x} \in \Omega$ during operating time, which is characterized by a scalar parameter $t \geq 0$, for which is possible to define the relation order. As the operating time we can be considered, in particular, the time from the beginning of operation, so further parameter $t \geq 0$ will be called as time. The law of behaviour of continuum medium will take the in accordance with the properties of structural materials.

Let denote as $\mathbf{u}^{(1)}$ the vector, whose components characterize the state of the equipment elements as a continuous medium and represent the temperature (or entropy), the components of the vectors of the heat flow and displacement, stress and strain tensors. Deformation of the considered equipment element can happen under the influence of creep processes, corrosion, diffusion, leading to the accumulation of damage in structural materials that can manifest itself as irreversible deformation, degradation of characteristics of the material and changes in any other manner. Let denote as $\mathbf{u}^{(2)}$ vector whose components describe the processes of damage in structural materials and could be represented, for example, as the creep strain tensor components, the concentration of corrosive components, as well as damage of various parameters [14]. As $\mathbf{v}$ let denote the vector, whose components characterize the external influencing factors. Naturally, the condition of the equipment elements as a continuous medium, the degree of damage of structural materials, as well as external influencing factors will generally be different in each point $\mathbf{x} \in \Omega$ and, furthermore, will change during the time parameter $t \geq 0$:

$$\mathbf{u}^{(1)} = \mathbf{u}^{(1)}(\mathbf{x}, t), \ \mathbf{u}^{(2)} = \mathbf{u}^{(2)}(\mathbf{x}, t), \ \mathbf{v} = \mathbf{v}(\mathbf{x}, t). \qquad (1)$$

Neglecting the inertia forces, as it is accepted, for example, in strength evaluations of the elements of nuclear power plants [10], we will present a model of deformation of the equipment element as a continuous medium in the form of a boundary value problem:

$$\mathbf{A}^{(1)}\left(\mathbf{u}^{(1)};\mathbf{u}^{(2)}\right) = \mathbf{f}^{(1)}(\mathbf{v}) \ \forall \mathbf{x} \in \Omega,$$
$$\mathbf{L}^{(1)}\left(\mathbf{u}^{(1)};\mathbf{u}^{(2)}\right) = \mathbf{p}^{(1)}(\mathbf{v}) \ \forall \mathbf{x} \in \Gamma, \qquad (2)$$

where $\mathbf{A}^{(1)}$ and $\mathbf{f}^{(1)}$ are the operators corresponded to the differential equations; but $\mathbf{L}^{(1)}$ and $\mathbf{p}^{(1)}$ – operators are corresponded to the boundary conditions of the mathematical model of equipment element deformation.

As the equations and boundary conditions for the problem (2) are presented usually the equations and boundary conditions of the theory of elasticity and thermal conductivity, which take into account the effect of processes of structural materials damage, which are characterized by the $\mathbf{u}^{(2)}$ vector. Examples include the equations and boundary conditions of thermal conductivity and elasticity theories, in which the properties of the materials constant (coefficient of thermal conductivity, modulus of elasticity, etc.) depend on the concentration of diffused hydrogen in the depth of the structural material [13], which may be included in the number of vector $\mathbf{u}^{(2)}$ components. Another example is the equations that describe the deformation of solid bodies, taking into account the creep deformation [15]. For given $\mathbf{u}^{(2)}$ vector the boundary value problem (2) may correspond to the boundary value problems of thermal conductivity and elasticity theories. At the same time determined by the operators $\mathbf{f}^{(1)}$ and $\mathbf{p}^{(1)}$ the volume and surface forces and volume heat sources are determined by the $\mathbf{v}$ vector, i. e., by external influencing factors. Experimental data on the elastic modulus, thermal conductivity and other such characteristics of structural materials, including its dependences on temperature are required for the boundary value problem (1) formulation. Such data is not much difficulty, and they are now obtained for many structural materials, and described, for example, in standards [12].

To take account of the possibility of operability losing due to the damage of structural material, the boundary value problem (2) must be considered together with equations that determine the change of structural materials damage. In point of mathematical modeling view the changes of the damage of structural materials in equipment elements in common case could be represented by the initial-boundary-value problem:

$$\frac{\partial \mathbf{u}^{(2)}}{\partial t} + \mathbf{A}^{(2)}\left(\mathbf{u}^{(2)};\mathbf{u}^{(1)};\mathbf{v}\right) = \mathbf{f}^{(2)}\left(\mathbf{u}^{(2)};\mathbf{u}^{(1)};\mathbf{v}\right) \ \forall \mathbf{x} \in \Omega,$$
$$\mathbf{u}^{(2)}(\mathbf{x},0) = \mathbf{u}_0^{(2)}(\mathbf{x}) \ \forall \mathbf{x} \in \Omega,$$
$$\mathbf{L}^{(2)}\left(\mathbf{u}^{(2)},\mathbf{u}^{(1)};\mathbf{v}\right) = \mathbf{p}^{(2)}(\mathbf{v}) \ \forall \mathbf{x} \in \Gamma, \qquad (3)$$

where $\mathbf{A}^{(2)}$ and $\mathbf{f}^{(2)}$ are the operators corresponding to the differential equations, but operators $\mathbf{L}^{(2)}$ and $\mathbf{p}^{(2)}$ are operators corresponding to the boundary conditions of the mathematical model of damaging processes in structural materials; $\mathbf{u}_0^{(2)}$ – field of $\mathbf{u}^{(2)}$ vector in initial time moment $t = 0$.

The operator $\mathbf{f}^{(2)}$ in equation (3) determines the material's damage rate, which is independent on the gradients of damage, such as under creep conditions [9, 11, 15]. The operator $\mathbf{A}^{(2)}$ in equation (3) determine the material's damage rate, which depends on the current gradient of damage, such as when the hydrogen diffusion into the interior of the material [13]. The operator $\mathbf{L}^{(2)}$ of the boundary conditions in the initial-boundary value problem (3) must be agreed with the operator $\mathbf{A}^{(2)}$ of differential equations. Solving boundary value problem (2) with the initial boundary value problem (3) by means of any known numerical method [16] we can establish the law of change of structural material's damage in the considered equipment element, taking into account external influencing factors inherent for the operating conditions, that will give the estimation of the structural material's operability.

Construction of the initial-boundary-value problem (3), which is essentially a model of behaviour of damaged structural material, in general, can be carried out on the basis of knowledge of the fundamental laws of fracture of solids. Obtaining such knowledge is possible by the experimental studies laws governing of different processes of damage in a variety of structural materials and scientific their generalization. Currently, these studies are partly performed to the some damageability processes only, such as processes for creep and fatigue [14]. However, the modelling of materials damageability is a very effective approach to theoretical evaluation of structural material's operability in the equipment elements of nuclear power plants. Complementing the boundary value problem (2) and the initial boundary value problem (3) by means of additional equations, we can consider the impact of various processes defectiveness. For example, by analogy with the vectors $\mathbf{u}^{(1)}$ and $\mathbf{u}^{(2)}$ we can introduce the $\mathbf{u}^{(3)}$ vector, whose components describe changing the size and shape of equipment elements due to of uniform corrosion attack:

$$\Omega = \Omega\left(\mathbf{u}^{(3)}\right), \quad \Gamma = \Gamma\left(\mathbf{u}^{(3)}\right). \qquad (4)$$

Some of components of the $\mathbf{u}^{(3)}$ vector may include, for example, the uniform corrosion destruction depth for equipment element surface. Herewith the vector $\mathbf{u}^{(3)}$ in generally can be different at $\mathbf{x} \in \Gamma$ points and can change during the time $t \geq 0$:

$$\mathbf{u}^{(3)} = \mathbf{u}^{(3)}(\mathbf{x}, t). \qquad (5)$$

The circumstance that the rate of uniform corrosion cannot depend on its gradient allows representing the model of the uniform corrosion in the generalized form as differential equations with the initial conditions:

$$\frac{\partial \mathbf{u}^{(3)}}{\partial t} = \mathbf{f}^{(3)}\left(\mathbf{u}^{(3)}; \mathbf{u}^{(2)}; \mathbf{u}^{(1)}; \mathbf{v}\right) \ \forall \mathbf{x} \in \Gamma,$$
$$\mathbf{u}^{(3)}(\mathbf{x}, 0) = \mathbf{u}_0^{(3)}(\mathbf{x}) \ \forall \mathbf{x} \in \Gamma, \qquad (6)$$

where $\mathbf{f}^{(3)}$ is the operator corresponding to the differential equations of mathematical model of uniform corrosion processes in structure materials; $\mathbf{u}_0^{(3)}$ is the field of $\mathbf{u}^{(3)}$ vector in the initial time $t = 0$, which, in particular, can be depended to the case of $\mathbf{u}_0^{(3)} = \mathbf{0}$.

The differential equations of the general form (6) means that the rate of uniform corrosion may depend not only on the current state of corrosion processes, but also on the temperature and stress-strain state and the current damage of the structural material of equipment element. This circumstance it seems clear, however, construction of a mathematical model of a uniform corrosion, which would take into account the effect of the stress-strain state and material damage at the present time is a very difficult task. It is caused by the fact that the uniform corrosion can be caused by different physical and chemical processes, and only some of these processes, corresponding to some individual species of uniform corrosion, are well understood at the present time. It is possible to use a simple model of a continuous corrosion, which $\mathbf{f}^{(3)}$ is independent of the $\mathbf{u}^{(1)}$ and $\mathbf{u}^{(2)}$ vectors. Thus, the solution of the boundary value problem (2) with the initial-boundary-value problem (3), taking into account the relations (4) and the model of a continuous corrosion (6) will allow to establish the law of changing of structural materials damage in the considered equipment elements, taking into account the continuous corrosion. It should be noted that taking into account a continuous corrosion leads to the boundary and initial-boundary problems with moving boundary (4), which creates some mathematical difficulties, however, it can be overcome, for example, in [16].

External influence factors that are represented in mathematical models (1), (3), (6) by the $\mathbf{v}$ vector can depend on the current state of equipment elements and their structural materials. An example would be the problem of fuel elements cladding operability in light water reactors [6]. Indeed, one of the external influencing factors for the fuel element cladding is the internal pressure, the magnitude of which is determined by the amount of the substance gaseous fission products and the internal volume of the fuel element cladding. It is natural that during the deformation of cladding, the internal volume is also changed, and therefore, the internal pressure depends on the strained state of fuel element cladding. This situation with the introduced notations using here can be represented as a ratio:

$$\mathbf{v} = \mathbf{v}\left(\mathbf{x}, t; \mathbf{u}^{(1)}\right). \qquad (7)$$

In the general case instead of (7) we have a more complex relationship

$$\mathbf{v} = \mathbf{v}\left(\mathbf{x}, t; \mathbf{u}^{(1)}; \mathbf{u}^{(2)}; \mathbf{u}^{(3)}\right). \qquad (8)$$

With equation (8) and taking into account it's in solving the problem (2)–(6), we can investigate the operability of structural materials in equipment elements of nuclear power plants with taking into account the influence between the current state of equipment elements and external influencing factors. At the same time the connection between the condition of the equipment elements and the external influencing factors are not always present in an explicit form (8), because such a relationship is often a non-obvious result of a complex set of multiple processes of different nature. In general, the relationship (8) can be represented implicitly, for example by means of differential equations. General approaches to constructing relations (8), apparently impossible to offer, and therefore each similar task requires the individual review.

In the mathematical models presented in the form (1)–(6), the effect of operating condition on the operability of structural materials in equipment elements taken into account by choosing the $\mathbf{v}$ vector. It is natural that there is a correspondence between the $\mathbf{v}$ vector, characterizing the external influencing factors of the equipment elements, and the operating mode of the nuclear power plant. In order to establish a relationship between the operation mode of nuclear power plants and external influencing factors of equipment elements, we introduce the $\mathbf{c}$ vector whose components are the parameters by which determines the position of all the control members existing on a nuclear power plant. Since any nuclear power plant has a finite number of control members (the control rods, valves, taps, etc.), then the $\mathbf{c}$ vector is naturally present as only on time depended:

$$\mathbf{c} = \mathbf{c}(t). \qquad (9)$$

Kind of function (9) corresponds to the laws of motion of control members of a nuclear power plant, i.e. determines the operation mode of a nuclear power plant. For example, in the steady state $\mathbf{c}$ vector is not changed and is a constant. Influence of the law (9) of nuclear power plant's control member's movement on the external influencing factors $\mathbf{v} = \mathbf{v}(\mathbf{x}, t)$ of equipment elements from the view point of mathematical modelling in general, can be represented in the form of an initial-boundary value problem:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{A}^{(\mathbf{v})}\left(\mathbf{v};\mathbf{u}^{(1)};\mathbf{u}^{(2)}\right) = \mathbf{f}^{(\mathbf{v})}\left(\mathbf{v};\mathbf{u}^{(1)};\mathbf{u}^{(2)};\mathbf{c}\right) \ \forall \mathbf{x} \in \Omega,$$

$$\mathbf{v}(\mathbf{x},0) = \mathbf{v}_0(\mathbf{x}) \ \forall \mathbf{x} \in \Omega,$$

$$\mathbf{L}^{(\mathbf{v})}\left(\mathbf{v};\mathbf{u}^{(1)};\mathbf{u}^{(2)}\right) = \mathbf{p}^{(\mathbf{v})}(\mathbf{c}) \ \forall \mathbf{x} \in \Gamma, \qquad (10)$$

where $\mathbf{A}^{(\mathbf{v})}$ and $\mathbf{f}^{(\mathbf{v})}$ are the operators corresponded to the differential equations; but $\mathbf{L}^{(\mathbf{v})}$ and $\mathbf{p}^{(\mathbf{v})}$ operators are corresponding to the boundary conditions of the mathematical models of technological processes in the considered nuclear installation; $\mathbf{v}_0$ is the field of $\mathbf{v}$ vector in the initial moment of the time $t = 0$.

As the equations and boundary conditions in (10) can serve equations of reactors physics (kinetics of nuclear reactions, neutron diffusion, etc.), the equation of creep processes and emission of gaseous fuel fission products, heat equation working environments and other equations that describe processes in nuclear power installations. With the introduction of the vector (9) the initial-boundary value problem (10) is more than a generalized representation of the relations (8). Indeed, considering together mathematical models (2)–(4), (6) and (10) we can evaluate the structural material's operability in the equipment elements for the different operating modes, which correspond to the different laws (9) of motion of control members of nuclear power plants.

RESULTS AND ITS DISCUSSION

Due to the development of generalized methodologies are further developed the approaches to mathematical modelling of the equipment elements of nuclear power plants for the theoretical research of structural materials operability. The proposed general methodology of modelling elements of nuclear power plants equipment is to provide mathematical models in the form of related boundary and initial-boundary value problems. Each of these boundary and initial-boundary value problems separately is a mathematical model of one or more processes that need to be taken into account in the theoretical study of structural material's operability in nuclear power plants equipment elements. These processes are damageability of structural materials by varied external influencing factors and others, which lead to irreversible deformation, changes in the properties of materials and any other changes in the state of equipment elements for various possible operating conditions of nuclear power plants. Many of these processes are now well understood and mathematical models for its describing are presented, for example, in [6]. At the same time for many well-known mathematical models is required modification to expand the number of factors taken into account, which can be implemented, for example, by the introduction to well-known mathematical models of any parameters, that characterize the influence of the required factors and additional equations that define these parameters.

Given the large number of factors affecting the structural materials operability in equipment elements of nuclear power plants will lead to a little studied at the present time the mathematical formulation in the form of related boundary and initial-boundary value problems in the general case for different types of equations, which virtually eliminates the possibility of analytic solutions and even numerical solution presents some difficulties. These difficulties are due to a number of mathematical problems, including the selection of suitable functional spaces for the vectors (1) and (5) as well as study the convergence of numerical methods for solving of the boundary and initial-boundary value problem (2)–(4), (6) with a fixed and with a moving boundary.

In most modern research the operability of structural materials in nuclear power plants equipment elements is considered, taking into account the impact of external influencing factors (pressure, temperature, etc.) generated by the operating conditions. Introduction to the consideration of a mathematical model of the external influencing factors, which from the point of view of mathematical modelling can be represented in the form of an initial-boundary value problem (10), allows investigating the impact of the operation modes of nuclear power plants on the structural materials operability that makes particularly interesting these proposed generalized approaches.

Proposed in this paper, a generalized representation of mathematical models (10)–(11) makes it possible to identify the main relatively independent sub-problems in the problem of evaluating of structural materials operability in nuclear power installations equipment elements. Among these sub-problems, at least, are the deformation simulations of equipment elements as a continuous medium (2); modelling of damageability of a structural material (3), (4), (6), as well as modelling of external influencing factors as a result of a predefined mode of operation of nuclear installation in the form (10). This seems very important because the absence of a generalized methodology, as, for example, in [6], makes difficult the using of the known partial results. Having the generalized representation of mathematical models (1)–(10), required for the theoretical study of structural materials operability in the equipment elements, we can proceed to the construction of these models for different equipment elements of nuclear power installations, for example, for fuel elements, fuel assemblies etc.

CONCLUSIONS

The presented results allow make conclusions that reflect the state of the problem of the structural materials operability in equipment elements of nuclear power plants, having interest for further research.

Analysis of published data shows that most of the known dangerous damages of critical equipment of nuclear power plants are associated with some disadvantages of the modern, including represented in the different standards and normative documents, approaches to evaluation of the structural materials operability in equipment elements of nuclear power plants.

It is shown that the possibility of an experimental study of operability of structural materials in equipment elements of nuclear power plants are limited due to a significant number of external factors, leading to timeconsuming multi-factorial experiments, as well as the complexity of the realization of test conditions that meet severe accidents. Due to this circumstance are very promising the theoretical researches of structural materials operability in equipment elements of nuclear power plants, based on mathematical modelling of equipment elements taking into account the experimental data on the properties of structural materials under different external influencing factors and their combinations.

In this paper, through the development a common methodology, which consists in the presentation of mathematical models in the form of related boundary and initial-boundary value problems, were further developed approaches to the mathematical modelling of the equipment elements of nuclear power installations for the theoretical research of structural materials operability. At the same time, consideration of external influencing factors of equipment elements as results of realization of specific mode operation of nuclear power installations that from the view point of mathematical modelling can be represented in the form of an initial-boundary value problem (10), allows to investigate the impact of operation modes of nuclear power installations on the structural materials operability in the elements equipment.

REFERENCES

1. Б.И. Лукасевич, Н.Б. Трунов, Ю.Г. Драгунов, С.Е. Давиденко. *Парогенераторы реакторных ус–тановок ВВЭР для атомных электростанций*. М.: ИКЦ «Академкнига», 2004, 391 с.

2. В.П. Денисов, Ю.Г. Драгунов. *Реакторные установки ВВЭР для атомных электростанций*. М.: «ИздАТ», 2002, 480 с.

3. О.М. Ивасишин, В.Н. Воеводин, А.И. Дехтяр, П.Е. Марковский, Н.Н. Пилипенко, С.Д. Лавриненко, Р.Г. Гонтарева. Особенности механического поведения трубок твэлов из сплава Zr-1%Nb в условиях имитации аварийного отключения охлаждения // *Вопросы атомной науки и техники. Серия «Физика радиационных повреждений и радиационное материаловедение»*. 2015, №5(99), с. 53-60.

4. В.Д. Шмелев, Ю.Г. Драгунов, В.П. Денисов, И.Н. Васильченко. *Активные зоны ВВЭР для атомных электростанций*. М.: ИКЦ «Академкнига», 2004, 220 с.

5. А.В. Ефимов, М.В. Максимов, Ю.В. Ромашов. Потеря устойчивости и форма возможного изгиба направляющих каналов тепловыделяющих сборок ядерных реакторов ВВЭР-1000 // *Ядерна та радіаційна безпека*. 2015, №4(68), с. 14-18.

6. Сузуки Мотоэ. *Моделирование поведения твэла легководного реактора в различных режимах нагружения*. Одесса: «Астропринт», 2010, 248 с.

7. С.Н. Пелых, М.В. Максимов. Метод управления перестановками ТВС с учетом поврежденности оболочек твэлов и глубины выгорания топлива // *Вопросы атомной науки и техники. Серия «Физика радиационных повреждений и радиационное материаловедение»*. 2013, №5(87), с. 84-90.

8. И.М. Неклюдов, Л.С. Ожигов, А.С. Митрофанов, С.В. Гоженко, В.М. Пышный, Н.А. Феофентов, А.В. Бажуков, П.Е. Мельник. Коррозионные повреждения теплообменных труб парогенераторов Южно-Украинской АЭС // *Вопросы атомной науки и техники. Серия «Физика радиационных повреждений и радиационное материаловедение»*. 2003, №6, с. 71-76.

9. O.K. Morachkovskii, Yu.V. Romashov. Continual model of propagation of corrosion cracks for the evaluation of the service life of structures // *Materials Science*. 2010, v. 46, N 2, p. 254-259.

10. *Нормы расчета на прочность элементов оборудования и трубопроводов атомных энергетических установок (ПНАЭ Г-7-002-86).* М.: «Энергоатомиздат», 1989, 525 с.

11. O.K. Morachkovskii, Yu.V. Romashov. Prediction of the corrosion cracking of structures under the conditions of high-temperature creep // *Materials Science*. 2011, v. 46, N 5, p. 613-618.

12. Ю.В. Ромашов. Метод определения ресурса эксплуатации и показателей долговечности элементов конструкций тепловых и ядерных энергоустановок // *Вісник Національного технічного університету «Харківський політехнічний інститут»*. 2013, №14(988), с. 62-71.

13. О.Є. Андрейків, О.В. Гембара. *Механіка руйнування та довговічність металевих матеріалів у водневмісних середовищах*. Київ: «Наукова думка», 2008, 344 с.

14. Jean Lemaitre Rodrigue Desmorat. *Engineering Damage Mechanics Ductile, Creep, Fatigue and Brittle Failures*. Springer Berlin Heidelberg New York, 2005, 394 p.

15. O.K. Morachkovskii, Yu.V. Romashov. Solving initial-boundary-value creep problems // *International Applied Mechanics*. 2009, v. 45, N 10, p. 1061-1070.

16. Ю. Ромашов. Узагальнене формулювання та наближене розв'язання задач про лінійно-пружне деформування тіл з рухомими границями для дослідження впливу суцільної корозії // *Теорія та практика раціонального проектування, виготовлення і експлуатації машинобудівних конструкцій:* Тези доповідей. Львів: КІНПАТРІ ЛТД, 2012, с. 50-51.

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ПРОБЛЕМА ОЦЕНКИ РАБОТОСПОСОБНОСТИ КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ В ЭЛЕМЕНТАХ ОБОРУДОВАНИЯ ЯДЕРНЫХ ЭНЕРГОУСТАНОВОК

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Приводится обзор литературных данных об опасных повреждениях ответственного оборудования на энергоблоках АЭС в процессе промышленной эксплуатации, которые свидетельствуют об актуальности проблемы оценки работоспособности конструкционных материалов в элементах оборудования ядерных энергоустановок. Отмечаются ограниченные возможности экспериментальных подходов и, в связи с этим обстоятельством, обсуждается оценка работоспособности конструкционных материалов в элементах оборудования ядерных энергоустановок на основе математического моделирования. Предложен подход, в котором оценка работоспособности конструкционных материалов в элементах оборудования ядерных энергоустановок сводится в общем случае к решению системы из нескольких связанных начально-краевых задач. Рассматриваются правила соответствия между математическими объектами и отношениями предлагаемого подхода с процессами в оборудовании и конструкционных материалах ядерных энергоустановок.

ПРОБЛЕМА ОЦІНКИ ПРАЦЕЗДАТНОСТІ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ В ЕЛЕМЕНТАХ ОБЛАДНАННЯ ЯДЕРНИХ ЕНЕРГОУСТАНОВОК

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Наводиться огляд літературних даних про небезпечні пошкодження відповідального обладнання на енергоблоках АЕС у процесі промислової експлуатації, які свідчать про актуальність проблеми оцінки працездатності конструкційних матеріалів в елементах обладнання ядерних енергоустановок. Відзначаються обмежені можливості експериментальних підходів і, в зв'язку з цією обставиною, обговорюється оцінка працездатності конструкційних матеріалів в елементах обладнання ядерних енергоустановок на основі математичного моделювання. Запропоновано підхід, в якому оцінка працездатності конструкційних матеріалів в елементах обладнання ядерних енергоустановок зводиться в загальному випадку до вирішення системи з декількох пов'язаних початково-крайових задач. Розглядаються правила відповідності між математичними об'єктами і відношеннями запропонованого підходу з процесами в обладнанні і конструкційних матеріалах ядерних енергоустановок.