System analysis methodology for decision making in the design problems of new generation nuclear reactors

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Abstract. The main goal of the article is to summarize the results of many years of work on the creation of a unified methodology for designing new generation nuclear reactors that meet the requirements for generating electricity on a given scale, economic efficiency, inherent safety, and fuel supply. The methodology is based on the methods of systems analysis and operations research. Accidents with unacceptable releases of radioactive substances outside the NPP in new generation reactors can be eliminated by using core materials with specified (obtained within the same methodology) properties.

The research methods are based on solving mathematical programming problems in different formulations, solving a number of multicriteria problems, using the non-formalized theory of conflict and informal procedures. As a result of the research, decision-making algorithms have been proposed; software has been developed and modernized to solve the problem of designing nuclear reactors. The practical significance of research in substantiating the fundamental possibility of creating safe nuclear power based on high-power reactors with lead cooling, cermet fuel and innovative structural materials.

1. Introduction
A nuclear reactor is a complex technical system with many connections. When designing such systems, a special role belongs to the mathematical modeling of nonlinear, non-stationary and heterogeneous processes. Of all the types of reactors in existence, fast reactors are the safest. Two concepts of fast reactors are being developed in the world: with sodium and lead coolant [1-7].

Among the non-stationary processes, the greatest attention in the design of the reactor should be paid to emergency modes. Among the emergency modes, the most dangerous are ATWS-type modes (anticipated transients without scram). In all reactors of existing types, ATWS-type modes lead to accidents with unacceptable releases of radioactive substances outside the Nuclear Power Plant (NPP). For this reason, it is necessary to exclude accidents in new generation reactors already at the initial stages of design [8]. ATWS modes can be classified as complex dynamic processes. Their mathematical modeling in conditions of uncertainty of development scenarios must be carried out already at the initial stages of reactor design. There are interrelated and independent processes in the ATWS overlay. One of the fundamental safety principles is the prevention and mitigation of the consequences of nuclear or radiation accidents [9]. From the point of view of the possibility of avoiding accidents, fast reactors with a lead coolant are the most preferable [2, 8]. The elimination of accidents is modeled by the fulfillment of restrictions for a number of functionals (for the maximum temperatures of the core components, power, pressure in the gas cavity of fuel elements, etc.), which characterize the entire set of emergency modes that cannot be excluded due to the laws of nature [10].
Mathematical modeling of a complex technical object represents a compromise between the calculation accuracy and the time spent on calculations. The development of computer technology makes it possible to mitigate the conflicting nature between these two requirements. When developing fundamentally new reactors, it is necessary to analyze information obtained from various sources. This information is characterized by a high degree of heterogeneity, fuzziness, uncertainty, at the same time redundancy and incompleteness. Fuzzy logic tasks are usually combined with a neural network approach [11-13]. Fuzzy technologies are actively developing within the framework of underdetermined mathematics. Approximate models are used at the initial stages of reactor design. However, at the initial stages of design, the promptness of obtaining certain parameters of the reactor is not a primary task. This makes it possible to abandon the use of neural networks at these stages. Uncertainties of heterogeneous information can be taken into account using the methods of game theory [8].

2. Materials and Methods

2.1. Materials

Ceramics UN-PuN or UO$_{1.8}$-PuO$_{2}$ is initially considered as a fuel. Liquid lead is considered as a coolant. Heterogeneous processes in fuel are usually associated with the release of free oxygen (oxide fuel) or nitrogen (nitride fuel), migration of a non-metal to the cladding of a fuel element, migration of fission products to the cladding, and the appearance of gaseous and liquid fission products in solid fuel. When using fuel based on micro-grains of ceramics and uranium metal nanopowder [8, 10], inhomogeneous processes also occur in the fuel. They are associated with a change in the state of aggregation of uranium nanopowder (solid - liquid) in the composition of nuclear fuel in emergency modes. Such a fuel can simultaneously contain substances in a solid, liquid and gaseous state of aggregation.

2.2. Methods

The need to predict the behavior of complex technical systems (nuclear reactors) at the initial design stages and to analyze complex (nonlinear, non-stationary and heterogeneous) processes requires the development of a new decision-making methodology. It is based on the use of systems analysis and operations research methods. The main task of the research is related to the development of the mathematical apparatus and the corresponding software, as well as the symbiosis of calculation and optimization programs with informal procedures. Within the framework of this methodology, it is important to solve problems of mathematical (computer) modeling of nominal and emergency (non-stationary) modes of nuclear reactors of a new generation and processes occurring in reactors (neutron-physical, thermal-hydraulic, strength, etc.). The analysis of emergency modes can be attributed to predictive modeling.

In the study of complex systems, a special role belongs to the development of problem decomposition methods [14-16]. Two directions should be highlighted: decomposition of a complex technical object (its representation in the form of separate connected components and assemblies: an active zone, coolant circulation systems, chain reaction control systems, protection systems, control systems, heating equipment, etc.) and decomposition of a mathematical model (according to degree of complexity and accuracy) of an individual node (for example, a core) [8].

The problem is solved by the example of high-power fast reactors (up to 2.5 GW-e). The prototype of the most preferred high-power reactor is the BREST-OD-300 low-power reactor project, developed at JSC NIKIET [2]. Ensuring safety requires the introduction of serious changes in the BN and BREST projects, related to the adjustment of the used coolant, fuel and structural materials [8, 10].

The studies were carried out using computational and optimization programs (Dragon-M [10]), emergency mode simulation programs (FRISS-2D [10]), separate auxiliary codes for solving multicriteria problems. These programs have been developed and modernized many times by the author. The studies used the well-known programs of "engineering" (WIMS-D/4 [17]) and precision (MCU [18]) neutron-physical calculation. On their basis, hierarchical software structures with
adjustable accuracy have been developed. In this article, the decomposition of the mathematical model (Dragon-M, FRISS-2D, and MCU) is used to analyze the ATWS.

3. Results

3.1. Features of the New Methodology

A unified methodology is proposed that combines the following groups of tasks that need to be solved on the basis of a system analysis. The following four hierarchical levels of tasks are considered (in descending order of the degree of formalization): problems of mathematical programming in a deterministic setting; problems of mathematical programming with undefined data; multi-criteria tasks (their formulation is more correct than the formulation of a mathematical programming problem); elements of an informal theory of conflict (they are used to reduce the dimension of the optimization problem by identifying emergency situations that neutralize and aggravate each other and exclude interrelated criteria).

The connecting link of theories, methods, procedures, approaches used in these four groups of problems is system analysis. The main problems of creating a methodology are as follows: a fundamentally new formulation of the reactor design problem, which requires taking into account safety already at the initial design stage; impossibility of complete formalization of the solution of the problem; a large number of considered emergency situations and the uncertainty of their scenarios; the need to solve auxiliary problems, etc. Of the many theories and methods used in operations research, only optimal control theory has been brought to the “engineering” level. The use of game theory criteria for choosing rational decisions (Wald, Savage, Laplace, Hurwitz, etc. [19]) in analysis and security problems with uncertain data is limited. In some cases, it is inappropriate to narrow the area of uncertainty.

In the tasks of designing a reactor, it is required to choose a single option. When solving multicriteria problems in conditions of uncertainty, there can be many preferable options: the Pareto set [20]. Minimization of the subjective factor is possible on the basis of differentiation of procedures performed by a computer to reduce the uncertainties associated with the fuzziness of human perception and thinking, and procedures where artificial intelligence does not have acceptable efficiency and accuracy (tasks associated with processing information that cannot be reduced to sets numbers with acceptable values of uncertainties and errors). This will minimize the volitional decision-making procedure. The multicriteria design problem is reduced to a mathematical programming problem through reformulation, and not in the traditional way (by choosing a global optimality criterion).

3.2. Basic Algorithms

The decision-making procedure (selection of the physical characteristics of the core) is based on the following several stages.

1. Collection of baseline information. The initial data should have the property of sufficiency (completeness), minimum redundancy and minimum uncertainty. It is convenient to represent a complex object in the form of a graph.

2. Drawing up a mathematical model. This includes the formulation of the problem, the choice of methods for its solution. The procedure involves identifying subtasks that require maximum mathematical formalization, determining the stages of solving the problem, the possibility and degree of subjective interference in the course of solving the problem. The formulation of the problem presupposes the choice of target functionals, components of the control vector (which includes the properties of the core materials) and the determination of the range of its admissible values, the choice of functionals for which it is necessary to formulate restrictions (including functionals characterizing emergency modes), as well as data, not changed during the optimization process. The analysis of the possibility of minimizing the dimension of the problem is carried out.

3. Solution of multi-criteria problems and problems of mathematical programming in a deterministic formulation and in conditions of uncertainty, parameterization and other procedures.
4. Analysis of the sensitivity coefficients of the functionals, the study of “near-optimal” options, the study of the self-protection region of the reactor (the maximum possible perturbations of the flow rate, reactivity, coolant temperature at the inlet to the core).

The decision-making procedure includes the following general steps.

1. Formulation and analysis of a problem situation, determination of the general goal of research and decision-making.
2. Formation of a system of quality criteria and mathematical formalization of the design problem statement.
3. Reduction of the original multicriteria reactor design problem to various mathematical programming problems. The problem associated with the large dimension of the problem can be solved on the basis of a preliminary ranking of the functionals of the problem according to the degree of significance (i.e., the importance of influencing the results of solving a specific problem).
4. Solving problems of mathematical programming, including under conditions of uncertainty of initial information. The stage is implemented using the Dragon-M code [10].
5. Parameterization, analysis of uncertainties, additional “extended” safety analysis, involving consideration of a wider set of emergency situations.
6. Determination of a set of additional criteria for the selection of preferred options, the formulation of a multi-criteria problem.
7. Solving a multicriteria problem by different methods, analysis of the stability of the solution to the selected methods, determination of preferred methods and options.
8. Additional analysis of the results based on high-precision (precision) calculations using the appropriate codes (for example, MCU [18]) and correction of the options obtained in the previous step.
9. Analysis of the preferred options obtained at the previous stages and their ranking according to the degree of preference from the point of view of a particular set of criteria with the involvement of previously “cut off” (less significant) information.
10. Making the final decision: choosing the only option for implementation.

4. Discussion
4.1. Benefits from the Implementation of the Methodology
On the basis of a systematic approach and well-known methods of applied mathematics, the author proposed and implemented a unified methodology for substantiating and analyzing the safety of fast reactors, which makes it possible to rationalize the decision-making procedure in the problems of the initial design stage. The exclusion of a volitional decision-making procedure is achieved due to a clear division of labor between a computer and a person and minimization of the dimension of tasks solved by a person.

The author proposes the following procedures, methods and models, which are applications of operations research and game theory.

(a) A method for ranking emergency situations according to the degree of hazard (significance for consideration in design tasks) is proposed. The method is based on solving a discrete multicriteria problem (by the max-min method) under conditions of uncertainty and incompleteness of the initial information. The method makes it possible to exclude from consideration some emergency modes (from the number of ATWS).

(b) A method for multicriteria optimization of a fast reactor layout is proposed, developed on the basis of the ideas of positional games and assuming sequential (step-by-step) decision-making based on sequential concessions.

(c) A method for solving problems without an optimality criterion for finding a set of safe reactor layouts in the control space is proposed.

(d) A model of sequential analysis of conflicts in the problems of optimal design of a reactor, a hierarchical structure of conflicts and methods of their resolution based on the ideas of game theory are proposed. The analysis of conflicts made it possible to reduce the dimension of the problem.
An approach to substantiating the safety of a reactor based on solving optimization problems is proposed.

In order to improve the efficiency of decision-making, hierarchical models with adjustable accuracy (based on MCU) have been developed for precision neutron-physical calculations of reactors and optimization of the layout of fast reactors, including two- and three-level models for taking into account safety functional in problems of optimal design and justification security. The hierarchical models are based on the decomposition of the mathematical model of the reactor.

New results have been obtained that illustrate the application of the proposed methodology.

(a) Optimal layouts of the fast reactor core with various coolants (including unconventional ones) were obtained [10]. Among the constraints of the problem, the constraints for the functionals characterizing safety were taken into account (in the conditions of uncertainty of scenarios for the development of emergency situations).

(b) The results of ranking the coolants according to the degree of preference were obtained, obtained on the basis of a systematic approach and solving multicriteria problems. For power reactors of high power, a heat carrier based on lead and thorium ores is preferable.

(c) The Dracon-M code has been used to obtain the permissible core material properties and to select the appropriate materials. The author proposed a new pellet fuel based on micro-grains of mononitride or oxide and uranium metal nanopowder (up to 40% by weight) [8, 10]. For a BREST type reactor [2, 3], with increasing power, it is necessary to use a coolant based on lead extracted from thorium ores with a high concentration of $^{208}\text{Pb}$ isotope (more than 75%). It is necessary to use structural materials (first of all, materials of fuel element cladding) based on nickel-free steels (EP832 [2]) with additions of yttrium and titanium nanooxides [21; 22] and tungsten coatings of cladding [10].

4.2. The practical relevance of research

The developed software makes it possible to obtain the layout of a fast reactor of a given power, taking into account the specified requirements for economics, reliability and safety. Restrictions for functionals are considered that simulate the failure-free termination of all ATWS-type processes (including their combinations), which are not deterministically excluded. The tasks were solved in the conditions of uncertainty of scenarios for the development of emergency modes.

The proposed effective hierarchical systems with adjustable accuracy based on known high-precision computer codes (MCU) are used to conduct exploratory computational experiments, substantiate and analyze safety (reactivity effects), experimental optimization methods, and post-optimization analysis. The systems allow you to analyze any type of reactor. When using hierarchical systems based on MCU, the calculation time is reduced by 7...12 times.

Reserves of the concept of power reactors in terms of improving safety have been identified. BN reserves are associated with the use of cermet fuel based on oxide or mononitride micro-grains and uranium metal nanopowder. BREST reserves relate to the use of a coolant based on thorium lead, tungsten coatings of fuel-element cladding, the use of nanooxides in the composition of steel of fuel-element cladding, fuel based on mononitride micro-grains and uranium nanopowder. The resulting reactor configurations of arbitrarily high power (at least up to an electric power of 2.5 GW) with a lead coolant are capable of safely emerging from any combination of ATWS modes.

5. Conclusion

The article represents the final stage in the development of a decision-making methodology in the design of new generation nuclear reactors. The joint systemic use of computational mathematics methods, optimization methods, decision-making ideas, and informal procedures (including the theory of conflict) made it possible to develop a unified decision-making methodology for the design of safe nuclear reactors of a new generation. In practical terms, the methodology makes it possible to automatically determine the required properties of the reactor materials and select the required materials based on combinations of the number of existing (well-studied) materials. As a result, it is possible to create reactors of high power, characterized by internal safety.
The results obtained supplement and concretize some sections of the IAEA documents on NPP safety justification (in particular, [23]).

References

[1] Vasilyev B A et al 2016 Innovative Design of the BN-1200 Power Unit as a Basis for Evolutionary Development of the SFR Area. Materials of 4th Int. Scientific and Technical Conf. "Innovative Design and Technologies of Nuclear Power" Moscow 38-39

[2] Lemekhov V V et al 2018 Present-Day Status and Development Prospects of Fast-Neutron Lead-Cooled Reactors. Materials of 5th Int. Scientific and Technical Conf. "Innovative Design and Technologies of Nuclear Power" Moscow 35-37

[3] IAEA 2003 IAEA-TECDOC-1348: Power Reactor and Sub-critical Blanket Systems with Lead and Lead-Bismuth as Coolant and/or Target Material. Utilisation and Transmutation of Actinides and Long Lived Fission Products (Vienna) 232

[4] IAEA 2013 IAEA-TECDOC-1691: Status of Fast Reactor Research and Technology Development (Vienna) 834

[5] IAEA 2015 Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios: FR13 (Vienna) 519

[6] IAEA 2013 Status of Innovative Fast Reactor Designs and Concepts, Information Booklet (Vienna) 70

[7] IAEA 2018 Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development: FR17 (Vienna) 260

[8] Okunev V S (2021) Prospects for the development of the concept of a safe nuclear reactor BREST of maximum limiting power for nuclear energetics of the middle of the XXI century IOP Conf. Ser.: Mater. Sci. Eng. 1100 012002

[9] IAEA 2020 IAEA-TECDOC-1903: INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Safety of Nuclear Fuel Cycle Facilities. INPRO Manual (Vienna) 170

[10] Okunev V S 2019 Designing of New Generation of the Nuclear Reactors AIP Conference Proceedings 2195, 020012 (2019); https://doi.org/10.1063/1.5140112

[11] Kruglov V V, Dli M I and Golubov R Yu 2001 Fuzzy Logic and Artificial Neural Networks (Moscow: Fizmatlit) 224

[12] Romanov L G, Gofman I D and Inishev D A 2002. Development of intelligent technology for underdetermined planning and project management Time-EX Scientific Bulletin of MSTU GA 2 13-17

[13] Dushkin R V and Rybina G V 1999 On one approach to automated extraction, presentation and processing of knowledge with non-factors Izv. RAN. Theory and control systems 5 34-44

[14] Tsurkov VI 1981 Decomposition in problems of large dimension (Moscow: Nauka) 352

[15] Mikhailевич V S and Volkovich V L 1982 Computational methods of research and design of complex systems (Moscow: Nauka) 288

[16] Mesarovich M D, Macko D and Takabara Y 1970 Theory of Hierarchical Multilevel Systems (Academic Press, New-York and London) 294

[17] Deen J R and Woodruff W L 1995 WIMS-D4M User Manual (Illinois, ANL-RERTR/TM-23) 95

[18] Gomin E A 2006 Status MCU-4 VANT, ser.: Physics of nuclear reactors 1 6-32

[19] Owen G 1995 Game Theory (Emerald Group Publishing Limited) 460

[20] Nogin V D 2020 The set and the Pareto principle (St. Petersburg) 100

[21] Saragadze V V, Shabashov V A, Litvinov A V et al. 2005 Reactor steels reinforced with nanooxides. VI Int. Ural seminar "Radiation physics of metals and alloys". (Snezhinsk) 7

[22] Azarenkov N A, Voevodin V N, Kirichenko V G and Kovtun G P 2010 Nanostructured materials in nuclear energy Visnyk of Kharkiv Nat. Univ.: Nuclei, particles, fields 887-1 (45) 4-24
[23] IAEA 2002 *Accident Analysis for Nuclear Power Plants* (Safety Reports Ser. 23, Vienna) 129