Improving Software Efficiency to Optimize the Next-Generation Fast Reactors*

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Abstract. The planned transition of Russia to large-scale nuclear power by the middle of the 21st century requires future professionals to design safe new-generation reactors. Their design differs significantly from the existing reactors in terms of materials used, safety systems, and relative simplicity of design. Software systems for optimizing the layout of fast reactors have been used in the educational process of Moscow Engineering Physics Institute since their introduction (the early 1970s). These programs are characterized by the possibility of obtaining the optimal reactor layout in automatic mode without taking into account the safe termination of emergency modes. I managed to supplement the optimization model with constraints for functionals simulating the accident-free termination of emergency modes (including the anticipated transient without scram). In addition, I managed to improve the software efficiency, which implies reducing the dimension of the problem without compromising the reliability of the results of its solution. Hence, a new optimization system can be used in the educational process. Minimization of the problem dimension is done by (1) combining emergency modes into a small number of groups, (2) reducing the number of functional capabilities describing each of the emergency modes, (3) preliminary analysis of possible neutralizations and exacerbations of emergency modes when they are imposed, (4) ranking emergency modes by the level of danger, (5) using an effective procedure for taking into account scenario uncertainties in the development of emergency modes.

Keywords: Effective software · Optimal design · Control parameters · Functionals · Optimality criterion · Fast reactor · Inherent safety · Decision-making process

1 Introduction

1.1 Relevance of the Problem

Students of higher technical educational institutions and universities face the problem of designing complex systems in the fourth year of study within the coursework or bachelor's thesis. Then, they continue to study the problems as part of a research project, a diploma project, or a master's degree thesis. During their subsequent professional activities, university graduates refine the studied approaches and apply them in the design of complex technical systems and optimization of complex technological processes.

The design must be optimal. A non-optimal design does not make sense. Often, during the decision-making process, it is suggested to choose one of several options. It is assumed that a person distinguishes up to three or five gradations in the verbal assessment. Therefore, to minimize the volitional (subjective) factor, the number of options the decision-maker must have should not exceed three or five. These options are usually Pareto optimal. Additional criteria or scientific intuition are required to select the preferred option.

In Russia, the transition to large-scale nuclear power is expected by 2050. From 2000 to 2050, the total capacity of nuclear power plants can increase by about ten times. This fact requires developing a new generation of reactors, for which severe accidents with unacceptable releases of radioactive substances must be excluded. The shift in priorities towards improving the safety of nuclear power plants requires developing new computational and optimization research methods necessary primarily for new reactor designs and concepts, including fast reactors with liquid metal cooling. For such reactors, the inherent security is quite achievable; they are promising structural elements for large-scale nuclear power engineering. The development of computational and optimization software systems for fast reactors of the new generation is relevant.

1.2. Research Goal

The research aims to increase the efficiency of computational and optimization models of decision-making by many criteria in the conditions of uncertainty and incompleteness of the initial information.

The National Research Nuclear University Moscow Engineering Physics Institute (MEPhI, Moscow, Russia) formed a scientific school for optimizing fast reactors. I am a follower of this school at the Bauman Moscow State Technical University (Bauman MSTU, Moscow, Russia). Since the 1970s, the MEPhI educational process includes programs for optimizing the layout of a fast reactor operating at rated power (Egorkina, Kuzmin & Moskalev, 1983; Geraskin, Kuzmin & Morin, 1983; Khromov & Kashutin, 1975; Khromov, Kuzmin & Kashutin, 1969, 1970; Khromov, Kuzmin & Orlov, 1978). I supplemented the optimization problem with functionals characterizing emergencies, including anticipated transients without scram [ATWS] (Kuzmin & Okunev, 1996). In the future, one can significantly reduce the dimension of the optimal design problem without compromising the reliability of the results of its solution; that is, to increase the software efficiency. All optimization programs allow for neutron-physical, thermal-hydraulic, strength, and economic calculations.

2 Materials and Methods

2.1 Problem statement: Nuclear Reactor as a Complex Technical System

The core of a nuclear reactor is a system of many elements that interact with each other. The study of such systems is usually carried out within a systematic approach (analysis). Systematic analysis of targeted actions is the primary method of operations research. It is a complex mathematical discipline that deals with the design, development, and application of mathematical models of decision-making. An operation is defined as performing an action or procedure with the source data, including its transfer. There are operations with numeric, logical, and lexical information. Research of operations is at the intersection of sciences and operates with both quantitative and qualitative factors. The elements of this kind of research are (1) mathematical programming, (2) multi-criteria optimization, (3) Markov models of decision-making, (4) decision-making procedures under conditions of risk and uncertainty, (5) game theory. All these elements are used to solve the problem of choosing the optimal physical characteristics of a fast reactor that meets several requirements (including safety), even at the initial design stage.

In general, the decision-making model is characterized by a large amount of heterogeneous information. It has large dimensions and many internal connections. In this regard, it is necessary to streamline the decision-making process. This stems from the need to improve decision-making efficiency in the presence of heterogeneous (numerical, logical, lexical) information containing fuzziness, uncertainty, nondeterminism, inaccuracy, or incompleteness.

2.2 Approaches to Solving Problems of Optimal Design of Nuclear Reactors

In the decision-making process, the problem of obtaining and processing information from heterogeneous sources is relevant. The sources may vary depending on the data access methods (Soloviev & Chesnavsky, 2004). Besides, the sources and recipients of information can be highly distributed and diverse. The integration of the neural network approach (neuroinformatics) and nondeterministic mathematics (fuzzy technologies) can contribute to solving this problem (Narinyani, 1980; Romanov, Hoffman, & Inishev, 2002). There is a well-known procedure for creating knowledge bases containing *non-factors* (vagueness, uncertainty, nondeterminism, inaccuracy, incompleteness) (Dushkin & Rybina, 1999).

In nuclear technology, the neural network approach is used (Demidovsky, 2019; Romanov, 2004; Volkov & Vetlugin, 2005). It has advantages and disadvantages (Manzhula & Fedyashov, 2011). To enhance the advantages and minimize the disadvantages, the neural network approach is combined with fuzzy logic (Kruglov, Dli & Golubov, 2001; Romanov, 2000, 2004; Terano, Asai & Sugeno, 1992; Zadeh, 1971).

Although the information in the initial stage of reactor design problems is heterogeneous (while numerical information prevails), its volume is not so large as to thoroughly ground the decision-making process on fuzzy neural networks. Well-known methods of game theory can solve the problem associated with the uncertainty of numerical information.

There is an efficient algorithm to solve the problem of determining the optimal and acceptable physical characteristics of the active zone safe fast reactors, in which rationalization (efficiency improvement) decision-making is based on (1) a preliminary study of the ability to neutralize and exacerbate emergency conditions when they overlap (which provides additional information to the solution of problems under uncertainty scenarios of emergencies and minimizes subjective factors); (2) complex analysis of conflicts in the optimal design problem (going beyond the traditional framework of research of operations); (3) a decomposition approach to optimization and post-optimization analysis; and (4) reduction of the dimension of the problem (by reducing the number of emergencies considered during optimization, and their combinations based on their ranking by the degree of danger; as well as reducing the number of functionals describing each of the considered emergencies). This algorithm is an application for research of operations to solve a practical problem related to the development of new-generation reactors. The research used the optimization software package *DRAGON-M* that I upgraded (the last upgrade was completed in 2019), as well as the auxiliary codes that I developed (Okunev, 2019).

The requirement of deterministic exclusion of potentially possible serious accidents is formalized in the form of restrictions for several functionals (safety functionals) corresponding to maintaining the operability of safety barriers. Game theory formulates the problem of optimal reactor design, according to which severe accidents are deterministically excluded, as a game with a thinking opponent, which with the appropriate formalization of some intuitive concepts, can be reduced to solving problems with different degrees of formalization. The following tasks (with a decrease in the degree of formalization) are the basis of a unified methodology for selecting the optimal physical characteristics of fast reactors related to the operational research.

Furthermore, I would like to dwell on the problems of mathematical programming in a deterministic setting (Minoux, 1983; Okunev, 2019). I regard the functionals characterizing the main requirements (safety, self-sufficiency in fuel, economic efficiency) for future energy sources as a criterion and limitation of the problem (Okunev, 2019). From this point of view, the optimization is complicated. A criterion related to reactor safety can be selected as the target functional; for example, the void reactivity effect (realized when the core or part of it is drained) when optimizing a fast reactor with a liquid metal coolant. I consider different control parameters, such as the dimensions of the reactor zones, the fuel enrichment in the zones, the geometric characteristics of the fuel rod lattice, the coolant flow rate, and many others.

Also, I solve mathematical programming problems with undefined data. The procedure for accounting for the uncertainty of emergency regimes plays a unique role. Besides, I examine discrete multi-criteria problems minimizing the dimension of the optimal design problem, namely, the task of ranking emergencies according to the degree of danger (significance – from the point of view of priority examination in optimal design problems). I solve these problems based on the max-min principle.

Discrete multi-criteria tasks allow the decision-maker to choose a single preferred option from several suggested ones. I use elements of the informal conflict theory to reduce the dimension of the optimization problem by detecting, neutralizing, and aggravating modes (when they overlap) and eliminating interrelated criteria.

2.3 Increasing the Reliability of the Solution and Minimizing the Dimension of the Optimal Design Problem

A mathematical programming problem is a problem with a single criterion (a target functional) and a set of constraints (for several other functionals). The functionals of the task characterize the main requirements for future energy sources, such as energy production on the required scale, economic efficiency, safety, and fuel availability.

As a target functional with particular tasks, one can choose a criterion related to the fast reactor safety (e.g., void reactivity effect). A strong spatial dependence characterizes the void reactivity effect. I consider two functions that characterize this effect. The first one corresponds to the drainage of the entire core, the other – to the drainage of the central part of the core.

The characteristics of the core are included in the vector of control parameters. These characteristics include (1) geometrical parameters (dimensions of the reactor zones, the geometry of the fuel element grid), (2) coolant flow rate, and (3) properties of the core materials (fuel, coolant, and structural materials, such as density, thermal conductivity, porosity, or viscosity.

Mathematical programming problems with undefined data $\boldsymbol{v}$ involve searching for a vector of control parameters

$$\boldsymbol{u} = \{u_k\};\ k = 1, 2,\ldots, K;\ \text{herewith}$$

$$F_0\,(\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{f}) \rightarrow min$$

and constraints

$$F_i(\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{f}) \leq F_i^*(\boldsymbol{v});\ i = 1, 2,\ldots,I;$$

where:

$$\boldsymbol{f} \equiv \boldsymbol{f}(\boldsymbol{u}, \boldsymbol{v});$$

$$A_m(\boldsymbol{v})\,\boldsymbol{f}_m(\boldsymbol{u}, \boldsymbol{v}) = 0;\ m = 1, 2,\ldots,M < K;$$

$$\boldsymbol{v} = \{v_n\};\ v_n^{min} \leq v_n \leq v_n^{max};\ n = 1, 2,\ldots, N,$$

In general case $u_k^{min} \equiv u_k^{min}(\boldsymbol{v})$, $u_k^{max} \equiv u_k^{max}(\boldsymbol{v})$.

It is assumed that data change laws are unknown; only the ranges of their changes are known. This fact is due to the requirements of a deterministic approach to analyzing the safety of new-generation nuclear reactors.

The problem is solved using sequential linearization (Khromov & Kashutin, 1975; Khromov, Kuzmin & Orlov, 1978). This method is well established, although it does not always converge. Convergence occurs in large-scale problems with constraints on the functionals characterizing the emergency operation of the reactor, especially if the implementation of the constraints is contradictory.

Among the constraints of the problem, I consider the constraints for the functionals (safety functionals) characterizing the ATWS modes.

From the perspective of designing safe reactors, problems in the conditions of uncertainty of scenarios for the development of emergencies are of the most significant interest. In this regard, I propose and implement a practical methodology for solving such problems (Okunev, 2019).

When designing a reactor, one must consider all emergency conditions (there are about 50 of them). Each of the modes is characterized by several security features. I consider a cylindrical reactor consisting of several homogenized zones of different compositions.

Minimizing the dimension of the optimal design problem is possible due to particular factors. First, it is necessary to minimize the number of considered emergency modes by combining them into a few groups. Emergency modes can be considered as a combination of disturbances in reactivity, coolant flow rate, coolant temperature at the inlet to the core.

Second, one must minimize the number of functionals describing each of the emergency modes. When analyzing some modes, it is necessary to limit the maximum temperature of the fuel, coolant, fuel pin cladding, and reactor power. The practice of solving optimal design problems shows that among the maximum temperatures of the coolants and cladding, one can choose only one functional; there is also one functional among the maximum temperature of the fuel and power. It is possible to identify the reactor zones where the values of the safety functionals are maximum. In other zones, only the values of the safety functions can be calculated.

Third, one must analyze the possible neutralization and aggravation of emergency modes when they are imposed and rank emergency modes by the degree of danger based on the *max-min* strategy of the cooperative game (Okunev, 2019). Moreover, one must primarily consider the restrictions characterizing the most dangerous emergency modes (from among the ATWS). Besides, I consider the emergency modes among the objects of the discrete multi-criteria problem of emergency ranking and the functionals characterizing these modes (maximum temperatures of the core components, reactor power, and pressure in the fuel cavity for collecting gaseous fission products). The simultaneous imposition of all perturbations of reactivity, flow rate, coolant temperature at the entrance to the core is usually less dangerous due to the neutralization of some of these disturbances.
Using an effective procedure to account for the uncertainty of emergency scenarios (Okunev, 2019). This procedure minimizes the number of deterministic analogs of the original problem formulated under conditions of uncertainty. Ideally, the problem can be reduced to two or three deterministic analogs, which is possible since the original problems have the property of decomposability.
The final decision on choosing the main (most preferred) version of the reactor layout is made based on additional analysis of Pareto optimal layouts (i.e., conditionally equally safe reactors).

3. Results

2.4 Analysis of Complex Emergency Mode Combinations

The modeling of complex dynamic (emergency) processes is a key issue of accounting for flight safety in the optimization model.

In most cases, the perturbations that initiate the emergency mode (perturbations of reactivity, flow rate, coolant temperature at the inlet), and emergency protection failure are independent (unrelated) events. Usually, some combinations of emergency modes can also be attributed to independent events. However, sometimes the initial perturbation of one or more parameters (the primary perturbation) can lead to a subsequent change in any of these parameters with some time delay (secondary perturbation). Such processes should be classified as complex interconnected dynamic modes. Perturbations that initiate an emergency operation can be classified as primary, secondary, and so on. Primary perturbations include perturbations of parameters occurring during the normal operation of the reactor and directly initiating an emergency transient. At the same time, the safety features are changing. As a rule, the primary perturbation is accompanied by a secondary one, which can sometimes aggravate the emergency mode. I can regard the change in the inlet temperature after the coolant passes through the primary circuit as a secondary perturbation.

It is not always possible to draw a clear conclusion about the neutralization or aggravation of primary and secondary perturbations in one emergency process. Primary and secondary perturbations are interrelated and characterize a single emergency associated with a complex process. When modeling such processes, it is convenient to consider secondary disturbances as independent emergency modes.

The problem arises of choosing the global maximum of the safety functional when applying time-separated perturbations (Fig. 1). The problem of *interference* of peaks (in the time dependence of the safety functionals) arises in the analysis of interrelated processes, such as a short transport time of the coolant along the primary circuit and in the study of combinations of independent modes. In both cases, one can get an unclear picture of the emergency; moreover, identifying the safety functional peak corresponding to a particular perturbation may be difficult. In these cases, it is necessary to analyze the possibility of neutralizing or exacerbating emergency modes when they are imposed. If the processes neutralize each other during the imposition, then the functionals that characterize such a combination can be excluded. When two or more modes are escalated (when imposed), the dominant process is determined, and the constraints on the safety functionals corresponding to the dominant process are considered.

In case of a significant change in the control vector (layout) during the optimization process, the nature of changes in the safety functionals in emergency conditions may change. Sometimes it is necessary to reformulate the problem during the solution process (for example, to include additional security functions in the optimization model). For this reason, the search for the optimum should not be fully automated.

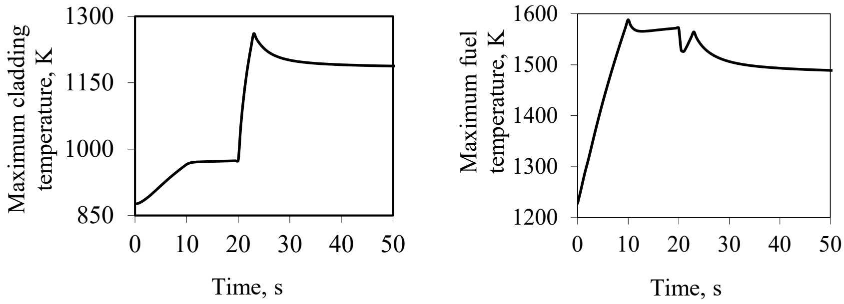

Fig. 1. The dependence of the maximum temperature on time in the imposition of ATWS overlay ("loss of flow" + "transient overpower" + "overcooling accident") in the BREST-300 core. *Source*: Compiled by the author.

4 Discussion

Given the above problems, I can propose a scheme for solving the optimal design problem.

The first stage includes a preliminary analysis of emergencies in the initial reactor layout. While neutralizing emergencies, when they are imposed, the restrictions for the corresponding safety functions are excluded from the task. With the aggravation of emergency conditions, when they are imposed, the dominant process is determined. The design task involves constraints for the safety functionals corresponding to this process.

The second stage implies the solution to the optimal design problem. Finally, the third stage presupposes making a decision based on the analysis of the results. This stage is the end of the calculation, if the nature of the change in the safety functionals has not changed qualitatively. One should proceed to the first stage if the nature of the safety functional change has changed qualitatively.

Similar tasks are solved in semi-automatic mode using the DRAGON-M software package. Full automation of calculations is impractical. First, it is advisable to provide for the possibility of user intervention at any research stage. Second, some of the problems that need to be solved are not strictly mathematical ones; they require informal procedures.

I found out that the danger of any combination of the imposition of emergency operations depends on the following factors: (1) each of the emergency modes (amplitude perturbation triggering the alarm process, the introduction of these perturbations, characteristics of safety systems, such as the response time of the pumps of the first and second circuits, the passive characteristics of emergency cooling systems, etc.); (2) time delay of a particular emergency mode when modes are imposed; and (3) from the dominance or neutralization of individual emergency modes.

The role of individual emergency modes in their imposition (dominance, neutralization) can change for long periods of relative delay of these processes, for example, comparable to the time of perturbation.

The nature of changes in the main parameters of the reactor when applying independent modes is the same as when combining complex interrelated processes. Some parameters, including those that characterize the relative delay of individual emergency states when they are imposed, are challenging to determine. This fact leads to the need to solve similar problems in the conditions of uncertainty of the initial data on the scenarios of the development of emergency modes.

5 Conclusion

Based on the research results, I can draw two essential conclusions. First, as a result of the procedures carried out, I managed to reduce the dimension of the optimal design problem for a fast reactor, taking into account the main requirements for future energy sources. To obtain reliable results, one can limit oneself to 10 to 15 control parameters, and 25 to 30 functions consider the safety of the reactor from these types of accidents and all the requirements for future energy sources. This fact allows one to use the optimization software package in the educational process.
Second, the modernization of the optimization complex *DRAGON-M* carried out in 2019, associated with the control vector expansion, allowed me to solve new urgent problems. The control parameters included the physical properties of the core materials, such as fuel, coolant, structural materials (density, thermal conductivity, heat capacity, cross-section of neutron interaction with the material, etc.). Therefore, one can solve a new class of problems related to selecting the most preferred materials, including those based on alloys and mixtures that contribute to achieving the internal safety of the reactor. Such tasks may be relevant and useful in the training of experts in reactor materials. To simplify the task of optimal design, sometimes all other control parameters, except for the properties of the main materials, should be converted to the category of source data that does not change during the optimization process. In this case, within the framework of a given reactor layout, one can select (adjust) the properties of the core materials that meet the obtained properties, increasing the safety, reliability, and power of the designed reactor.

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