TOMSK POLYTECHNIC UNIVERSITY — ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Министерство науки и высшего образования Российской Федерации
федеральное государственное автономное
образовательное учреждение высшего образования
«Национальный исследовательский Томский политехнический университет» (ТПУ)

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Направление подготовки 14.04.02 Ядерные физика и технологии
Научно-образовательный центр международного ядерного образования и карьерного сопровождения иностранных студентов ТПУ

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
Применение решателей систем дифференциальных уравнений на базе Python для моделирования динамики реактора

УДК 621.039.58:519.876

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School of Nuclear Science & Engineering
Field of training: 14.04.02 Nuclear Science and Technology
Specialization: Nuclear Power Engineering
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MASTER THESIS

Topic of research work
Application of Python based ODE's solvers for modeling reactor dynamics

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Tomsk – 2023

LEARNING OUTCOMES

Competence code	Competence name
Universal competences	
UC(U)-1	Ability to make critical analysis of problem-based situations using the systems analysis approach, and generate decisions and action plans.
UC(U)-2	Ability to run a project at all life-cycle stages.
UC(U)-3	Ability to organize and lead the teamwork and generate a team strategy to achieve the target goal.
UC(U)-4	Ability to use modern communication technologies to realize academic and professional interaction.
UC(U)-5	Ability to analyze and account for cultural diversity in the process of intercultural interaction.
UC(U)-6	Ability to set and pursue individual and professional activity priorities and ways to modify professional activity based on the self-esteem.
General professional competences	
GPC(U)-1	Ability to formulate goals and objectives of the research study, select assessment criteria, identify priorities for solving problems.
GPC(U)-2	Ability to apply modern research methods, evaluate and present the results of the performed research.
GPC(U)-3	Ability to present research outcomes in the form of articles, reports, scientific reports and presentations using computer layout systems and office software packages.
Professional competences	
PC(U)-1	Ability to manage personnel, taking into account the motives of behavior and ways of developing business behavior of personnel, apply methods for assessing the quality and performance of personnel, develop and implement measures aimed at preventing industrial injuries and environmental violations.
PC(U)-2	Ability to develop and ensure the implementation of measures aimed at improving, modernizing, unifying manufactured devices, facilities and their components, developing standards and certificates, improving reliability of equipment operation.
PC(U)-3	Ability to apply basic methods, techniques and means of obtaining, storing, processing information to plan and manage the life cycle of manufactured products and their quality.
PC(U)-4	Ability to create theoretical and mathematical models describing the condensed state of matter, the propagation and interaction of radiation with matter, the physics of kinetic phenomena, processes in reactors, accelerators, the effect of ionizing radiation on materials, humans and environmental objects.
PC(U)-5	Ability to use fundamental laws in the field of nuclear physics, nuclear reactors, condensed matter, ecology in a volume sufficient for independent combination and synthesis of real ideas, creative self-expression.
PC(U)-6	Ability to evaluate prospects for the development of the nuclear industry, use its modern achievements and advanced technologies in research activities related to the development of technologies for obtaining new types of fuel and materials, radioactive waste management methods and techniques.
PC(U)-7	Ability to assess risks and determine safety measures applied for new facilities and technologies, draw up and analyze scenarios of potential accidents, develop methods to reduce the risk of their occurrence.

PC(U)-8	Ability to analyze technical and computational-theoretical developments, take into account their compliance with the requirements of laws in the field of industry, ecology and safety, and other regulations.
PC(U)-9	Ability to carry out independent experimental or theoretical research to solve scientific and technical problems using modern equipment, calculation and research methods.
PC(U)-10	Ability to draw up technical assignments, use information technology, standard design automation tools and application software packages in the design and calculation of nuclear facilities, materials and devices, apply knowledge of methods of ecological efficiency and economic-value analysis in the design and implementation of projects.
PC(U)-11	Ability to develop design process documentation, execute engineering design and production projects.
PC(U)-12	Ability to conduct training sessions and develop instructional materials for the training courses within the cycle of professional training programs (bachelor degree programs).

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School of Nuclear Science & Engineering
Field of training: 14.04.02 Nuclear Science and Technology
Specialization: Nuclear Power Engineering
Research and Training Centre for International Nuclear Education and Career, School of Nuclear Engineering

APPROVED BY:
Program Director
_____________ Verkhoturova V.V.
«____» ____________ 2023

ASSIGNMENT
for the Graduation Thesis completion

In the form:

Master Thesis

For a student:

Group	Full name
0АМ1И	Nikita Yevgenyevich Bortulev

Topic of research work:

Application of Python based ODE's solvers for modeling reactor dynamics	
Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	№ 136-86/c dated May 16, 2023

Deadline for completion of Master Thesis:	06.06.2023

TERMS OF REFERENCE:

Initial date for research work: *(the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.)*	Development of simplified mathematical model of reactor dynamics with required accuracy and potential to introduce it to safety and protection system of such reactor. Complete coded model in compare with others software, simplifies reactor operation and makes one more step to development of autonomous reactor controller

List of the issues to be investigated, designed and developed *(analytical review of literary sources with the purpose to study global scientific and technological achievements in the target field, formulation of the research purpose, design, construction, determination of the procedure for research, design, and construction, discussion of the research work results, formulation of additional sections to be developed; conclusions).*	- To review the literature - To compose a system of dynamics equations representing a mathematical model - To code mathematical model via python programming language and open source library SciPy - To compare results obtained via mathematical model with open sources of information - To make discussions and conclusions
List of graphic material *(with an exact indication of mandatory drawings)*	

Advisors to the sections of the Master Thesis
(with indication of sections)

Section	Advisor
One: Literature Review	Head of department Alexey G. Goryunov
Two: Materials and Methods	Head of department Alexey G. Goryunov
Three: Results and Discussion	Head of department Alexey G. Goryunov
Four: Financial management, resources efficiency and conservation	Associate Professor Ekaterina V. Menshikova
Five: Social Responsibilities	Associate Professor Yuriy V. Perederin

Date of issuance of the assignment for Master Thesis completion according to the schedule	03.02.2023

Assignment issued by a scientific supervisor / advisor (if any):

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0АМ1И	Nikita Yevgenyevich Bortulev		

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Field of training (specialty): 14.04.02 Nuclear Science and Technology
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Research and Training Centre for International Nuclear Education and Career, School of Nuclear Engineering
Period of completion: spring semester 2022/2023 academic year

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Master Thesis

SCHEDULED ASSESSMENT CALENDAR
for the Master Thesis completion

Deadline for completion of Master's Graduation Thesis:	06.06.2023

Assessment date	**Title of section (module) / type of work (research)**	**Maximum score for the section (module)**
07.02.2023	Creation and approving of technical specification	*5*
18.02.2023	Searching and selection of material for research	*5*
01.03.2023	Development of general methodology of the research	*5*
16.03.2023	Reviewing of manuals and list of literature	*15*
20.04.2023	Performing of mathematical model of reactor	*30*
03.05.2023	Processing of obtained results	*10*
17.05.2023	Analysis and description of the results	*10*
06.06.2023	Composition of master's thesis	*10*

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Abstract

This master's thesis consists of 94 pages, 17 figures, 27 tables, 41 sources and 1 appendix.

Key words: reactor dynamics, mathematical model, PWR type reactor, Python programming language, open source library SciPy, Runge-Kutta method, ordinary differential equations solvers.

The objectives of research are prediction of behavior of reactor under external influence

The purpose of this research is to create a model of reactor dynamics that will describe the change in power, fuel and coolant temperature, with the introduction of reactivity.

During the research process the necessary information about the dynamics of reactor systems was collected and analyzed, with further recording of the system of differential equations and coding of the mathematical model into Python programming code

In the result of the research the results of solving the reactor dynamics equations obtained using the model were compared with the results from other possible sources, and the current capabilities of the created model were demonstrated.

Content

Introduction

Recently, the digitalization of all industries, including the nuclear industry, has grown rapidly. In the nuclear industry there is a tendency to simplify the management of nuclear reactions and consequently the management of the nuclear reactor as much as possible. In accordance with this trend, a lot of work has already been done, which has led to the safe management of the latest generations of reactors. Thus, even the grossest operator mistake would only trigger the safety systems and return to a controllable state.

More recently, the idea has emerged that the control of the reactor can be completely left to the computer, but to implement such an idea, it is necessary to train such a computer to understand how to properly control such a reactor. The first step in this direction is to teach the computer to understand the processes going on inside the reactor. At the moment there are a lot of programs for the calculation of reactors, nevertheless it was not possible to integrate them directly into the reactor safety system, either because of their complexity or because they are outdated. Therefore, the main idea is to create a reactor model that can be easily integrated into the reactor system and that will also be able to accurately calculate and predict the processes that take place inside the reactor.

Conventionally, such a reactor model can be divided into two components. The static model, which calculates the neutron-physical parameters of the reactor at a certain point in time, and the dynamic model, which calculates the change in reactor parameters over time when a perturbation is introduced into the reactor. This paper proposes the following approach: to neglect the neutron-physical parameters of the reactor, and to make a model based on an analytical representation of the reactor dynamics, in which the actual parameters of the reactor system are selected by selection. This approach, firstly, makes it possible to avoid the cumbersome calculations that are carried out for the static model of the reactor, and this model can then be given as reference for machine learning model.

The most obvious approach is to make a model that will at least approximately describe the processes that occur in the most common type of reactor, the PWR. And the set of monitored parameters will be small, in our case it is only power, fuel and coolant temperature.

Purpose of work: to create a model of reactor dynamics that will describe the change in power, fuel and coolant temperature, with the introduction of reactivity. The model will be written using the Python programming language.

The following tasks were set in order to fulfill the purpose of the work:

1. To collect and analyze the relevant information on equations of reactor dynamics and approaches of its solution

2. To compose a system of dynamics equations representing a mathematical model

3. To code mathematical model via Python programming language and open source library SciPy

4. To compare results obtained via mathematical model with results from open sources of information.

List of notations and abbreviations

PWR – pressurized water reactor

VVER - vodo-vodyanoj energeticheskij reactor (water power reactor)

NPP – nuclear power plant

ODE – ordinary differential equation

RC – reactivity coefficient

PRC – power reactivity coefficient

RK4 - Runge-Kutta 4th order

SWOT – strengths weaknesses opportunities threats

Ph. D – philosophy doctor

D. Sc – doctor of science

ESNT - engineering school of nuclear technologies

NFCD - nuclear fuel cycle department

IRT-T - issledovatel'skij reaktor teplovoj – Tomskij (thermal research reactor-Tomsk)

PC – personal computer

EMF – electromagnetic field

HPL – highest permissible level

1 Literature review

1.1 Reactor neutron physics processes review

1.1.1 Reactor kinetics

Reactor kinetics is the study of the time-dependent behavior of nuclear reactors, particularly the changes in the neutron population and power output in response to changes in the reactor control systems or other external factors. The behavior of a nuclear reactor is described by a set of coupled, nonlinear differential equations, which are typically solved numerically using simulation software. [1]

The dynamics of a nuclear reactor are governed by the interaction between the neutron population and the reactor materials, including the fuel, coolant, and control rods. The neutron population is affected by a number of factors, including the rate of neutron production from fission reactions, the rate of neutron absorption by fuel and other materials, and the rate of neutron leakage from the reactor. The power output of the reactor is directly proportional to the neutron population and is therefore affected by these same factors.

Reactor kinetics is important for understanding and predicting the behavior of nuclear reactors under a variety of operating conditions, including startup, shutdown, and transient events such as power excursions or reactor scrams. Accurately modeling reactor kinetics is essential for ensuring the safety and reliability of nuclear power plants, as well as for optimizing their performance and efficiency [2].

In this paper, the reactor kinetics is represented by a system of nonlinear differential equations for six groups of delayed neutrons, with the equations themselves obtained analytically

The differential equation for power is as follows [3]:

$$\frac{dN}{dt} = \frac{\rho - \beta}{l} N + \sum_{i=1}^{6} \lambda_i C_i \ , \tag{1.1}$$

where ρ - excessive reactivity or amount of reactivity lower than critical state;

l – average neutron generation lifetime;

λ_i – decay constant of i-group of delayed neutron emitter;

C_i – concentration of i-group of delayed neutron emitters;

β – average fraction of delayed neutrons.

Since the differential equation contains the sum of six groups of neutrons, and their concentrations vary over time, the differential equation for each group of delayed neutrons must be written accordingly:

$$\frac{dC_i}{dt} = \frac{\beta_i}{l} N - \lambda_i C_i \,. \qquad (1.2)$$

Combining (1.1) and (1.2) we obtain a system of nonlinear differential equations of reactor kinetics:

$$\left.\begin{aligned} &\frac{dN}{dt} = \frac{\rho-\beta}{l} N + \sum_{i=1}^{6} \lambda_i C_i \\ &\frac{dC_1}{dt} = \frac{\beta_1}{l} N - \lambda_1 C_1 \\ &------------- \\ &\frac{dC_6}{dt} = \frac{\beta_6}{l} N - \lambda_6 C_6 \end{aligned}\right\} \qquad (1.3)$$

The system of equations (1.3) is the basis for studying the reactor behavior in nonstationary modes. In deriving the equations, we did not consider the presence of a neutron source, due to its low power density compared to the entire reactor.

If we consider the stationary mode of operation of the reactor:

$$\frac{dN}{dt} = 0, \quad \frac{dC_i}{dt} = 0\,,$$

then it is possible to obtain the concentrations of delayed-neutron emitter nuclei at a given reactor power:

$$\begin{aligned} &\lambda_1 C_1 = \frac{\beta_1}{l} N_0 \\ &------- \\ &\lambda_6 C_6 = \frac{\beta_6}{l} N_0 \end{aligned}\,,$$

thus, we can determine the boundary conditions for solving the Cauchy problem, if the initial reactor power is known.

The stationary mode of reactor operation, according to the system of equations (1.3) can be achieved at any initial neutron density, but necessarily at zero reactivity, to switch the reactor from one power to another, it is necessary to provide the reactivity change, and when the necessary power is reached, again provide zero reactivity [3].

As mentioned earlier, the resulting system of equations is used as the basis for studying the behavior of the reactor, however, the real picture looks different; the reactor is a complex system in which there are many variables that affect its resulting power in one way or another. A simple example is the inverse reactivity effects that result from changes in fuel density and temperature, or coolant density and temperature. Taking these effects into account when forming a mathematical model gives a more accurate idea of how the reactor as a whole works. Such a model that takes these effects into account is called a reactor dynamics model. The basic concepts of reactor dynamics will be presented below

1.1.2 Reactor dynamics

Previously, kinetic equations were derived that allowed to describe the temporal behavior of reactor power with changes in its reactivity. Solutions to these equations were obtained under the assumption that reactivity is independent of reactor power. In practice, this is true for low power levels (less than 0.1-1% of nominal power) when fission heat releases from fuel nuclei have no effect on core temperature and pressure. It is known that the reactivity of a reactor depends, in principle, on almost all technological and neutron-physical parameters of the core. Moreover, the perturbation of any one parameter causes many interconnected transients, as a result of which of almost all other reactor parameters of the reactor. In practice, as a rule, this is observed at so-called power levels (more than 1-6% of nominal power), when the energy release in the reactor is enough to change temperature, pressure, density, and other parameters of the core materials [4].

Let's explain this with an example. If in a fast reactor operating at some power level, change the coolant flow rate by increasing or decreasing the number of the pumps, then with the reduction of the pump rotation speed the coolant flow rate through the reactor core will decrease. Decrease the reduced coolant flow rate will immediately affect reactivity, because the upper ends of the fuel assemblies will then shift slightly toward the center of the core (this is a small reactivity effect). Reducing the coolant flow rate for the same reactor power will cause the coolant to heat up and hence lead to an increase in the temperature of the fuel. Because of the negative temperature reactivity effect on the coolant temperature, the reactor power of the reactor will begin to decrease. The drop-in power will decrease the temperature of the fuel and give a positive reactivity effect due to the negative reactivity coefficient on the fuel temperature. Eventually, with negative reactivity coefficients, after reducing pump rotation speeds, the reactor will stabilize at a different, lower power level [5].

It is pertinent to note that in the case of positive reactivity coefficients for fuel and coolant temperature, the reactor will, after reducing the coolant flow rate, increase its power without external influence to increase its capacity. In other words, negative feedbacks make the reactor stable, and with positive feedbacks will make the reactor unstable: when the reactor will increase its power when positive reactivity is introduced, and when negative reactivity is introduced, the reactor will stop without external influences. In case of negative reactivity on temperature of fuel and coolant, when positive or negative reactivity is introduced into a reactor positive or negative reactivity, its power after a certain transition period will stabilize at a new level (without additional external impact on the reactor) [6].

Other examples can be given, from which it will be clear that changes in almost any technological parameters of a reactor lead to larger or smaller reactivity effects. But it makes sense to consider all of these effects using examples of specific reactors.

If we imagine the reactor as a certain object to be controlled then reactivity can be considered as a control action (input) and power as a controlled parameter (output). The influence of the output on the input is called feedback. The equations of kinetics, supplemented by feedback equations that consider various reactivity coefficients, are called either the equations of kinetics with feedback, or (more often) reactor dynamics equations. The equations of dynamics should enable a description of reactor behavior in all normal and i.e., the solutions to the equations of dynamics allow one to get information about the reactor's response to changes of any parameters (not only reactivity, power and temperature in the core, but also load on the turbine generator, thermal-hydraulic parameters of steam generators, heat exchangers, etc.) [4].

It is when considering the equations of dynamics that the idea of calculating and measuring reactivity coefficients becomes clear. It is the parametric representation of the basic dependences of the reactivity makes it possible to use fairly simple kinetic equations and reactivity coefficients to model (and thereby predict) reactor behavior with all its many connections and characteristics.

In principle, it is possible to carry out a detailed calculation of the reactor core at different temperatures and power levels, which requires changing the neutron-nucleus interaction cross sections in the neutron transport equation. However, calculation of reactor power growth with allowance for changes over time of interaction cross sections of neutrons with nuclei, reactor size and the calculation of reactor power growth in view of the time variation of the neutron-nucleus interaction cross sections and the reactor size and material density requires considerable computational resources and is very difficult, especially in real time.

The use of the equations of kinetics and reactivity coefficients allows us to solve the problem of modeling time behavior of a reactor when various perturbations occur in it [7].

Let's set a simple feedback problem: find the time behavior of reactor power if reactivity is introduced according to a certain algorithm and it is known that power growth decreases reactivity (negative power feedback). Besides, the PCR in the general case dependent on power.

If we write the relation between reactivity and reactor power in the form ρ(w), the equations of dynamics (kinetics with power feedback without an external source of neutrons will look like [4]:

$$\frac{dw}{dt}=\frac{\rho(w)-\beta}{l}w+\sum_{i=1}^{6}\lambda_i C_i,$$
$$\frac{dC_i}{dt}=\frac{\beta_i}{l}w-\lambda_i C_i, \tag{1.4}$$
$$\rho(w)=\rho(w_0)+\alpha_w(w_0-w),$$

where α_w – independent power independent reactivity coefficient.

Then the desired function w(t) in the right-hand side of the equation will be in quadratic and linear forms. Even in this simplest case there is no obvious analytical solution and finding w(t) is a matter of a computer

It is clear from the previous arguments that the proposed problem is very far from reality because it is impossible to describe in detail the reactor behavior considering all its technological parameters with the help of the power coefficient of reactivity alone, even depending on power.

However, the solution can be constructed on a qualitative level. First of all, it is clear that when instantaneous reactivity is introduced, for example, positive reactivity will increase the power (jump on instantaneous neutrons). As the power increases, the reactivity will decrease (negative feedback is given) and this process will continue until the introduced reactivity will be compensated by the negative reactivity due to an increase in reactor power.

If the PRC is independent of power, then after the introduction of positive reactivity ρ_0 there will be an increase in power by ρ_0/α_w. The rate at which the new power level is established will depend on the lifetime of the delayed neutrons, which will determine the duration of the transition process. But if the power is small, the power increment when positive reactivity is introduced reactivity will be small. Consequently, the appearance at the expense of negative reactivity will be small.

Thus, the process of bringing the reactor to a new power level will be long (longer than the time it takes to for the transient process on delayed neutrons).

If negative reactivity is introduced into the reactor - after the reactor will stabilize again, but at a lower power level. Typically, negative reactivity feedback power feedback improves reactor stability.

It is not difficult to conclude from similar reasoning that in the case of positive power feedback or the reactor left to itself will accelerate, if as a result of changes in process parameters there will be positive reactivity, or the power will decrease, if negative reactivity appears as a result of the changes. The presence of positive power feedback causes instability of the reactor. It will be very difficult to reliably control such an unstable system [8].

It would seem that a power feedback equation written through the PRC can provide a comprehensive description of reactor behavior in any situation. In this case, it is only necessary to specify the dependence of the PRC on power. And in this case, the question really arises: what are the other reactivity coefficients, which have been discussed in such detail. However, in the real case, the power factor of reactivity cannot be written in such a simple form - as a function of one variable (power).

The fact is that with changes in power, other technological parameters and their variations depend on the scenario under which in which the power change occurs. And the PRC value is a function of other technological parameters (e.g. input and output coolant temperatures, coolant flow rate, absorber concentration in the coolant, or the location of compensator rods in the reactor core, finally, the burnup depth of the fuel). In addition, when the power is changed, the heating of the coolant (at an unchanged flow rate), the reactor core inlet coolant temperature (unless special measures are taken to the reactor core temperature (unless special measures are taken to stabilize it by, for example, changing the feedwater flow rate and its temperature).

Therefore, if one tries to write down the equations of dynamics with all the kinetics equations should be supplemented with equations linking, for example, the input temperature to the reactor power of the coolant with the reactor power, and add the relation of reactivity with the coolant inlet temperature. Then the reactivity will directly depend not on the power, but on the input temperature. By the way, the coolant temperature at the inlet to the core can change even if the reactor power is constant. Then there will also be a change in reactivity, which will entail change in the reactivity, which will lead to a change in power, etc. In order to explain the necessity of introducing many reactivity coefficients, let's look at several examples.

Let us use the reactivity coefficients (RC) for PWR reactors given earlier. Recall that the reactivity coefficient will be understood as the change in reactivity related to the change of some parameter under the condition of constancy of all other parameters are constant. In this case, the change in reactivity in time ρ(t) will be represented as the sum of the reactivity increments due to changes in several parameters [4]:

$$\rho(t) = \rho_0 - |\alpha_в| \Delta T_в - |\alpha_m| \Delta T_m , \quad (1.5)$$

where ρ_0 – reactivity of reactor at the moment t_0;

$|\alpha_в|$ and $|\alpha_m|$ – reactivity coefficients of coolant and fuel temperature respectively;

$\Delta T_в$ and ΔT_m – the time increment of water and fuel temperature, respectively.

The obtained dependence of reactivity on time should be substituted in equations (1.4) written above and find the dependences, linking power and temperature of fuel, power and temperature of water.

Taking this into account, to equations (1.4) it will be necessary to add equations linking reactivity with temperatures of fuel and coolant temperatures:

$$\rho(t) = \rho_0 - |\alpha_в| (T_{в0} - T_в) - |\alpha_m| (T_{m0} - T_m) , \quad (1.6)$$

where 0 stands for temperatures and power at time t = 0.

Equation linking power and fuel temperature:

$$m_f C_f \frac{dT_f}{dt} = w - K_f (T_f - T_c) . \quad (1.7)$$

Equation linking the temperature of the coolant and fuel:

$$m_c C_c \frac{dT_c}{dt} = K_f (T_f - T_c) - C_c G_c (T_{c2} - T_{c1}), \qquad (1.8)$$

where $m_f C_f$ - mass and specific heat of the fuel; $m_c C_c$ and G_c - mass in the core, flow rate and specific heat capacity of the coolant; K_f - proportionality factor (heat transfer coefficient from the fuel through the fuel element wall to the coolant, multiplied by the heat exchange area); T_{c2} and T_{c1} - temperatures of the coolant at the inlet and outlet of the core.

Finally, the equation that relates the core coolant temperature to the core inlet and core outlet temperatures zone, for example, in a simplified form:

$$T_c = \frac{T_{c2} + T_{c1}}{2}. \qquad (1.9)$$

The system of equations including relations (1.6), (1.7), (1.8), (1.9) and (1.4) are solved together and give a description of the time behavior of the reactor power, coolant temperature, and fuel temperature.

It should be noted that the above ratios are very approximate, since they do not consider, for example, the temperature gradient in water and fuel and dependence coefficient of heat transfer from the velocity (flow rate) of the coolant is not considered. Other parameters (boric acid content in water, position of regulating organs, etc.) are not considered, which influence the neutron balance. Not considered the constantly appearing negative reactivity due to fuel burn-up, the reactivity effects appearing due to xenon accumulation, etc. are not recorded. In addition, and this is particularly important for PWRs, the temperature RCs, as noted above, depend in a complex way on both the temperature and power level, and the concentration of boric acid. Therefore, it will be necessary to add the above system of equations the relationships listed above [4].

In the above examples, the written equations of dynamics in various approximations do not allow us to obtain analytical solution. However, it is possible to find analytical solutions for several problems of practical importance. This, it turns out, can be done for two extreme cases: very fast processes, when the influence of delayed neutrons can be neglected, and when the processes are so slow that a simple instantaneous jump model can be used.

In this paper, solutions to the equations of dynamics are considered for the instantaneous jump model (introduces reactivity instantaneously), since the time intervals at which reactor parameter changes in time will be considered range from 20 seconds to several minutes, which is a large value compared to the lifetime of the neutron.

1.2 Heat transfer process description of unit cell

1.2.1 General description of heat transfer process

When describing the heat transfer process, the proportional coefficient K_f appears (equation 1.7 and 1.8) when writing the differential equation. It is essentially a value of W/K, and shows how much heat is transferred to the heat transfer medium per unit time at a temperature difference of 1 K. The coefficient K_f is a function of temperature, and the form of this dependence can be obtained by solving the differential thermal conductivity equation. To solve this problem, the fuel element can be decomposed into its constituent parts - the fuel part and the helium layer and the fuel element cladding (described in section 2). The fuel part can be represented as a cylindrical rod with internal heat sources, the remaining elements can be considered as cylindrical walls. Further, the solutions of such equations and the final form of writing the coefficient K_f will be considered, respectively.

1.2.2 Thermal conductivity of homogeneous fuel rod

Consider a circular cylinder (Fig. 1.2) whose radius is small compared to its length. Under these conditions, the temperature will change only along the radius. The considered problem corresponds to the case of a cylindrical fuel element without a shell (a long fuel rod or a column of cylindrical fuel pellets) [9].

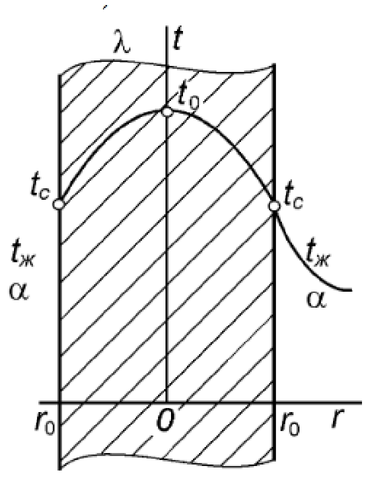

Fig. 1.2 - Thermal conductivity of a homogeneous cylindrical rod

The internal heat sources are uniformly distributed over the volume of the body. The ambient temperature $t_{жс} = const$ and the heat transfer coefficient constant over the entire surface are set.

Under these conditions, the temperature at all points on the outer surface of the cylinder will be the same.

Equation of thermal conductivity:

$$\frac{d^2t}{dr^2} + \frac{1}{r}\frac{dt}{dr} + \frac{q_v}{\lambda} = 0 . \tag{1.10}$$

Boundary conditions:

$$\left.\begin{aligned} & r = 0;\ \left(\frac{dt}{dr}\right)_{r=0} = 0 \\ & r = r_0;\ -\lambda\left(\frac{dt}{dr}\right)_{r=r_0} = \alpha(t_c - t_{жс}) \end{aligned}\right\} \tag{1.11}$$

By integrating equation (1.10) and finding the constants C1 and C2 we obtain equation of temperature distribution in the rod:

$$t(r) = t_{жс} + \frac{q_v r_0}{2\alpha} + \frac{q_v}{4\lambda}(r_0^2 - r^2),\ 0 \le r \le r_0 . \tag{1.12}$$

Let now have boundary conditions of the first kind, i.e. temperature of cylinder surface t_c. These conditions correspond to a particular case of the previous problem, if we assume that the heat transfer coefficient has an infinite $\alpha = \infty$. In this case, obviously $t_c = t_{ж}$. Then equation (1.12) will take the form:

$$t(r) = t_c + \frac{q_v r_0^2}{4\lambda}\left[1 - \left(\frac{r}{r_0}\right)^2\right],\ 0 \le r \le r_0 . \tag{1.13}$$

Cylinder axis temperature (r = 0):

$$t_0 = t_c + \frac{q_v r_0^2}{4\lambda} . \tag{1.14}$$

Further on, to obtain the proportionality factor, we need to convert the volumetric heat release power q_v into the heat release power per unit surface of the rod q_l. We can relate q_v and q_l as follows:

$$q_v = \frac{q_l}{\pi r^2} . \tag{1.15}$$

Thus, by relating (1.14) and (1.15) it is possible to represent the temperature at the center of the cylinder through the heat release power from the surface:

$$t_0 = t_c + \frac{q_l}{4\pi\lambda} . \tag{1.16}$$

Formula (1.16) will then be used to determine the proportionality factor. Thus, knowing the dependence of the temperature of the wall and the center of the cylinder, we can relate the temperature t_c to the following cylindrical layers. The solution of the heat conduction equation for the cylindrical wall layer will be presented below

1.2.3 Thermal conductivity of cylindrical wall

Consider a steady-state heat conduction process in a cylindrical shell (tube) with inner diameter $d_1 = 2r_1$ and outer diameter $d_2 = 2r_2$ (Fig. 1.3).

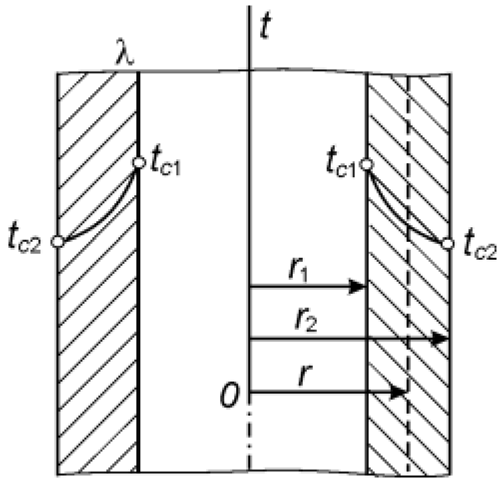

Fig. 1.3 Thermal conductivity of cylindrical wall

The wall surfaces are given constant temperatures t_{c1} and t_{c2}. In a given temperature range the heat transfer coefficient of the wall material λ is a constant value. Find the temperature distribution in the cylindrical wall and the heat flux through it.

Equation of thermal conductivity for cylindrical wall [9]:

$$\frac{d^2t}{dr^2}+\frac{1}{r}\frac{dt}{dr}=0. \tag{1.17}$$

Boundary conditions:

$$\left.\begin{aligned} r=r_1;\ t=t_{c1} \\ r=r_2;\ t=t_{c2} \end{aligned}\right\} \tag{1.18}$$

If we solve equation (1.17) together with (1.18), we obtain the equation of the temperature field in a cylindrical wall:

$$t(r)=t_{c1}-(t_{c1}-t_{c2})\frac{\ln\frac{r}{r_1}}{\ln\frac{r_2}{r1}},\ r_1\le r\le r_2.$$

To find the amount of heat that passes through a cylindrical surface of magnitude F per unit time, Fourier's law can be used:

$$Q=-\lambda\frac{dt}{dr}F.$$

With the fact that F:

$$F = 2\pi r l\,.$$

Finally get:

$$Q = \frac{2\pi\lambda l(t_{c1} - t_{c2})}{\ln\frac{d_2}{d_1}}\,.$$

Heat flow through a unit length of pipe:

$$q_l = \frac{Q}{l} = \frac{2\pi\lambda(t_{c1} - t_{c2})}{\ln\frac{d_2}{d_1}} = \frac{\pi(t_{c1} - t_{c2})}{\frac{1}{2\lambda}\ln\frac{d_2}{d_1}}\,.$$

The expression in the denominator is the linear thermal resistance of the cylindrical wall. It is known that in steady-state condition the linear heat flux density ql varies along the wall thickness and is determined by the formula:

$$q_l = \frac{\pi(t_{c1} - t_{c(n+1)})}{\sum_{i=1}^{n}\frac{1}{2\lambda}\ln\frac{d_2}{d_1}}\,. \qquad (1.19)$$

The fact that the q_l does not vary with wall thickness will be used to describe the linear heat transfer coefficient.

1.2.4 Linear heat transfer coefficient

In order to describe the heat transfer process in a unit cell, it was necessary to somehow relate the temperature of the fuel element to the temperature of the coolant. For this purpose, the heat transfer process through a cylindrical rod and cylindrical wall was described. Now it is necessary to connect these two processes as well as to relate the thermal conductivity of the coolant to them. It is known that linear heat flow in steady state does not vary along the thickness of cylindrical wall, so let's write down the following system consist of equations (1.16) and (1.19):

$$\left.\begin{aligned}
q_l &= 4\pi\lambda_{UO_2}(t_0 - t_{c1}) \\
q_l &= \frac{\pi(t_{c1} - t_{c2})}{\frac{1}{2\lambda_{He}}\ln\frac{d_2}{d_1}} \\
q_l &= \frac{\pi(t_{c2} - t_{c3})}{\frac{1}{2\lambda_{ZrNb}}\ln\frac{d_3}{d_2}} \\
q_l &= \alpha\pi d_4(t_{c3} - t_{ж})
\end{aligned}\right\} \qquad (1.20)$$

Where t_0 temperature in center of fuel cell; t_1, t_2, t_3 temperatures on the edge of each annular zone consequently; $t_{ж}$ temperature of coolant; d_1, d_2, d_3, d_4 diameters of each annular zone consequently; α - heat transfer coefficient of coolant (described in 1.3.5).

If to express the temperatures of the layers one by one and substitute everything in one expression, you get the following [10]:

$$t_0 - t_{ж} = \frac{q_l}{\pi}\left(\frac{1}{4\lambda_{UO_2}} + \frac{1}{2\lambda_{He}}\ln\frac{d_2}{d_1} + \frac{1}{2\lambda_{ZrNb}}\ln\frac{d_3}{d_2} + \frac{1}{\alpha d_4}\right).. \qquad (1.21)$$

Linear heat transfer coefficient:

$$k = \frac{1}{\left(\frac{1}{4\lambda_{UO_2}} + \frac{1}{2\lambda_{He}}\ln\frac{d_2}{d_1} + \frac{1}{2\lambda_{ZrNb}}\ln\frac{d_3}{d_2} + \frac{1}{\alpha d_4}\right)}.$$

Reduce expression (1.21) to the following form:

$$k\pi(t_0 - t_{ж}) = q_l .$$

And then multiply both parts by the length of the fuel column l:

$$Q = k\pi l(t_0 - t_{ж}),\ \ W .$$

The resulting expression in fact represents one of the terms of equation (1.7):

$$k\pi l(t_0 - t_{ж}) = K_f(T_f - T_c) .$$

And hence the required coefficient of proportionality in the system of differential equations:

$$K_f = \frac{\pi l}{\left(\frac{1}{4\lambda_{UO_2}} + \frac{1}{2\lambda_{He}} \ln\frac{d_2}{d_1} + \frac{1}{2\lambda_{ZrNb}} \ln\frac{d_3}{d_2} + \frac{1}{\alpha d_4}\right)}. \quad (1.22)$$

As already mentioned, there is a heat transfer coefficient in the fluid in the equation α. Its value will be defined in section (1.2.5).

1.2.5 Heat transfer coefficient of coolant

Previously, a proportionality factor formula that describes the heat transfer process from fuel rod to coolant in the cell of a PWR was defined. One of the terms of the formula contains the coefficient α, which describes the intensity of heat exchange between the cylindrical wall and the coolant. Then write down step by step how the α coefficient was determined for the task at hand.

First of all, let's write down what the α coefficient is [11]:

$$\alpha = \frac{Nu\lambda}{d},$$

where Nu – Nusselt number,

λ – heat conduction coefficient of coolant on average temperature,

d – equivalent diameter.

First, let's define how the equivalent diameter is written. By definition the hydraulic diameter [12]:

$$D_h = \frac{4A}{P},$$

where A – cross-sectional area of the fluid flow, P – wet perimeter (is the length of the part of the channel boundary touching the fluid).

In the given task the channel is circular, i.e. the central part is occupied by the fuel cell and a coolant flows around its perimeter.

Hydraulic diameter for the annular channel:

$$D_h = \frac{4 \cdot 0,25\pi\left(D^2 - d^2\right)}{\pi(D+d)} = D - d.$$

where D and d – inner and outer diameters respectively.

Now let 's move on to the definition of the Nusselt number. The Nusselt number is one of the main criteria for the similarity of thermal processes, characterizing the relationship between the intensity of heat exchange due to convection and the intensity of heat exchange due to thermal conductivity. The form of writing the Nusselt number depends on the flow mode of the coolant and the coolant material. For PWR type reactors, the turbulent flow mode of the coolant is characteristic, therefore, the Nusselt number will be recorded for the case of coolant flow in pipes and channels for the turbulent flow mode. The criterion equation is following [11]:

$$Nu = 0,021\mathrm{Re}^{0,8}\,\mathrm{Pr}_c^{0,43}\left(\frac{\mathrm{Pr}_c}{\mathrm{Pr}_w}\right)^{0,25},$$

where Re – Reynolds number; Pr_c, Pr_w – Prandtl number of coolants at the wall temperature and the average temperature if coolant respectively.

The Reynolds number is defined as follows [13]:

$$\mathrm{Re} = \frac{\omega d \rho}{\mu},$$

where ω – coolant velocity in channels,

d – hydraulic diameter;

μ – dynamics viscosity;

In fact, before determining the criterion equation for the Nusselt number, it was necessary to obtain the value of the Reynolds number, however, guided by the fact that PWR type reactors operate in turbulent conditions, the equation was determined in advance.

The dynamic viscosity in the definition of the Reynolds number is a function of:

$$\mu = f(p,T).$$

The numerical value of the dynamic viscosity is determined in the program code (described in Section 2) using a special library that contains tabular values of water and water vapor parameters. According to the same principle, the values for the density of water, its heat capacity and thermal conductivity, as well as the Prandtl number are determined.

It was mentioned above that the Prandtl number can be determined by using libraries with tables of water and water vapor, nevertheless it is worth writing it down by definition [14]:

$$\Pr = \frac{\nu}{\alpha_t},$$

where ν – kinematic viscosity;

α_t – coefficient of thermal conductivity.

In fact, the Prandtl number considers the influence of the physical properties of the coolant on heat transfer. Here, kinematic viscosity, by analogy with dynamic viscosity, is also a function of:

$$\nu = f(p,T).$$

Coefficient of thermal conductivity:

$$\alpha_t = \frac{\lambda}{C_p \rho}.$$

The Prandtl number was written above, as well as the coefficients included in its composition, although in the written program the Prandtl numbers are written as a function determined from two parameters:

$$\Pr = f(p,T).$$

Thus, in Sections 1.1-1.2, the equations of reactor dynamics and kinetics, the description of the heat transfer process in the PWR reactor, and the relationship between them were presented. The next section will present the object of the study, which is the simulation of reactor dynamics, as well as the method that was used to solve the problem.

2 Object and method of research

2.1 Object of research

Predicting the behavior of physical systems using computer power has recently become quite relevant. It is especially relevant for predicting emergency situations and their variants of events. In order to avoid consequences for different physical systems, so-called mathematical models of predictive control are used, which allow predicting the state of a system when an external influence is introduced. A similar mathematical system can also be arranged for the reactor plant. For this purpose, it is necessary to write down a system of equations of dynamics and solve it accordingly for each point of interest in time.

Thus, the object of the study is modeling equations of dynamics using computer capabilities. Tools used in modeling of equations of dynamics, as well as methods and approaches to solve the system of differential equations will be discussed in the next section.

2.2 Problem statement

2.2.1 General description of problem

Because the reactor is too complex a system, it requires a lot of computing power to describe it accurately. Nevertheless, there is a generally accepted approach that avoids cumbersome calculations, for examplse, for a three-dimensional reactor model, which literally takes all factors into account. This approach is the use of some elementary geometric reactor cell, which, in fact, by adding many such cells together, represents one large reactor. Therefore, if, say, we describe the physical processes taking place inside one cell, then they can accordingly be approximated to the rest of the reactor, but this is not exactly true.

First, in this approach we neglect the non-uniformity of energy release within the core, and, accordingly, if we need to obtain parameters for any particular fuel assembly, the calculated data obtained by such an approximation will itself differ from the real picture. However, this approach helps to obtain a generalized picture of the changes in the core parameters when reactivity is introduced, while minimizing the computational power consumption. Such an approach will be very useful for modeling accidents in real time.

Thus, to solve the equations of dynamics, we represent the reactor as a set of elementary cells with the same parameters, and assume that the resulting reactor power is a value linearly proportional to the number of such cells. As discussed earlier, this approach allows us to obtain only a general idea of the change in reactor parameters (rather, the output value of any of the reactor parameters is the average value for the entire reactor). Nevertheless, this solution also deserves attention, and even at this stage it can be used for training purposes, as well as for developing more accurate solutions in the future using this methodology.

The following will provide a description of the unit cell, its constituent parts, and a brief description of the materials of such a cell.

2.2.2 Unit cell of reactor assumed for solution of problem

The choice of the unit cell and its geometry was due to two criteria, the first and most obvious is that for such a cell it would be easy enough to describe the process of heat transfer from fuel to coolant, and second is the prevalence of such a cell in known reactors. The choice fell on the elementary cell of the PWR reactor. The consistency of the model for PWR can already serve as an argument for its use in more complex geometric cells.

The elementary cell of the PWR reactor is essentially a fuel element surrounded by a coolant - water. Fuel rod, in turn, is uranium fuel, which is a heat source surrounded by a shell. Geometrically, all this can be represented as a set of annular zones, the boundaries of which are a section of the medium (that is, the boundaries between the materials of the elementary cell) [15].

The representation of the element cell in the form of annular zones (although in fact the PWR cell is a hexagon, which will cause discrepancies in the future, respectively) makes it possible to more easily describe the heat transfer process and, accordingly, save on computing power.

Unit cell of reactor assumed for calculations presented below (Figure 2.1):

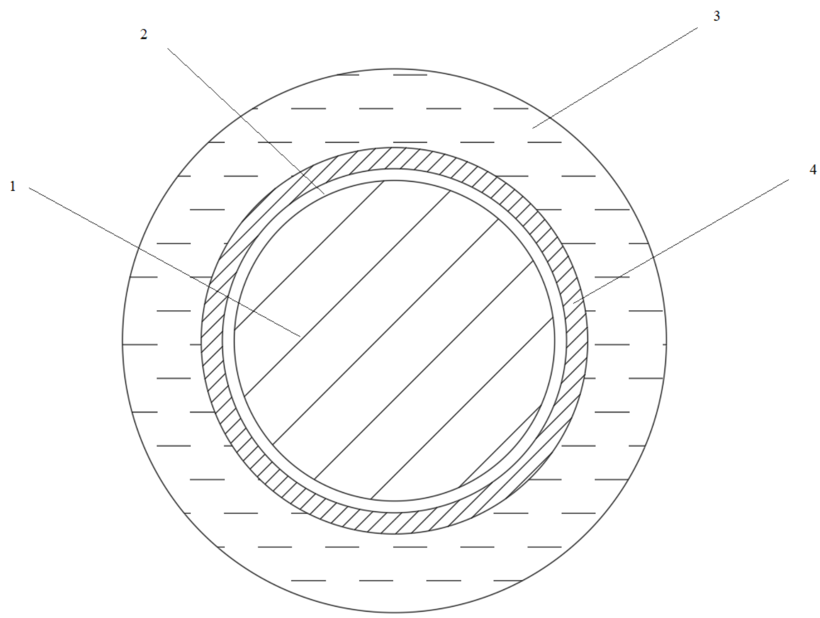

Fig. 2.1 – Unit cell of reactor PWR assumed for calculations 1 – uranium fuel, 2 – helium gap, 3 – coolant, 4 – fuel shell

It is also necessary to note the materials that make up the unit cell, as well as their features that affect the results of calculations.

Uranium dioxide is used as fuel, parameters such as the fraction of delayed neutrons and their decay constants depend on the fuel. Parameters mentioned above for U^{235} presented in a Table 2.1.

Table 2.1 – Parameters of delayed neutrons group [16]

Group number	Fraction of neutrons	Delay time, s
1	0.00021	54-56
2	0.00140	21-23
3	0.00126	5-6
4	0.00252	1.9-2.3
5	0.00074	0.5-0.6
6	0.00027	0.17-0.27

Uranium dioxide is the most common type of fuel, which actually became the reason for choosing this type. It is also worth noting that the calculation will consider such parameters as heat capacity and thermal conductivity, which are actually functions of temperature [17]:

$$\lambda_{UO_2} = f(T), \;\; C_{UO_2} = f(T).$$

The heat capacity and thermal conductivity of the functions are non-linear, which makes it difficult to write them into the code of the mathematical model. More details on how the recording of these functions is implemented will be written in the following chapters.

It is assumed that there is a gap filled with helium between the fuel and the fuel cladding. The gap itself is made to allow the fuel column to expand in a horizontal direction, while helium, in turn, serves as an inert heat-conducting medium. The thermal conductivity of helium varies within the operating temperature limits, but its change in the calculations did not give significant deviations, therefore, it was customary to consider the thermal conductivity of helium as a constant.

$$\lambda_{He} = 0.5 \frac{W}{m \cdot K} = const\,.$$

It is also worth mentioning that in this work all calculations were carried out at a constant pressure in the primary circuit equal to 16 MPa, which corresponds to the usual nominal value of the pressure in the circuit at nominal mode. This choice is due to the fact that at the initial stage it was necessary to ensure the stable operation of the mathematical model within the operating limits of the reactor. In the future, with the successful implementation of the current model, it can already be used for modeling outside operating limits, as well as emergency situations.

As mentioned above, the operation of the model at the time of writing is at constant pressure in the main circuit. From this, respectively, are determined and the limits in which to calculate the properties of the coolant, which in this work is water.

Similar to fuel, when calculating the heat transfer, it is necessary to consider the change in heat capacity and thermal conductivity of water. In general, water and water vapor parameters can be defined as a function of two parameters of pressure and temperature [18]:

$$\lambda_c = f(p, T), \;\; C_c = f(p, T).$$

In fact, describing the process of heat exchange between water and the walls of the fuel element is a more complex task, especially if the coolant is a steam-water mixture. This happens if the temperature regime approaches the phase transition point (in our case, the boiling point of water). However, in order to obtain the initial calculation results, we had to come to some assumptions, and considering that the model performed (at least for now) works only within the reactor power range of 1 to 100 percent, we can say that the phase transition of water to steam will not occur. Because of this, there are corresponding problems in the calculations, as will be shown later.

The last remaining cell element is the fuel cladding. The shell material is a zirconium-niobium alloy. It is logical to assume that the properties of this alloy vary within operating temperatures, but due to the fact that, firstly, there is no ready library of thermal conductivities and heat capacities that can be easily written into the code, and finding a systematic table with dependence of these parameters on temperature proved to be quite a challenge, it was decided to set these parameters as constants, just as with helium:

$$\lambda_{ZrNb1\%} = 15 \frac{W}{m \cdot K} = const$$

The permissibility of this solution can also be caused by the geometrically smaller size of the annulus of the shell compared to, say, fuel, the temperature along the radius of which varies much more.

Thus, it is known that the material properties of the unit cell change within the operating temperatures, which naturally affects the heat transfer process. Several assumptions were also mentioned, which were adopted when setting the task of describing the reactor dynamics

2.3 Research method and tools

2.3.1 Choice of programming language

This kind of model, which was described in the chapters above, is usually built using either MatLab or libraries using the Python language. The choice of Python was due to the fact that its arsenal has many libraries with which you can describe the change in material properties, for example, a change in temperature, which already greatly simplifies the work on the mathematical model and eliminates the recording of additional functions needed to describe some properties. In addition, all known libraries and programming environments of the language are free and exclude the possibility of copyright infringement. Thus, the choice was made for the Python programming language.

2.3.2 Set of libraries for solving the problem

2.3.2.1 NumPy library

NumPy - is the free and most common library used for mathematical problems. Its main task is to structure data into arrays, and perform mathematical operations on such arrays. NumPy is a popular Python library used for numerical computing. It provides a powerful array data structure that can efficiently store and manipulate large multi-dimensional datasets. Here are a few notable features of NumPy.

N-dimensional array object: NumPy provides a powerful N-dimensional array object, which is a table of elements (usually numbers), indexed by a tuple of positive integers. These arrays can be manipulated using a variety of mathematical operations, making it easy to perform complex numerical computations.

Broadcasting: NumPy allows for broadcasting, which is a way of performing arithmetic operations on arrays of different shapes and sizes. This eliminates the need for explicit loops and makes the code more concise and readable.

Mathematical functions: NumPy provides a wide range of mathematical functions, including trigonometric functions, logarithms, and exponentials. These functions can be applied to entire arrays, making it easy to perform complex mathematical operations.

Integration with other libraries: NumPy can be easily integrated with other libraries, such as Matplotlib for data visualization and Pandas for data analysis.

Overall, NumPy is a powerful library that provides a wide range of tools for numerical computing in Python. Its efficient array data structure and mathematical functions make it a popular choice for scientific computing and data analysis [19].

2.3.2.2 Matplotlib library

Matplotlib is a popular Python library used for creating static, animated, and interactive visualizations in scientific computing and engineering. It provides a wide range of tools for creating plots, charts, histograms, heatmaps, and other visualizations, and supports a variety of data formats, including NumPy arrays, Pandas dataframes, and Python lists.

Some notable features of Matplotlib include:

– Support for a wide range of 2D and 3D plots, including line plots, scatter plots, bar plots, pie charts, histograms, and heatmaps.

– Customizable plot settings, including axis labels, titles, colors, markers, line styles, fonts, and sizes.

– Integration with other Python libraries, such as NumPy, Pandas, SciPy, and Seaborn.

– Support for multiple output formats, including PDF, PNG, SVG, and EPS.

– Interactive features, such as zooming, panning, and saving plots in interactive formats like HTML and JavaScript.

– A vast collection of examples and tutorials available in the official documentation.

Matplotlib is widely used in scientific research, data analysis, and engineering applications, and is supported by a large community of users and developers [20].

2.3.2.3 Pyfluids library

Pyfluids - library containing the properties of water and water vapor [21]. This is an example of a function for obtaining the value of thermal conductivity of water presented in the Figure 2.2.

```
def lam_c(t):

    """ Thermal conductivity of water [W/m*C] """

    conductivity = Fluid(FluidsList.Water).with_state(Input.pressure(16e6), Input.temperature(t))
    return conductivity.conductivity
```

Fig 2.2 – Example of writing a function for determining the thermal conductivity of water

Here the heat transfer function is written as follows:

$$lam\_c = Fluid(p,T).conductivity\ ,$$

where lam_c – function returning the value of water conductivity, $Fluid(p,T)$ – function from *pyfluids* library, *conductivity* - Fluid class method returning the value of water conductivity.

Here *Fluid* is a class containing many values of water parameters, but entering the method of *conductivity* class we get exactly the parameter we are asking for. The same principle will be used for obtaining all other parameters for water and water vapor properties.

The last library that has already been used directly to solve the equations of dynamics is *SciPy*.

2.3.2.4 SciPy library

SciPy is a Python library used for scientific computing and technical computing. It builds on top of NumPy and provides a wide range of tools for solving optimization, integration, interpolation, eigenvalue problems, signal processing, linear algebra, and other scientific computing problems. Here are a few notable features of SciPy:

Integration and optimization: SciPy provide functions for numerical integration, such as quad and trapz, and for optimization, such as minimize and root. These functions are useful for finding the minimum or maximum of a function and for solving systems of equations.

Interpolation: SciPy provides functions for interpolating data, such as interp1d and interp2d, which can be used to generate smooth curves or surfaces from discrete data points.

Signal processing: SciPy provides functions for signal processing, such as convolve, fft, and lfilter, which can be used to filter and analyze signals.

Linear algebra: SciPy provides a suite of linear algebra functions, including matrix multiplication, decomposition, eigenvalues, and eigenvectors. These functions are optimized for performance and can handle large matrices efficiently.

Sparse matrices: SciPy provides a module for sparse matrices, which are useful for storing large, mostly empty matrices efficiently.

Integration with other libraries: SciPy can be easily integrated with other libraries, such as Matplotlib for data visualization and Pandas for data analysis.

Overall, SciPy is a powerful library that provides a wide range of tools for scientific computing in Python. Its integration with NumPy and other libraries makes it a popular choice for scientific computing and data analysis [22].

Next, let's look at the SciPy library, its classes and methods, which were directly used to solve the problem.

2.3.3 SciPy for solving the system of ODE’s

Above we talked about the capabilities of SciPy in general, but now we will look directly at its application to solve differential equations. One of the library modules, called *integrate*, contains many different types of solvers. The *solv_ivp* solver will be used. *Solv_ivp* actually represents a class method that returns the values of the solution to a differential equation at a given time interval. The method is written as follows [23]:

$$\begin{cases} s = solv\_ivp(f(x,t), t, x_0) \\ \dfrac{dx}{dt} = f(x,t) \\ x(0) = x_0 \end{cases}$$

where s – solution of differential equation represented as an array which consist of values x at respective points t. Now suppose there is a differential equation of the following kind:

$$\frac{dx}{dt} = 3x^2 - 5$$

and now let's write it into the program code, an example is shown in Figure 2.3.

```
import numpy as np
from scipy.integrate import solve_ivp


def dxdt(t, x):
    return 3*x**2 - 5


x0 = 0
t = np.linspace(0, 1, 100)
s = solve_ivp(dxdt, t_span=(0, max(t)), y0=[x0], t_eval=t)
```

Fig. 2.3 – Example of writing a differential equation into program code

Here we import the previously mentioned module NumPy, which is used to set the time interval t for which we want to obtain the values of x. The solution of the differential equation c is written as mentioned above.

The resulting solution of the example differential equation for the value of x on the time interval t from 0 to 1 is shown in Figure 2.4.

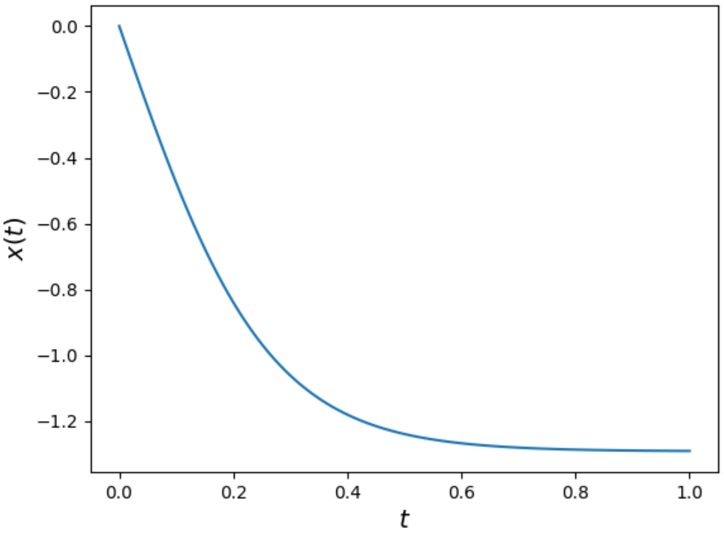

Fig. 2.4 – Graphical representation of the solution to an example of a differential equation

As for the system of differential equations, its notation can be presented as follows. Let us imagine that there is a conditional system of the following kind [23]:

$$y_1' = y_1 + y_2^2 + 3x \quad y_1(0) = 0$$
$$y_2' = 3y_1 + y_2^2 - \cos(x) \quad y_2(0) = 0$$

Imagine that the desired solution is a vector S, that is:

$$\vec{S} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

Then dS:

$$\frac{d\vec{S}}{dx} = \vec{f}(x, \vec{S}) = \vec{f}(x, y_1, y_2)$$

Consequently, dS are a vector containing the value for several functions. In the program code it will be written as follows (Figure 2.5).

```python
def dSdx(x, S):
    y1, y2 = S
    return [y1 + y2**2 + 3*x,
            3*y1 + y2**3 - np.cos(x)]
y1_0 = 0
y2_0 = 0
S_0 = (y1_0, y2_0)
```

Fig. 2.5 – Example of writing a system of differential equations

Accordingly, the graphical representation of this solution is as follows (Figure 2.6):

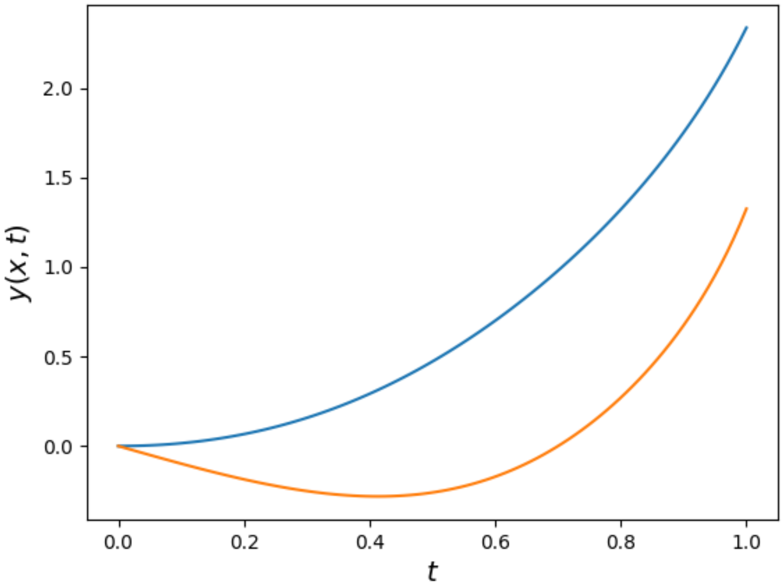

Fig. 2.6 – Graphical representation of the solution to an example of system of differential equations

According to the above principle, the equations of reactor dynamics were also written.

The approach to solving a system of differential equations was described above in this chapter, and examples of such solutions were shown. In addition to this, it should be said that behind such solutions, there is a rather complicated mathematical apparatus, which has not been mentioned up to this point. The solution of the system of equations is made by the Runge-Kutta method. In fact, this is a large class of numerical methods used to solve the Cauchy problem. A brief note on the method for solving ODE is in the next section.

2.3.4 Runge-Kutta method

In numerical analysis, the Runge–Kutta methods. are a family of implicit and explicit iterative methods, which include the Euler method, used in temporal discretization for the approximate solutions of simultaneous nonlinear equations.

The most widely known member of the Runge–Kutta family is generally referred to as "RK4", the "classic Runge–Kutta method" or simply as "the Runge–Kutta method".

Let an initial value problem be specified as follows [24]:

$$\frac{dy}{dt} = f(y,t),\ y(t_0) = y_0$$

Here y is an unknown function (scalar or vector) of time t, which we would like to approximate; we are told that $\frac{dy}{dt}$, the rate at which y changes, is a function of t and of y itself. At the initial time t_0 the corresponding y value is y_0. The function f and the initial conditions t_0, y_0 are given.

Now we pick a step size h >0 and define:

$$y_{n+1} = y_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4)$$
$$t_{n+1} = t_n + h$$

for n = 0, 1, 2, 3, ..., using:

$$k_1 = f(t_n, y_n)$$
$$k_2 = f(t_n + \frac{h}{2}, y_n + h\frac{k_1}{2})$$
$$k_3 = f(t_n + \frac{h}{2}, y_n + h\frac{k_2}{2})$$
$$k_4 = f(t_n + h, y_n + hk_3)$$

Here y_{n+1} is the RK4 approximation of $y(t_{n+1})$, and the next value y_{n+1} is determined by the present value y_n plus the weighted average of four increments, where each increment is the product of the size of the interval, h, and an estimated slope specified by function f on the right-hand side of the differential equation.

The method described above is implemented in the SciPy library. It is worth mentioning that, in general, there are many Runge-Kutta methods of different orders. The so-called classical 4th-order method was described above and is used in the solver. There are also explicit and implicit methods. It is necessary to understand which one is the most suitable for a particular problem. In the case of the reactor dynamics equations, the problem is stiff and the implicit method must be used to solve it [4].

The construction of the model and the results of its calculations will be presented in Section 3.

3 Reactor dynamic model and it results

3.1 Assumptions of model

According to the work plan, it was necessary to build a model that describes the change in power, fuel temperature and coolant temperature with the introduction of external influence. In fact, a system of 9 equations consisting of formulas (1.4), (1.7) and (1.8) is sufficient to describe such a model. It is known that reactor dynamics involves not only changes in the technological parameters of the core, but also, for example, changes in fissile isotope concentrations, reactor poisoning, etc.

As part of the work was meant to create a pilot version of the model, to demonstrate its minimal capabilities. For this purpose, it is necessary to make a number of assumptions:

– the reactor dynamics model does not consider changes in concentrations of any isotopes in the core, thus not considering such phenomena as poisoning and slagging, burnup and reproduction;

– the non-uniformity of energy release over the height and width of the core is not considered;

– the change in the thermal conductivity and heat capacity coefficients over the thickness of the material layer is not considered;

– the pressure in the circuit does not change and is 16 MPa;

– temperature across the thickness of the coolant does not change.

According to the mentioned assumptions, we can say the following: with the help of the built model it is possible to predict the reactor behavior in short time intervals (it was experimentally determined that the maximum calculation time is about 1000 sec), and the fuel and coolant temperatures are the values average for the whole reactor. Thus, it is possible to predict the general state of the reactor, without any minor details.

The next section will look at the backend component of the model.

3.2 Model backend description

An example of how functions are written down and examples of solutions of differential equations were discussed earlier in Section 2.3. Here we will briefly describe the principle by which the written program works, without details and extracts from the code.

The calculation is performed as follows: the input to the program is the initial conditions (the current state of the reactor), according to the initial conditions all necessary functions are calculated, such as heat capacity, thermal conductivity, and so on (in fact, these functions are much more). Then, using the pre-recorded constants, which include geometric parameters of the unit cell, and some neutron-physical properties, and the functions calculated according to the initial conditions, the information enters the differential equation solver of the SciPy library. After that, the list is fed to the matplotlib graphics library, which subsequently displays information on graphs.

A graphical diagram describing the operation of the program is presented in Appendix A.

3.3 Model approval

In order to give any further calculation results, it was necessary to confirm the validity of the model. To do this, the results of calculations of the dynamics equations from other sources were compared, which give the initial conditions that need to be entered into the model, with the results of calculations obtained using the model.

The comparison was carried out in several stages. The problems for the model were introduced with increasing complexity, from the simplest differential equation, as was done in Section 2.3.3, to solving a complete system of dynamic equations considering feedback on reactivity.

for example, solutions of kinetic equations obtained using a model with a book source were compared.

The results of solving the kinetic equations for a zero-power reactor with the introduction of different reactivity values are presented in Figures 3.1 and 3.2, respectively. The original form of the drawing from the source is preserved, the inscriptions are translated.

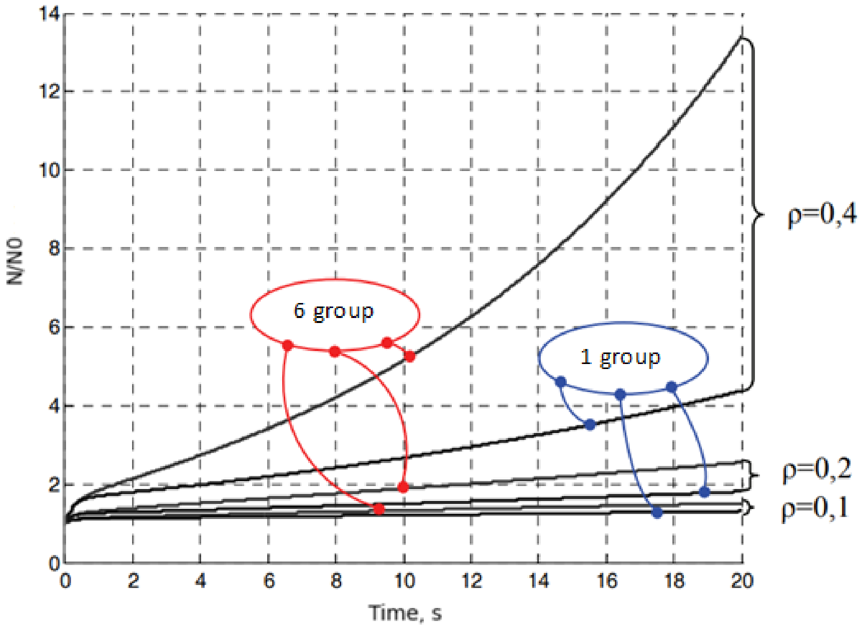

Fig 3.1 – Solutions of kinetic equations with the introduction of different reactivity values from a literary source [4]

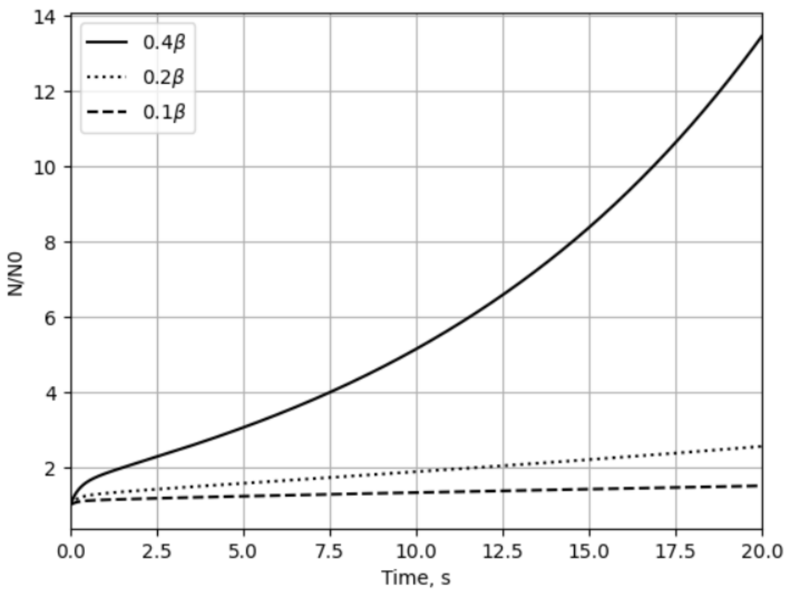

Fig 3.2 – Solutions of kinetic equations with the introduction of different reactivity values from a model

Another step in checking the model consistency was to compare the solutions of the system of 9 equations with given initial conditions and a given power reactivity. Graphical representation of the solution of the equations of dynamics with initial conditions: $w_0 = 0.1w_{nom}$, $\rho = \rho_0 + \alpha_w \Delta w$, $\alpha_w = 1.28 \cdot 10^{-4}$ is presented on Figures 3.3 and 3.4.

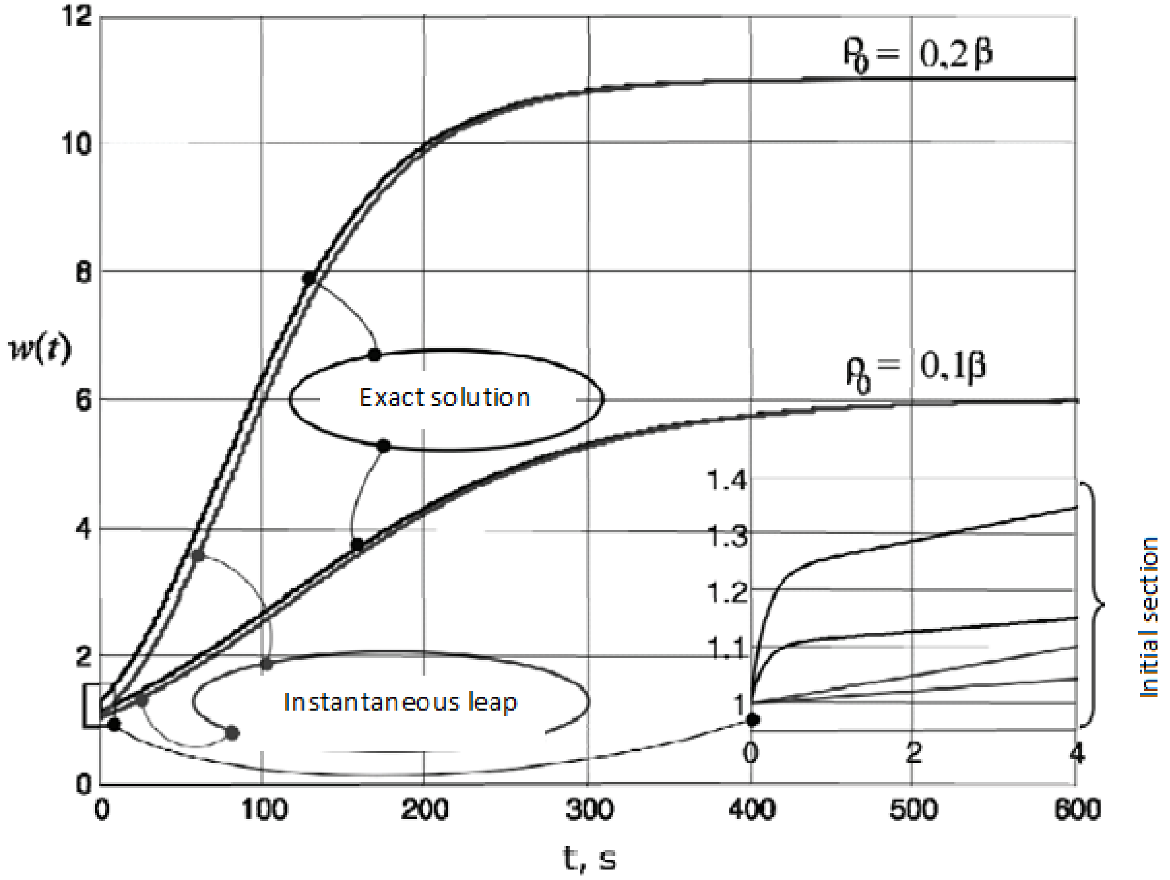

Fig 3.3 – Solution of dynamic equations with the introduction of different reactivities from a literature source [4]

It is worth noting that the solution of the equations in the graph is presented for two cases, the exact solution, and the approximation of the instantaneous jump in reactivity.

As can be seen over a fairly long period of time, the solutions do not differ, the main difference occurs just in the first seconds, at the moment of power surge due to fast neutrons, therefore, specifically in this work, the model calculations were carried out in the instantaneous jump approximation. The result of solving the above problem using the model is shown in Figure 3.4

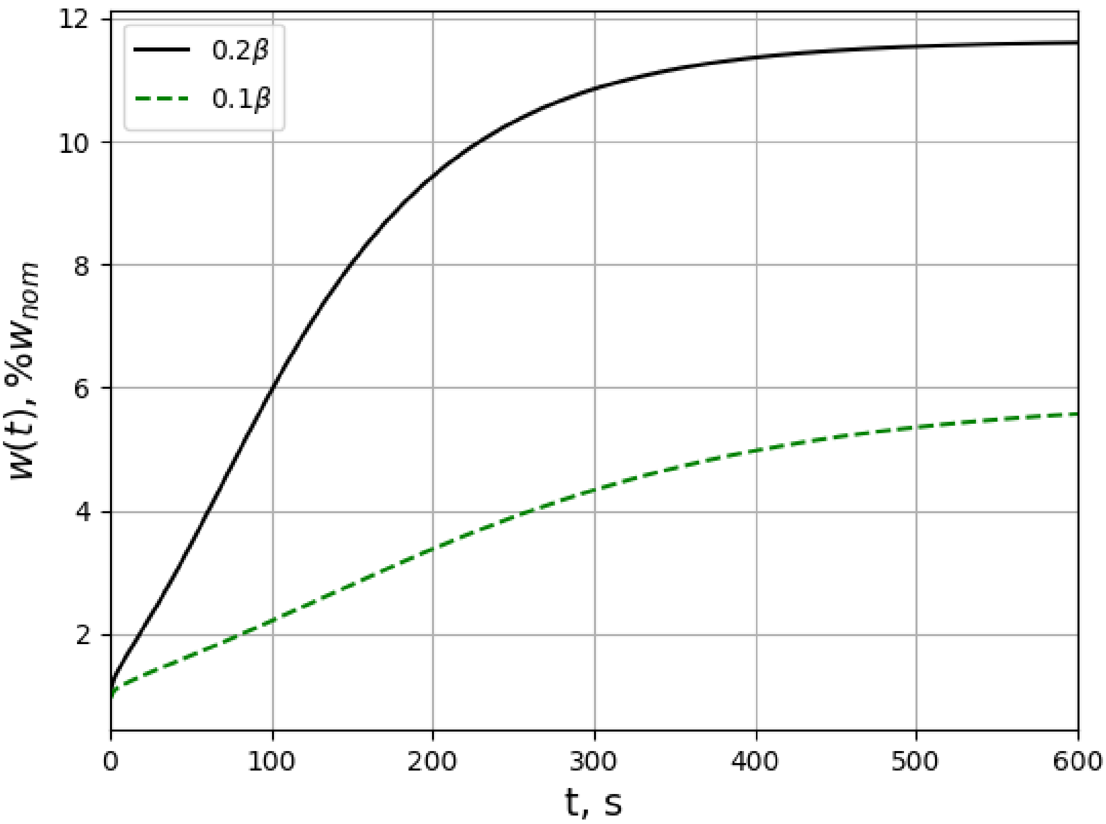

Fig 3.4 – Solution of dynamic equations with the introduction of different reactivities from reactor dynamics model

At this stage of verification, unfortunately, there is already a discrepancy between the solutions about 6%.

However, it should be borne in mind that the input constants in either variant could be slightly different, but because of this, respectively, a difference could arise. Therefore, for example, with the further possible application of this model on a real object, it will be necessary to carefully select and verify all the input information that enters the program code in order to more accurately predict the behavior of the system.

According to the principle described above, the consistency of the model was checked, in the next section the current capabilities of the model will be considered.

3.4 Current model features

In order to show the current capabilities of the model, it was necessary to set some minimum set of constants that would describe the geometry of the reactor and other feature. A Russian-made PWR (VVER type) reactor was taken as a reference. The following data presented in Table 3.1 were used for modeling [25].

Table 3.1 – Input constants

Parameter	Value
Fuel pellet diameter	3.7 mm
Shell inner diameter	8.1 mm
Shell outer diameter	9.1 mm
Quantity of fuel rods	50000
Fuel	UO_2 (3.5%, $\rho = 10960 g/m^3$)
Pressure in circuit	16 MPa

The neutron-physical parameters of such a model were already mentioned earlier in section 2.2.2, which indicated groups of delayed neutrons as well as constants.

It is also worth mentioning about another parameter - this is the rate of pumping of the coolant, which determines the flow rate of the coolant through the circuit. This parameter was varied in the work in order to track its effect on the result.

Further, the results of calculations for various reactor states will be presented directly. So, for example, if you set the following initial conditions in the code:

$$w_0 = 10MW, \ \ T_c = 280°C, \ T_f = 280°C$$

and set 2 cases of the external influence to following values:

$$\rho_1 = 0.2\beta, \ \rho_2 = 0.4\beta$$

then the results will be as follows as shown in Figures 3.5-3.7. The coolant pumping rate has been equal to $v = 2m/s$.

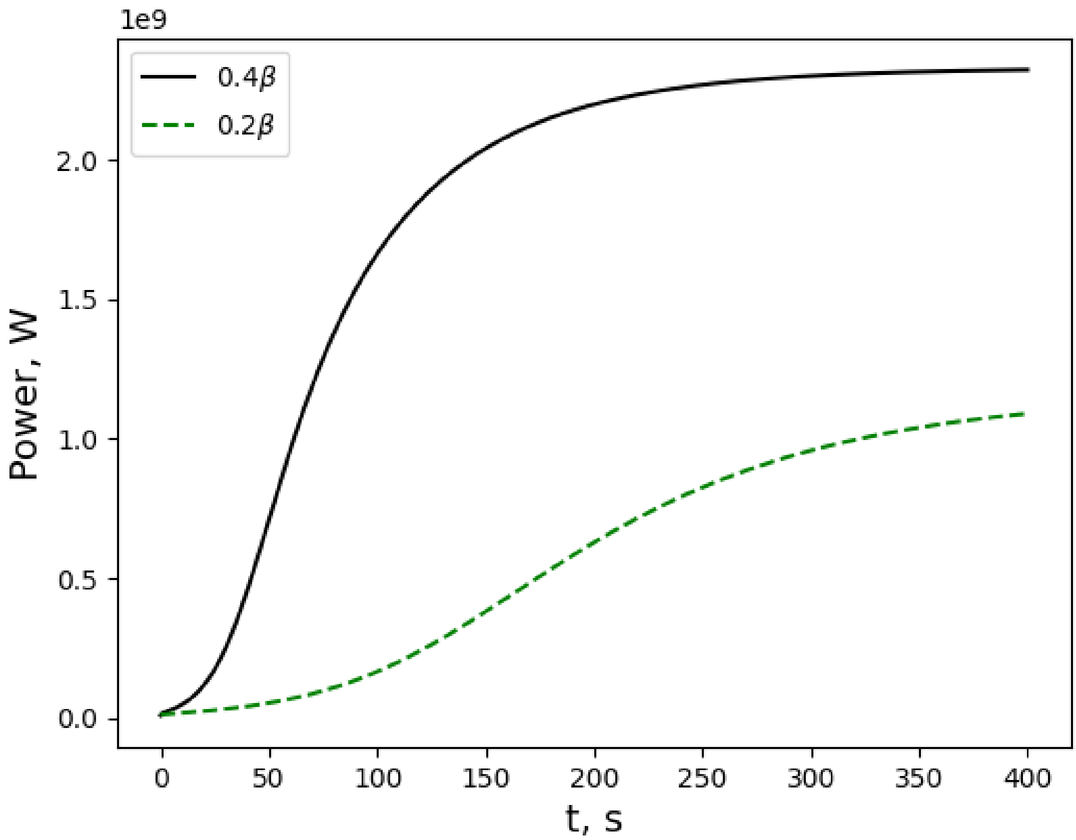

Fig 3.5 – Change in reactor power when exerting external influence

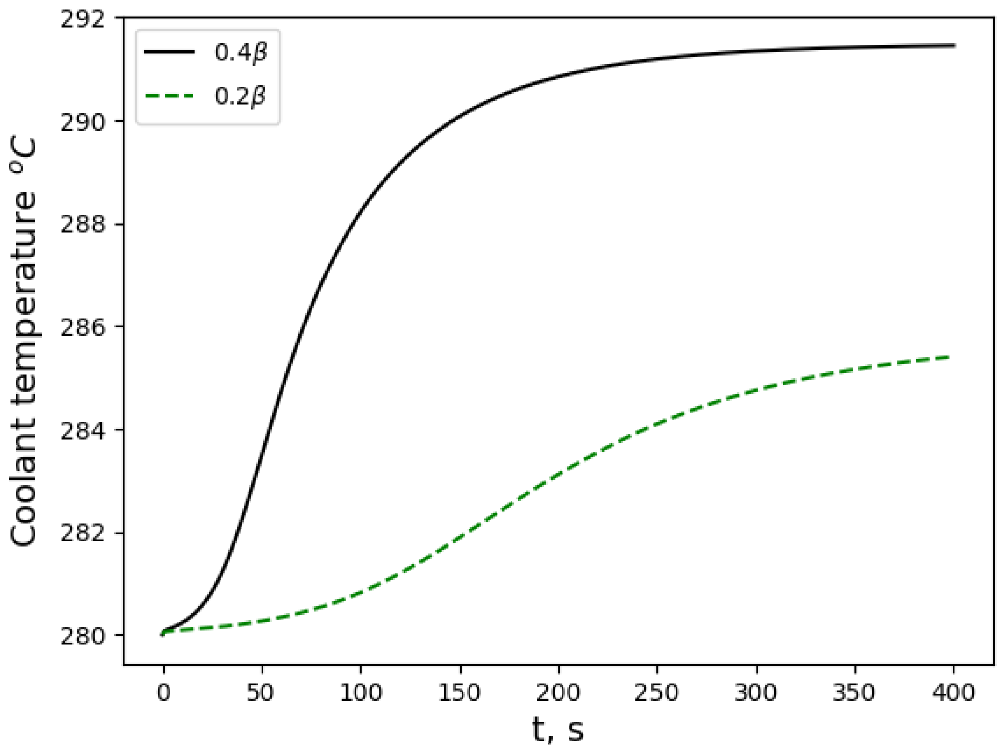

Fig 3.6 – Change in coolant temperature when exerting external influence

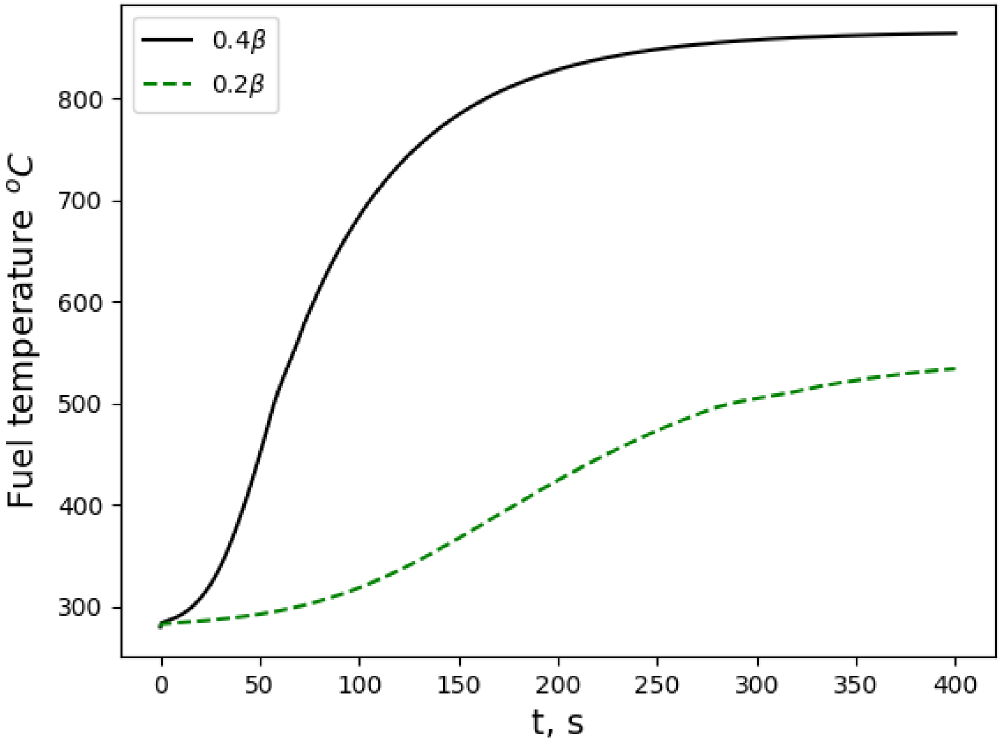

Fig 3.7 – Change in fuel temperature when exerting external influence

It is worth mentioning that the temperature values shown in Figures 3.6 and 3.7 are the average temperature of the fuel and coolant throughout the reactor core. To obtain the temperature distribution in the core by diameter and height, it is necessary to add equations from the physical theory of nuclear reactors describing the unevenness of energy release.

During the analysis of the obtained model of reactor dynamics, the values of the coolant pumping rate varied. So, let's say for the same initial conditions and the rate of coolant pumping $v = 5m/s$ the following results were obtained presented in Figures 3.8 and 3.9.

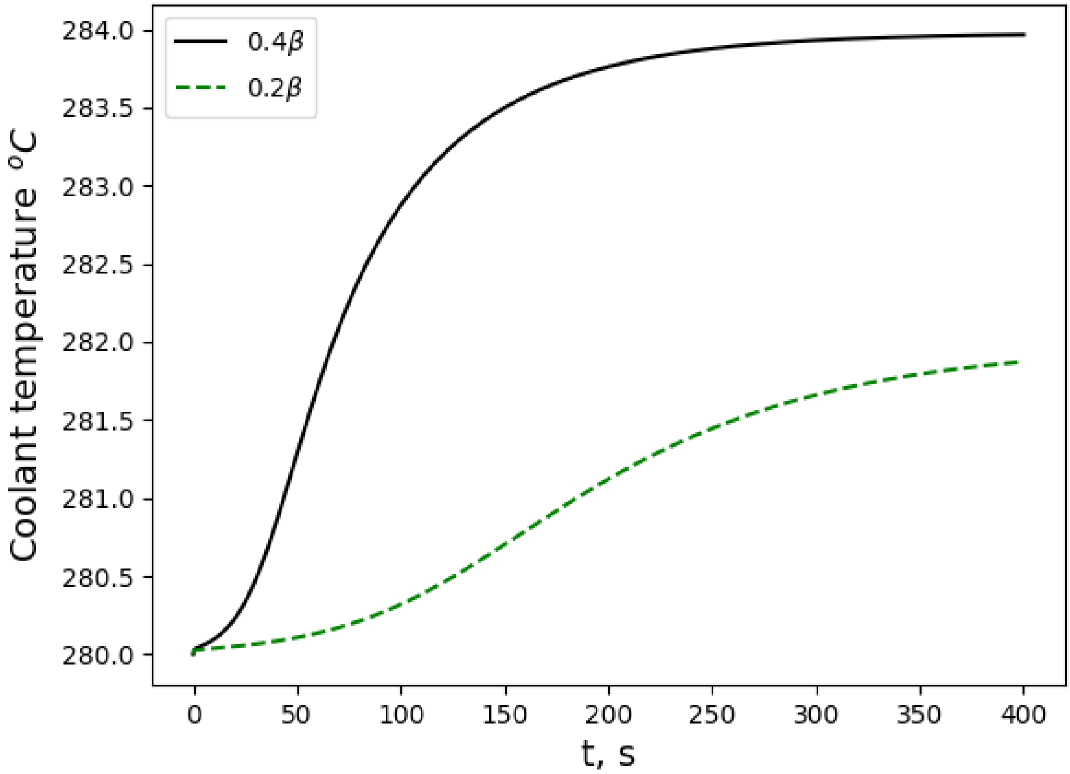

Fig 3.8 – Change in coolant temperature when exerting external influence

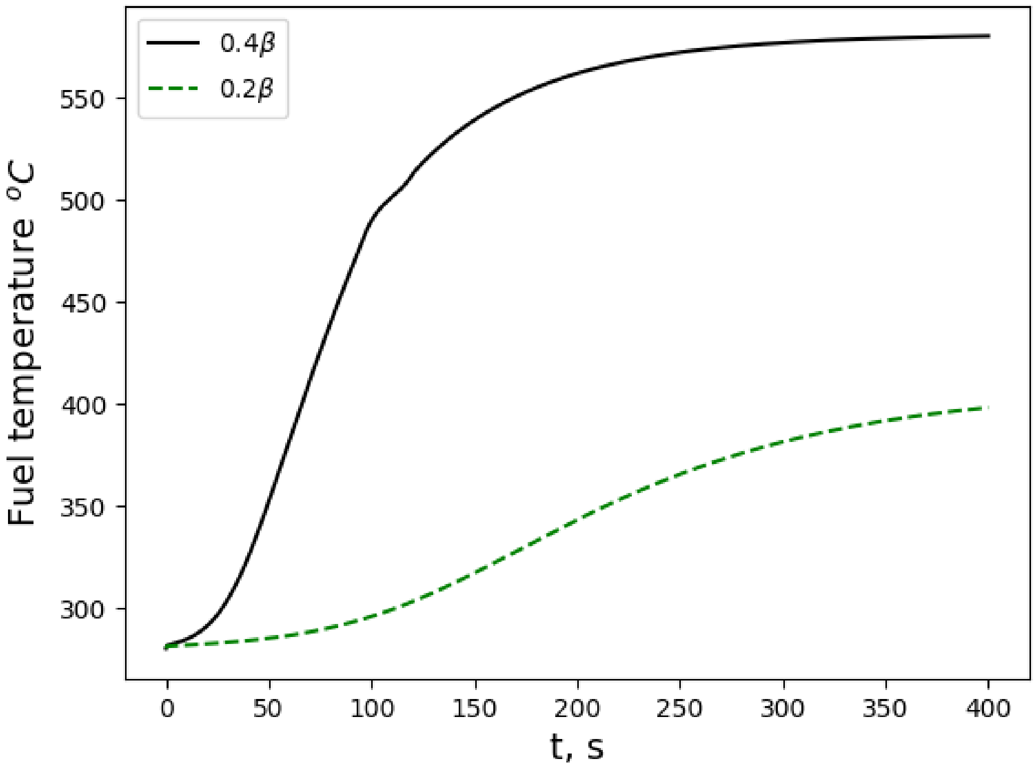

Fig 3.9 – Change in coolant temperature when exerting external influence

Thus, using a mathematical model, it is already possible to carry out some standard analysis of the influence of one or another parameter on another. So by increasing the coolant pumping rate by 2.5 times, the average coolant temperature decreases quite slightly, while, for example, the average fuel temperature in the core becomes less by 300°C.

It is worth saying that within the framework of this work, it is not intended to conduct a detailed analysis of the influence of one technological parameter on another, but only to demonstrate the current capabilities of the constructed mathematical model. The reactor model recorded in the program code represents only the most minimal approximation of a PWR type reactor, and a real idea of the behavior of such a system can be obtained only using parameters taken directly from a real object.

Thus, the current capabilities of the model were presented in this section. Using the initial data and the magnitude of the external impact, you can get an approximate behavior of the system for a specified period of time. It is also possible to conduct a minimal analysis of the influence of a particular parameter on the system.

The next section will discuss the prospects for using the created model, as well as recommendations for its use.

3.5 Prospects of model and recommendations for it use

In the previous Sections 3.1 - 3.4, a brief description of the operation of the model, the accepted simplifications, as well as its current capabilities were provided. The mathematical model presented in the work at the moment, with a competent selection of parameters, and better with its direct use at a nuclear power plant, can predict the behavior of the system under external influence in the limits of 1-100% of the nominal power of a reactor of the PWR type. At the same time, the model does not describe long-term phenomena, such as fuel burnout or reactor poisoning. Also, the model cannot be used to predict behavior in emergency situations.

Technically speaking, the model can be used for any type of reactor. The geometry of the cell described in Section 2.2.2, in this case, should be replaced by the geometry of another reactor that needs to be described.

The same will need to be done when replacing the cell materials. It will be necessary to rewrite the heat exchange process described in Section 1.2.

If we talk about the future of the written model, now this is just the first step towards creating a full-fledged model of predictive control of reactors and this work will serve as a basis for further research in this area in the future.

If we talk about a full-fledged model, then such a model can be integrated into the workplace of the operator, who will already set the desired parameters and predict the behavior of the reactor according to the model and, in accordance with the prediction, decide.

TASK FOR SECTION
«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

To the student:

Group	Full name
0АМ1И	Nikita Yevgenyevich Bortulev

School	SNTE	**Division**	**DNFC**
Degree	Masters	**Educational Program**	14.04.02 Nuclear Physics and Technology, Nuclear power engineering

Input data to the section «Financial management, resource efficiency and resource saving»:	
1. Resource cost of scientific and technical research (STR): material and technical, energetic, financial and human	– Salary costs – 191504 rubles – STR budget – 409502 rubles
2. Expenditure rates and expenditure standards for resources	– Electricity costs – 5.8 rub per 1 kW
3. Current tax system, tax rates, charges rates, discounting rates and interest rates	– Labor tax – 27.1 %; – Overhead costs – 60%;
The list of subjects to study, design and develop:	
1. Assessment of commercial and innovative potential of STR	– comparative analysis with other researches in this field;
2. Development of charter for scientific-research project	– SWOT-analysis;
3. Scheduling of STR management process: structure and timeline, budget, risk management	– calculation of working hours for project; – creation of the time schedule of the project; – calculation of scientific and technical research budget;
4. Resource efficiency	– integral indicator of resource efficiency for the developed project.
A list of graphic material *(with list of mandatory blueprints):*	
1. Competitiveness analysis *2. SWOT- analysis* *3. Gantt chart and budget of scientific research* *4. Assessment of resource, financial and economic efficiency of STR* *5. Potential risks*	

Date of issue of the task for the section according to the schedule	03.02.2023

Task issued by adviser:

Position	Full name	Scientific degree, rank	Signature	Date
Associate professor	E.V. Menshikova	PhD		

The task was accepted by the student:

Group	Full name	Signature	Date
0АМ1И	Nikita Yevgenyevich Bortulev		

4 Financial management, resource efficiency and resource saving

At the moment, two approaches are used to simulate reactor dynamics. Manual calculation using the diffusion approximation of the reactor in statics and calculating its state at each point, as well as using the Monte Carlo method. Both methods are widely used in reactor design and control, but they have a number of drawbacks, which makes the search for new reactor modeling methods urgent. As a competitive solution, the method of modeling dynamics with the help of ODE solvers based on the Python language will be considered.

4.1 Competitiveness analysis of technical solutions

In order to find sources of financing for the project, it is necessary, first, to determine the commercial value of the work. Analysis of competitive technical solutions in terms of resource efficiency and resource saving allows to evaluate the comparative effectiveness of scientific development. This analysis is advisable to carry out using an evaluation card.

First of all, it is necessary to analyze possible technical solutions and choose the best one based on the considered technical and economic criteria.

Evaluation map analysis presented in Table 4.1. The position of your research and competitors is evaluated for each indicator by you on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators determined by you in the amount should be 1. Analysis of competitive technical solutions is determined by the formula:

$$C = \sum W_i \cdot P_i ,$$

C – the competitiveness of research or a competitor;

Wi – criterion weight;

Pi – point of i-th criteria.

The results of calculations of the competitiveness of technical solutions are presented in Table 4.1.

Table 4.1 – Evaluation card for comparison of competitive technical solutions

Evaluation criteria	**Criterion Weight** *Wi*	**Points**			**Competitiveness**		
		P_f	P_1	P_2	C_f	C_1	C_2
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Calculation speed	0.2	5	2	2	1	0.4	0.4
2. Integrability into CPS	0.15	5	1	3	0.75	0.15	0.45
3. Research basis	0.05	1	5	5	0.05	0.25	0.25
4. Versality	0.05	5	2	5	0.25	0.1	0.25
5. Accuracy	0.15	4	3	5	0.6	0.45	0.75
6. Complexity	0.05	5	1	3	0.25	0.05	0.15
7. Applicability limits	0.05	5	2	5	0.25	0.1	0.25
8. Verifiability	0.05	3	3	5	0.15	0.15	0.25
Economic criteria for performance evaluation							
1. Cost of computing power	0.15	3	5	3	0.45	0.75	0.45
2Cost of method-based software	0.1	3	1	3	0.3	0.1	0.3
Total	**1**	**39**	**25**	**39**	**4.05**	**2.5**	**3.5**

The following conventions were adopted in Table 1.

P_f – python-based solvers

P_1 – manual diffusion approximation method

P_2 – Monte-Carlo method

The results show that the method of modeling the equations of dynamics using solvers based on the Python programming language exceeds the current competitiveness, but due to the fact that the method is fairly new for it has not yet gained enough scientific basis for its implementation, but it is easy to learn and, in the future, can be integrated into the safety system of nuclear power plants.

4.2 SWOT analysis

Complex analysis solution with the greatest competitiveness is carried out with the method of the SWOT analysis: Strengths, Weaknesses, Opportunities and Threats. The analysis has several stages. The first stage consists of describing the strengths and weaknesses of the project, identifying opportunities and threats to the project that have emerged or may appear in its external environment.

Table 4.2 – SWOT analysis

	Strengths: S1. Modeling reactor dynamics with ODE solvers allows for much faster calculations S2. It is much easier to create a program to calculate using ODE solvers S3. The solver-based program is much easier to integrate into the protection system of reactor S4. The method is universal and can be applied to any reactor type	**Weaknesses:** W1. This method of reactor modeling is still poorly understood compared to existing W2. At the moment, the accuracy of reactor calculation using this method does not exceed the accuracy of other methods W3. The method usage involves the training of special staff
Opportunities: O1. Model predictive control trend essence of which is to predict the behavior of system after external influence O2. Growing demand for trained personnel for nuclear power plants, whose training requires new technology O3. The need for modeling and predicting possible emergency situations		
Threats: T1. Existing methods so far fully cover the needs of the market in the field of reactor modeling T2. The project may not receive sufficient funding for its development T3. The scientific community may not support the introduction of a new method		

The second stage consists of identifying the compatibility of the strengths and weaknesses of the project with the external environmental conditions. This compatibility or incompatibility should help to identify what strategic changes are needed. As part of this stage it is necessary to build an interactive project matrix. Its use helps to understand the different combinations of interrelationships of the areas of the SWOT matrix. Each factor is labeled with either a "+" (signifying strong alignment of strengths with opportunities) or a "-" (signifying strong alignment of strengths with opportunities). The first factor is either a "+" (signifying a strong alignment of strengths with opportunities) or a "-" (meaning a weak alignment). 0" if there is any doubt about what to put "+" or "-". The interactive matrices are presented in Tables 4.3 - 4.6.

Table 4.3 – Interactive matrix of the project "Strengths and opportunities

Strengths					
Opportunities		S1	S2	S3	S4
	O1	+	+	+	+
	O2	-	-	+	-
	O3	+	-	+	+

Table 4.4 – Interactive matrix of the project "Weaknesses and Opportunities

Weaknesses				
Opportunities		W1	W2	W3
	O1	+	+	-
	O2	+	-	+
	O3	+	-	-

Table 4.5 – Interactive Project Matrix "Strengths and Threats"

Strengths					
Threats		S1	S2	S3	S4
	T1	-	+	+	-
	T2	-	-	-	+
	T3	-	+	+	-

Table 4.6 – Interactive project matrix "Weaknesses and Threats"

Weaknesses				
Threats		W1	W2	W3
	T1	+	+	
	T2	+	-	
	T3			

Thus, in the third stage, the final SWOT analysis matrix should be compiled, which is presented in Table 4.7.

Table 4.7 – SWOT analysis

	Strengths: S1. Modeling reactor dynamics with ODE solvers allows for much faster calculations S2. It is much easier to create a program to calculate using ODE solvers S3. The solver-based program is much easier to integrate into the protection system of reactor S4. The method is universal and can be applied to any reactor type	**Weaknesses:** W1. This method of reactor modeling is still poorly understood compared to existing W2. At the moment, the accuracy of reactor calculation using this method does not exceed the accuracy of other methods
Opportunities: O1. Model predictive control trend essence of which is to predict the behavior of system after external influence O2. Growing demand for trained personnel for nuclear power plants, whose training requires new technology O3. The need for modeling and predicting possible emergency situations	Opportunity to enhance reactor plant safety using the model Facilitation of operator work in reactor maneuvering mode	Prediction of reactor systems operation in emergency situations with at least minimal accuracy may be a reason to develop the proposed direction
Threats: T1. Existing methods so far fully cover the needs of the market in the field of reactor modeling T2. The project may not receive sufficient funding for its development	Show the possibility of applying this method to literally every type of reactor	Present the current work and compare the readings of the available model with the readings at the real nuclear power plant

Thus, as a result of the SWOT analysis, the strengths and weaknesses of the project, opportunities and threats, and their mutual relationship to each other were identified. In the course of the analysis, the possible options for development and events and outcomes for the project that may arise were identified

4.3 Project initiation

The initiation process group consists of processes that are performed to define a new project or a new phase of an existing one. In the initiation processes, the initial purpose and content are determined and the initial financial resources are fixed. The internal and external stakeholders of the project who will interact and influence the overall result of the research project are determined (Table 4.8, 4.9).

Table 4.8 – Stakeholders of the project

Project stakeholders	**Stakeholder expectations**
Nuclear power plants	Presentation of the ability of the resulting model to predict reactor behavior with acceptable accuracy
Designers of NPP	

Table 4.9 – Purpose and results of the project

Purpose of project:	Apply ODE solvers to simulate reactor dynamics and be able to predict changes in its power, fuel temperature, and coolant temperature under external influences
Expected results of the project:	Ready code containing a pilot version of the mathematical model of reactor dynamics Mathematical model that can predict changes in power, fuel temperature and coolant temperature
Criteria for acceptance of the project result:	The error of the model results should not exceed 15%
Requirements for the project result:	Project should be finished to the 1st of June
	The results of the project should meet the criteria for acceptance.
	The results of this research should be demonstrated at Russian conference.

The organizational structure of the project

It is necessary to solve some questions: who will be part of the working group of this project, determine the role of each participant in this project, and prescribe the functions of the participants and their number of labor hours in the project (Table 4.10).

Table 4.10 – Structure of the project

№	Participant	Role in the project	Functions	Labor time, hours (working days (from table 7) × 6 hours)
1	A.G. Goryunov, PhD, ESNT NFCD Head of department	Research advisor	Control of project	144
2	N.Ye. Bortulev, ESNT IRT-T, engineer	Master student	Performing the reactor dynamics mathematical model	534

Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members (Table 4.11).

Table 4.11 – Project limitations

Factors	**Limitations / Assumptions**
3.1. Project's budget	409502
3.1.1. Source of financing	TPU
3.2. Project timeline:	February 2023 – June 2023
3.2.1. Date of approval of plan of project	03.02.2023
3.2.2. Completion date	01.06.2023

Project Schedule

As part of planning a science project, you need to build a project timeline and a Gantt Chart, so the project schedule was done (Table 4.12).

Table 4.12 – Project Schedule

Job title	Duration, **working** days (without holidays and weekends)	Start date	Date of completion	Participants
1.Creation and approving of technical specification	4	The 3rd of February 2023	The 7th of February 2023	Research advisor
2.Searching and selection of material for research	10	The 8th of February 2023	The 18th of February 2023	Master's student
3.Selection of study way	2	The 20th of February 2023	The 21th of February 2023	Research advisor
4.Development of general methodology of the research	6	The 22th of February 2023	The 1st of March 2023	Research advisor, master's student
5.Calendar planning of research activities	2	The 2nd of March 2023	The 3rd of March 2023	Research advisor
6.Reviewing of manuals and list of literature	10	The 4th of March 2023	The 16th of March 2023	Master's student
7.Performing of mathematical model of reactor	30	The 17th of March 2023	The 20th of April 2023	Master's student
8.Processing of obtained results	10	The 21th of April 2023	The 3rd of May 2023	Master's student
9.Analysis and description of the results	10	The 4th of May 2023	The 17th of May 2023	Research advisor, master's student
10.Composition of master's thesis	13	The 18th of May 2023	The 1st of June 2023	Master's student

A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule (Table 4.13). This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The width of the horizontal bars in the graph shows the duration of each activity.

Table 4.13 – Gantt chart

№	Activities	Participants	T_c, days	Duration of the project											
				February			March			April			May		
				1	2	3	1	2	3	1	2	3	1	2	3
1	1.Creation and approving of technical specification	RA	5												
2	2.Searching and selection of material for research	MS	10												
3	3.Selection of study way	RA	2												
4	4.Development of general methodology of the research	RA, MS	6												
5	5.Calendar planning of research activities	RA	2												
6	6.Reviewing of manuals and list of literature	MS	10												
7	7.Performing of mathematical model of reactor	MS	30												
8	8.Processing of obtained results	MS	5												
9	9.Analysis and description of the results	RA, MS	10												
10	10.Composition of master's thesis	MS	5												

Icons show participations activity, ■ -master's student, ▧ - research advisor.

4.4 Scientific and technical research budgets

The amount of costs associated with the implementation of this work is the basis for the formation of the project budget. This budget will be presented as the lower limit of project costs when forming a contract with the customer.

To form the final cost value, all calculated costs for individual items related to the manager and the student are summed.

In the process of budgeting, the following grouping of costs by items is used:

– material costs of scientific and technical research;

– costs of special equipment for scientific work (depreciation of equipment used for design);

– basic salary;

– additional salary;

– labor tax;

– overhead.

The study used only a PC and free software. No materials were involved in the work, so it will be necessary only to calculate the depreciation of the PC:

$$D = \frac{C_{in} \cdot H_a}{100} = \frac{C_{in}}{T_l}$$

where D - annual amount of depreciation;

C_{in} - initial cost of the equipment;

$H_a = \frac{100}{T_l}$ - rate of depreciation;

T_l - life expectancy.

Life expectancy of PC approximately 5 years (60 months). Initial cost is 122 thousand rubles. The total duration of the project takes 4 months, so the amount of depreciation charges for this period will be as follows:

$$D = \frac{122000}{60} \cdot 4 = 8133 rub$$

4.4.1 Basic salary

This point includes the basic salary of participants directly involved in the implementation of work on this research. The value of salary costs is determined based on the labor intensity of the work performed and the current salary system

The basic salary (S_b) is calculated according to the formula:

$$S_b = S_a \cdot T_w$$

where S_b – basic salary per participant;

T_w – the duration of the work performed by the scientific and technical worker, working days;

S_d – the average daily salary of a participant, rub.

The average daily salary is calculated by the formula:

$$S_d = \frac{S_m \cdot M}{F_v}$$

where S_m – monthly salary of a participant, rub.;

M – the number of months of work without leave during the year:

at holiday in 48 days, M = 11.2 months, 6 day per week;

F_v – valid annual fund of working time of scientific and technical personnel (251 days).

Table 4.14 – The valid annual fund of working time

Working time indicators	
Calendar number of days	365
The number of non-working days - weekend - holidays	 52 14
Loss of working time - vacation - sick absence	48
The valid annual fund of working time	251

Monthly salary is calculated by formula:

$$S_{month} = S_{base} \cdot (k_{premium} + k_{bonus}) \cdot k_{reg}$$

where S_{base} – base salary, rubles;

$k_{premium}$ – premium rate;

k_{bonus} – bonus rate;

k_{reg} – regional rate.

Table 4.15 – Calculation of the base salaries

Performers	S_{base}, rubles	$k_{premium}$	k_{bonus}	k_{reg}	S_{month}, rub.	W_d, rub.	T_w, work days	W_{base}, rub.
Research advisor	39300	1.1	1.1	1.3	61818	2758	24	66192
Masrer's student	20064				31560	1408	89	125312

4.4.2 Additional salary

This point includes the amount of payments stipulated by the legislation on labor, for example, payment of regular and additional holidays; payment of time associated with state and public duties; payment for work experience, etc.

Additional salaries are calculated on the basis of 10-15% of the base salary of workers:

$$W_{add} = k_{extra} \cdot W_{base}$$

where W_{add} – additional salary, rubles;

k_{extra} – additional salary coefficient (10%);

W_{base} – base salary, rubles.

4.4.3 Labor tax

Tax to extra-budgetary funds are compulsory according to the norms established by the legislation of the Russian Federation to the state social insurance (SIF), pension fund (PF) and medical insurance (FCMIF) from the costs of workers.

Payment to extra-budgetary funds is determined of the formula:

$$P_{social} = k_b \cdot (W_{base} + W_{add})$$

where k_b – coefficient of deductions for labor tax.

In accordance with the Federal law of July 24, 2009 No. 212-FL, the amount of insurance contributions is set at 30%. Institutions conducting educational and scientific activities have rate - 27.1%.

Table 4.16 – Labor tax

	Project leader	**Engineer**
Coefficient of deductions	30%	
Salary (basic and additional), rubles	72811	137843
Labor tax, rubles	21843	41352

4.4.4 Overhead costs

Overhead costs include other management and maintenance costs that can be allocated directly to the project. In addition, this includes expenses for the maintenance, operation and repair of equipment, production tools and equipment, buildings, structures, etc.

Overhead costs account from 30% to 90% of the amount of base and additional salary of employees.

Overhead is calculated according to the formula:

$$C_{ov} = k_{ov} \cdot (W_{base} + W_{add})$$

where k_{ov} – overhead rate.

Table 4.17 – Overhead costs

	Project leader	**Engineer**
Overhead rate	60%	
Salary, rubles	72811	137843
Overhead, rubles	43686	82705

4.4.5 Other direct costs

Energy costs for equipment are calculated by the formula:

$$C = P_{el} \cdot P \cdot F_{eq}$$

where P_{el} − power rates (5.8 rubles per 1 kWh);

P − power of equipment, kW;

F_{eq} – equipment usage time, hours.

Equipment usage time F_{eq} is taken from Table 10 for student and equal 534 hours. Power of PC equal to approximately 0.3 kW. Then energy costs for equipment:

$$C = 5.8 \cdot 0.3 \cdot 534 = 929\,rubles$$

4.4.6 Formation of budget costs

The calculated cost of research is the basis for budgeting project costs. Determining the budget for the scientific research is given in the Table 4.18.

Table 4.18 – Items expenses grouping

Name	**Cost, rubles**
1. Equipment costs	8133
2. Basic salary	191504
3. Additional salary	19350
4. Labor tax	63195
5. Overhead	126391
6. Other direct costs	929
Total planned costs	**409502**

As can be seen from the table, the bulk of the project budget is the basic salary. The point is that the project is purely theoretical and does not include the cost of materials to create anything.

4.5 Evaluation of the comparative effectiveness of the project

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the definition of two weighted average values: financial efficiency and resource efficiency.

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of the technical problem is taken as the calculation base (as the denominator), with which the financial values for all the options are correlated.

The development of the project was done using the Python programming language (version 1.), as an alternative, the same can be done using another language - C++. Conventionally, when using C++, the duration of work, and therefore the cost of the work will increase by half. Thus, the cost of the second execution will be 710 thousand rubles.

The integral financial measure of development is defined as:

$$I_f^d = \frac{C_i}{C_{\max}}$$

where I_f^d – integral financial measure of development;

C_i – the cost of the i-th version;

$C_{\max}$ – the maximum cost of execution of a research project (including analogues).

The obtained value of the integral financial measure of development reflects the corresponding numerical increase in the budget of development costs in times (the value is greater than one), or the corresponding numerical reduction in the cost of development in times (the value is less than one, but greater than zero).

Since the development has one performance, then I_f^d = 1.

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows:

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a \qquad I_m^p = \sum_{i=1}^{n} a_i b_i^p$$

where I_m – integral indicator of resource efficiency for the i-th version of the development;

a_i – the weighting factor of the i-th version of the development;

b_i^a , b_i^p – score rating of the i-th version of the development, is established by an expert on the selected rating scale;

n – number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in the form of Table 4.19.

Table 4.19 – Evaluation of the performance of the project

Criteria	Weight criterion	Var. 1	Var. 2
1. Energy efficiency	0.05	5	5
2. Reliability	0.2	5	5
3. Safety	0.05	5	5
4. Functional capacity	0.2	5	5
Economic criteria for performance evaluation			
1. The cost of development	0.1	5	3
2. Market penetration rate	0.2	5	5
3. Expected life	0.1	3	5
4. After-sales service	0.1	5	5
Total	1	4.8	4.8

The integral indicator of the development efficiency (I_e^p) is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_e^p = \frac{I_m^p}{I_f^d} \quad I_e^a = \frac{I_m^a}{I_f^a}$$

Comparison of the integral indicator of the current project efficiency and analogues will determine the comparative efficiency. Comparative effectiveness of the project:

$$E_c = \frac{I_e^p}{I_e^a}$$

Thus, the effectiveness of the development is presented in Table 4.20.

Table 4.20 – Efficiency of development

№	Indicators	Var. 1	Var. 2
1	Integral financial measure of development	0.5	1
2	Integral indicator of resource efficiency of development	4.8	4.8
3	Integral indicator of the development efficiency	9.6	4.8
4	Comparative effectiveness of the project	2	0.5

TASK FOR SECTION "SOCIAL RESPONSIBILITY"

To the student:

Group	Full name
0АМ1И	Nikita Yevgenyevich Bortulev

School	SNTE	Research and Education Center	DNFC
The level of education	Masters	Direction/ specialty	14.04.02 Nuclear Physics and Technology, Nuclear power engineering

Initial data for the section "Social responsibility":	
1. Characteristics of the research object (substance, material, device, algorithm, technique, working area) and its scope	Development of a mathematical model with implementation of Python based ODE solvers. Modeling performed via usage of computer in room 321 in 10^{th} building of TPU.
List of questions to be researched, designed and developed:	
1. Legal and organizational security issues: - special (typical for the operation of the research object, the projected working area) legal norms of labor legislation; -organizational measures for the layout of the working area.	- Labor Code of the Russian Federation from December 30, 2001 N 197-FZ - SanPiN 1.2.3685-21. Hygienic standards and requirements to ensure safety and (or) harmlessness for humans of environmental factors. - SNiP 21-01-97. Fire Safety of Buildings and Structures - SNiP 41-01-2003 Construction norms and rules of the Russian Federation. Heating, Ventilation and Air Conditioning
2. Industrial safety: 2.1. Analysis of the identified harmful and dangerous factors 2.2. Rationale for mitigation measures	Harmful and dangerous factors: – Enhanced electromagnetic radiation level – Insufficient illumination of workplace – Excessive noise – Deviation of microclimate indicators – Electric shock – Increased level of ionizing radiation
3. Safety in emergencies:	- selection and description of a typical emergencies – fire, electrical shock, fall. - justification of measures to prevent emergencies; - the order of actions in the event of an emergency.

Date of issue of the task for the section on a line chart	03.02.2023

The assignment was given by the consultant:

Position	Full name	Academic degree, title	Signature	Date
Associate Professor	Yuriy Vladimirovich Perederin	Ph.D		

The student accepted the assignment:

Group	Full name	Signature	Date
0АМ1И	Nikita Yevgenyevich Bortulev		

5 Social Responsibility

In this paper, reactor dynamics are simulated with the help of ODE solvers based on the Python language. The work is performed using a personal computer in classroom 321 of the 10th building of TPU. The section deals with hazardous and harmful factors possible during research work, legal and organizational issues, as well as measures in emergency situations.

Occupational safety and health regulations are introduced to prevent accidents, ensure safe working conditions for employees, and are mandatory for workers, managers, engineers and technicians.

According to [26], a hazardous industrial factor is an industrial factor, the impact of which under certain conditions leads to injury or other sudden, dramatic deterioration of health.

A hazardous production factor is a production factor, the impact of which on the worker, under certain conditions, leads to illness or reduction of ability to work.

5.1 Legal and organizational security issues

According to the Labor Code of the Russian Federation [26], every employee has the right to:

– a workplace that meets the requirements of occupational safety and health;

– to receive reliable information from the employer, the relevant state bodies and public organizations about the conditions and labor protection at the workplace, the existing risk of health damage, as well as measures to protect against the effects of harmful and (or) dangerous production factors;

– refusal to perform work in case of a threat to his/her life and health due to violation of labor safety requirements, except in cases of

– provision of personal and collective protective equipment;

– training in safe work methods and techniques at the expense of the employer;

– unscheduled medical examinations in accordance with medical recommendations with retention of his/her job and average earnings during the examination;

– guarantees and compensations established in accordance with this Code, collective agreement, agreement, local normative act, employment contract, if he/she is employed in harmful and (or) dangerous working conditions.

5.2 Analysis of detected harmful and dangerous factors arising during the study

Harmful and dangerous factors affecting the employee are established in accordance with GOST 12.0.003-2015 [27] "Hazardous and harmful production factors. Classification".

Harmful factors when performing work using a computer are as follows:

- deviations of microclimate indicators;
- increased level of electromagnetic radiation;
- increased noise level;
- nervous-psychic overload;
- insufficient illumination of the working area.

The above factors can have an impact on the health of researchers, so compliance controls should be established.

It will also be necessary to consider the case of increased ionizing radiation level, since the final qualification work of specialty of nuclear physics and technologies must include section with radiation safety in case of working in the reactor hall.

5.3 Deviations of the microclimate indicators

In order to ensure the quality of work and the normal activity of the worker, the room must provide the appropriate meteorological conditions that affect the person during work. Microclimate is a complex of factors affecting the thermoregulation of the human body, its well-being and productivity, as well as its health. The main parameters of the microclimate are temperature, humidity, air speed. In connection with working conditions when calculating using a computer category 1a is set. The requirements for the microclimate are set in accordance with [28]. For category 1a, the optimal microclimate parameters are presented in Table 5.1.

Table 5.1 – Optimal indicators of the microclimate

Period of the year	Air temperature, ^0C	Relative air humidity, %	Air velocity, м/с
Cold	22-24	15-75	Less then 0,1
Warm	23-25	15-75	0.1-0.2

Computer rooms should be cleaned daily and systematically ventilated after every hour of work. Ventilation, air conditioning, and heating systems are used to maintain normal microclimate parameters in the work area.

Ventilation helps to create normal hygienic and sanitary conditions in the premises. The ventilation process makes it possible to continuously remove polluted air from the production room and simultaneously supply fresh air in such an amount that the concentration of harmful substances in the air will be below the maximum allowable, and the temperature, humidity and air flow rate comply with sanitary norms. According to SNiP 41-01-2003 [29] this classroom requires an air change rate of 20 m^3/h per person. Classroom 321 is designed for 12 workplaces, so the ventilation capacity will be:

$$L = 20 \cdot 12 = 240\ \mathrm{m}^3 / h.$$

This capacity is provided by a Vents 150 type fan with a maximum capacity of 292 m^3/h and a power of 24 W [30].

5.4 Increased level of electromagnetic radiation

Electromagnetic radiation poses a significant hazard to humans compared to other harmful factors. In this case, the source of electromagnetic radiation is computer equipment (monitor and system unit). Prolonged exposure to intensive electromagnetic radiation can cause increased fatigue, the appearance of heart pain, disruption of the central nervous system. It should be noted that processor heating during operation causes production of some harmful compounds, which in turn lead to deionization of the surrounding space.

The norms of electromagnetic fields created by PCs are given in Table 5.2 in accordance with [28].

Table 5.2 - Permissible levels of EMF created by PCs at workplaces

Parameter	Frequency Range	HPL EMF
Electric field strength	5 Hz – 2 kHz	25 V/m
	2 kHz – 400 kHz	2,5 V/m
Magnetic flux density	5 Hz – 2 kHz	250 nT
	2 kHz – 400 kHz	25 nT
Electrostatic potential of the video monitor screen		500 V

There are a number of recommendations that can be followed to reduce the negative effects of computer equipment:

– if several computers or laptops are constantly in the same room, you should place them around the perimeter of the room, leaving the center free, because the sides and rear surface of the monitor generate much more harmful radiation;

– switch off your computer when you finish working: the longer it is on, the more radiation it generates and releases a significant amount of harmful substances into the environment;

– usage of a special protective film;

– systematic wiping of dust, wet cleaning and the use of ionizers [28].

In accordance with [28], measures to reduce electromagnetic field level in Class 321 of 10th building of the TPU are taken. EMF level does not exceed the limit.

5.5 Increased noise level

Noise in the workplace has an irritating effect on workers, increases their fatigue, and when performing tasks that require attention and concentration, can lead to increased errors and longer task completion times. Prolonged exposure to noise causes the employee to go deaf or even completely deaf.

Table 5.3 shows the permissible noise levels in the working area of PC use.

Table 5.3 – Noise TAC values [28].

Sound pressure levels (dB) in octave bands with geometric mean frequencies, Hz									Maximum sound level, dBA
31,5	63	125	250	500	1000	2000	4000	8000	
79	63	52	45	39	35	32	30	28	55

The noise level in the 321 10 enclosure room during work on the PC should not exceed 55 dBA. To reduce the noise level, the ceiling or walls should be lined with sound-absorbing material with the maximum sound-absorption coefficient in the frequency range from 63 to 8000 Hz [31]. Additional sound absorption is provided by curtains on the windows, made of dense heavy fabric.

In accordance with [31], measures to reduce noise levels in Class 321 of 10^{th} building of the TPU are taken. The overall noise level does not exceed 55 dBA.

5.6 Nervous-psychic overload

Nervous-psychic overload is subdivided into:

– mental overload, including that caused by information load;

– analyzer overstrain, including that caused by information load;

– monotony of work - emotional overload.

Overstrain of the visual analysers can lead to fatigue and impaired contractile function of the eye muscles. Nervous-emotional tension can be caused by responsibility for the work performed, high requirements for the quality of work performed, complexity of work, especially in conditions of time deficit. Nervous-emotional tension can disturb the functional state of the cardiovascular and central nervous system [32].

To reduce the impact of harmful factors, limits are set on the duration of breaks. Table 5.4 shows the total rest time for each category of work [6].

Table 5.4 – Total break time depending on work category and workload

Job category	Load level per work shift for types of work with a computer			Total time of regulated breaks at 8-hour shifts, min
	group «А», number of characters	group «Б», number of characters	Group «В», hours	
I	less than 20 000	less than 15 000	less than 2	50
II	less than 40 000	less than 30 000	less than 4	70
III	less than 60 000	less than 40 000	less than 6	90

In this case, the load level refers to group «B», work category III. According to the table, it is required to set breaks, the sum of which during the shift will be not less than 90 minutes, i.e. breaks of 15 minutes each working hour [33].

In accordance with [33], measures were taken when working at the PC in classroom 321 of 10^{th} building of TPU. Breaks of 15 minutes were taken each working hour.

5.7 Insufficient lighting of the work area

Three different types of lighting are used in production facilities [34]: natural, artificial and mixed.

Illumination on the surface of the table in the area where the working document is placed should be 300-500 lux. Lighting should not create glare on the screen surface. Illumination of the screen surface should not be more than 300 lux.

The required number of luminaries n is determined as follows:

$$n = \frac{E \cdot S \cdot Z \cdot K}{F \cdot \Phi \cdot m};$$

where E – normalized illumination, E = 300 lux;

S – area of the room, $S = 40\ m^2$;

Z – lighting irregularity factor, Z = 1.15;

K –safety factor, K=1.1;

F – luminous flux of one lamp, F=1050 lm;

Φ – utilization factor, F=0.52;

m – number of lamps in the luminaire, m=4.

$$n = \frac{300 \cdot 40 \cdot 1.15 \cdot 1.1}{1050 \cdot 0.52 \cdot 4} = 6.95\, units$$

In order to avoid zones with insufficient lighting, the required number of luminaires is rounded upwards to a whole number. Thus, to illuminate classroom 321 in Building 10, the number of luminaires will be 7, which is exactly equal to the actual number of luminaires in the class.

5.8 Fire and explosion safety

According to [35], depending on the characteristics of the substances used in production and their quantity, rooms are divided into categories «А», «Б», «В», «Г», «Д». Classroom 321 belongs to class «В», since it contains solid combustible substances, such as wooden cabinets and tables.

Fire prevention measures are divided into: organizational, technical, operational and regime measures.

Organizational measures include proper operation of equipment, proper maintenance of buildings and territories, fire instruction of workers and employees, training of production personnel in fire safety rules, publication of instructions, posters, availability of an evacuation plan.

Technical measures include: compliance with fire safety rules, standards in the design of buildings, installation of electrical wiring and equipment, heating, ventilation, lighting, proper placement of equipment.

Regulatory measures include the establishment of rules for the organization of work, and the observance of fire protection measures. To prevent fires from short circuits, overloads, etc., it is necessary to observe the following fire safety rules:

– the use of non-combustible or hardly combustible materials in the construction and finishing of buildings;

– correct operation of the equipment (proper connection of the equipment to the power supply network, control of the heating of the equipment);

– training of staff in fire safety rules;

– issuing instructions, posters, having an evacuation plan;

– compliance with fire safety rules and regulations when designing buildings, installing electrical wiring and equipment, heating, ventilation and lighting;

– correct placement of the equipment;

– timely preventive maintenance inspection and repair of equipment.

If an emergency situation occurs [36]:

– inform the management;

– call the emergency service or the Ministry of Emergency Situations – 112.

– take measures to eliminate the accident in accordance with the instructions.

5.9 Electrical Safety

According to the REI [37], this room belongs to the 1st category of electrical safety, as there are no electrical installations with voltages over 1000 V. The main requirements for category 1:

– air humidity does not exceed 60%;

– availability of supply and exhaust ventilation;

– absence of conductive dust and chemical compounds in the air;

– air temperature not exceeding 35 ^{0}C;

– non-conductive floors.

Do not work with the computer in conditions of high humidity (relative humidity exceeds 75%), high temperature (over 35 °C), conductive dust, conductive floors and the possibility of simultaneous contact with metal elements connected to the ground and the metal housing of the electrical equipment. A computer operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

– by direct contact with live parts during repair of the computer;

– touching live, non-current parts that have been energized (if the insulation of live parts has been disturbed);

– by touching the energized floor or walls;

– in case of a short circuit in high-voltage units: power supply unit and display scanning unit.

If any parts of the computer malfunction, the enclosure can become live, which can cause electric shock or injury. To eliminate this, ensure that the metal housings of the equipment are connected to a grounding conductor.

Organizational measures for electrical safety are periodic and unscheduled safety instructions. Periodic safety instructions are carried out for non-electrotechnical personnel who perform the following work: switching on and off electrical appliances, cleaning the premises near electric boards, sockets and switches, etc. [38].

Non-electrotechnical personnel are certified for the first qualification group for electrical safety. Periodic safety instructions are carried out at least once a year. Unscheduled safety instructions are carried out by the head of the subdivision when new technical electrical equipment is put into operation [38].

5.10 Radiation safety

Ionizing radiation is radiation that could ionize molecules and atoms. This effect is widely used in energetics and industry. However, there is health hazard. In living tissue, this radiation could damage cells that result in two types of effects.

Deterministic effects (harmful tissue reactions) due to exposure with high doses and stochastic effects due to DNA destruction and mutations (for example, induction of cancer).

To provide radiation safety with using sources of ionizing radiation one must use next principles [39]:

– keep individual radiation doses from all radiation sources not higher than permissible exposure;

– forbid all activity with using radiation sources if profit is low than risk of possible hazard;

– keep individual radiation doses from all radiation sources as low as possible.

There are two groups of people related to work with radiation: personnel, who works with ionizing radiation, and population (see Table 5.5).

Table 5.5 – Dose limits for groups of people related to work with radiation

Quantity	Dose limits	
	personnel	population
Effective dose	20 mSv per year in average during 5 years, but not higher than 50 mSv per year	1 mSv per year in average during 5 years, but not higher than 5 mSv per year
Equivalent dose per year in eye'slens	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	50 mSv

Effective dose for personnel must not exceed 1000 mSv for 50 years of working activity, and for population must not exceed 70 mSv for 70 years of life.

In addition, for women from personnel of age below 45 years there is limit of 1 mSv per month of equivalent dose on lower abdomen. During gestation and breast-feeding women must not work with radiation sources.

For students older than 16, who uses radiation sources in study process or who is in rooms with increased level of ionizing radiation, dose limits are quarter part of dose limits of personnel.

According to [39], dose rate in classroom 321 of 10 building of TPU does not exceed permissible limits.

5.11 Safety in emergency situations

Table 5.6 considers emergency situations that may arise during the performance of work in 321 classroom 10 of TPU building.

Table 5.6 – Emergency situations, prevention measures and actions in case of occurrence [36, 40, 41].

№	Emergencies	Preventive measures of emergencies	Actions in the event of emergency
1	Fire	- Check the condition of electrical devices, in case of a malfunction do not proceed to fix it yourself; - comply with fire safety rules according to the requirements of regulatory documentation; - conduct training and safety instruction of employees, practice firefighting skills	- disconnect electrical equipment; - use powder and carbon dioxide fire extinguishers; - in case of a life-threatening situation, evacuate; - call 01, 101, 112
2	Electrocution	- Conduct training and safety instructions of employees on working with electrical devices It is forbidden: - work with wet and dirty hands; - touching the connectors of connecting cables; - to troubleshoot the equipment by oneself - touching power wires and grounding devices	- eliminate the exposure of the victim to current; - lay the victim on a hard surface; - check for breathing and pulse; - Call 03(103) or 112 in all cases
3	Injury due to a fall from a height	- Conduct training and safety instructions of employees - make sure that computer wires are not in the path of travel, in case of violation inform the supervisor; - do not use a chair, table, etc. instead of a ladder;	- Examine the victim's body and head for open wounds and abrasions; - Ask for fingertip movements to rule out damage to the spine; - Move the arms and legs to rule out fractures; - question the victim about general well-being disorders:

		- Avoid placing equipment and documentation on shelves and cabinets that cannot be accessed without a stepladder; - always hold on to the handrail and watch your step when climbing stairs; - never carry your hands in your pockets because if you fall, your instinctive movements will help you stay on your feet; - never carry objects by holding them in front of you, blocking your view; - Clean dirt, ice, and other contaminants from your shoes before entering the building	dizziness, drowsiness, nausea - these signs are indicative of a concussion; - if there are no serious injuries, put a cold compress on the bruised area and accompany the victim home; - If you are seriously injured, call 03(103) or 112 and report the incident. Do not try to lift the injured person under any circumstances.

Conclusion

In the course of the research work, the following tasks were accomplished:

– The information on equations of reactor dynamics was reviewed. Methods and approaches to solving differential equations were reviewed. The most relevant approach to solving the system of differential equations of reactor dynamics is the numerical Runge-Kutta methods. One of the libraries of the Python programming language, which uses Runge-Kutta method, was used in the work.

– A system of equations of dynamics based on six groups of delayed neutrons was compiled. The resulting system consists of 9 equations, 7 of which independently describe the reactor kinetics, while the remaining two are used to describe changes in fuel and coolant temperature depending on the reactivity introduced.

– The system of 9 equations was further coded in the python programming language and using the free open source library SciPy. The program provides numerical values as well as a graphical representation of how the reactor power, fuel temperature, and coolant temperature change.

– The resulting graphical representations of parameter changes over time were then compared with the graphs and available literature. The parameters given in the literature were written into the model and then compared. The discrepancy in the values between 1 and 100 percent of nominal power is no more than 6%.

In section of financial management was developed stages for design and create competitive development that meet the requirements in the field of resource efficiency and resource saving.

The first stage was an analysis of competitive solutions, evaluation of already used options and comparing them with our own project.

The second stage included a SWOT analysis, which included an assessment of the strengths, weaknesses, threats and opportunities of the project, as well as their relationship to each other.

In the third stage, a work plan for the research project was drawn up, deadlines for its implementation were outlined, and a Gantt chart was drawn up.

In the fourth stage, the costs of the research project were estimated. And also calculated the approximate cost, which amounted to 409502 rubles.

The last stage included an assessment of the integral effectiveness of the project, which involved comparing the current version of the execution, with a potentially possible. In the course of the analysis, it was found that the current variant of execution is optimal.

The section of social responsibility deals with harmful and dangerous factors:

– deviations of microclimate indicators [28, 29];
– increased level of electromagnetic radiation [28];
– increased noise level [28];
– nervous-psychic overload [32, 33];
– insufficient illumination of the work area [34].
– increased ionizing radiation level [39]

It has been determined that Classroom 321 of TPU Building 10 belongs to:

– category «B» for fire and explosion safety [35];
– class 1 for electrical safety [37].

When considering emergency situations in the workplace, prevention and elimination measures are proposed. The most likely emergency situation is a short circuit followed by a fire. To prevent such cases, it is necessary to regularly check the condition of devices and observe precautions against electric shock [41].

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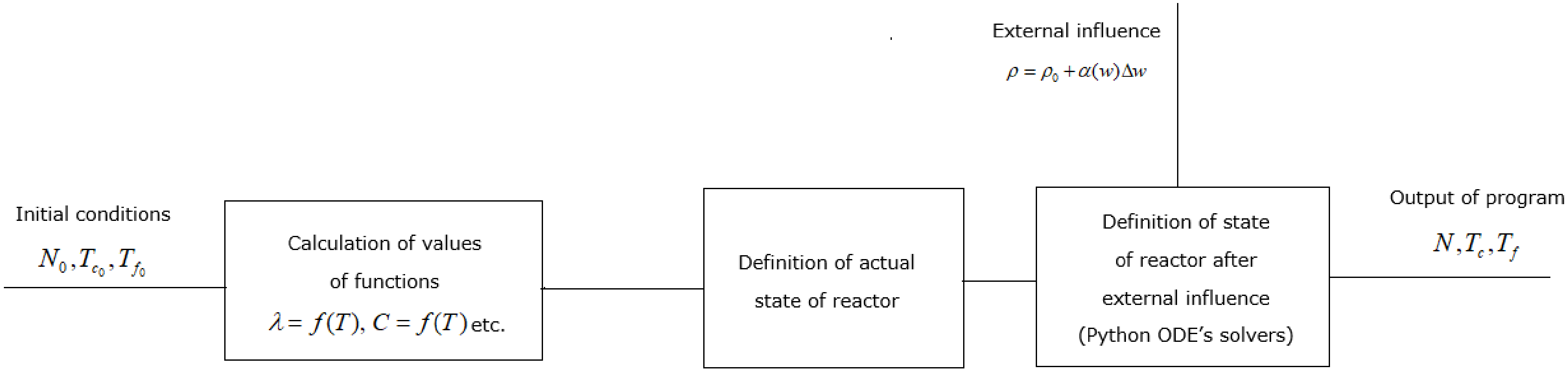
Appendix A


External influence
$\rho = \rho_0 + \alpha(w)\Delta w$
Initial conditions
N_0, T_{c_0}, T_{f_0}
Calculation of values
of functions
$\lambda = f(T)$, $C = f(T)$ etc.
Definition of actual
state of reactor
Definition of state
of reactor after
external influence
(Python ODE's solvers)
Output of program
N, T_c, T_f