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)

Инженерная школа ядерных технологий
Направление подготовки 14.04.02 Ядерные физика и технологии
Отделение ядерно-топливного цикла

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
Исследование влияния повышения мощности реактора ИРТ-Т на интенсивность разогрева материалов биологической защиты

УДК 621.039.55:621.039.538

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School of Nuclear Science & Engineering
Field of training: 14.04.02 Nuclear Science and Technology
Specialization: Nuclear Power Engineering
Nuclear Fuel Cycle Division

MASTER THESIS

Topic of research work
Influence of increasing of IRT-T reactor power on intensity of biological shielding heating

UDC 621.039.55:621.039.538

Student

Group	**Full name**	**Signature**	**Date**
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Associate Professor	Luibov Y. Spicyna	PhD		

Section «Social Responsibility»

Position	**Full name**	**Academic degree, academic rank**	**Signature**	**Date**
Associate Professor	Yuriy V. Perederin	PhD		

ADMITTED TO DEFENSE:

Programme Director	**Full name**	**Academic degree, academic rank**	**Signature**	**Date**
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Tomsk – 2022

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
Nuclear Fuel Cycle Division

APPROVED BY:
Program Director
_____________ Verkhoturova V.V.
«____» ____________ 2022

ASSIGNMENT
for the Graduation Thesis completion

In the form:

Master Thesis

For a student:

Group	Full name
0AM0I	Tereshin Ivan Andreevich

Topic of research work:

Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	№ 32-6/c dated February 1, 2022

Deadline for completion of Master Thesis:	06.06.2022

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.)*	– IRT-T reactor biological shielding; – reactor power of 6 MW, 6.6 MW and 10 MW; – biological shielding materials – steel 12X18H10T, Portland cement, AD-1 aluminum alloy, super heavy concrete with densities of 5.2 and 6.2 t/m^3. – IRT-T neutronic model
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).*	– calculation of heat release in the most heat-stressed part of biological shielding; – detailed design of a the most heat-stressed part of biological shielding thermohydraulic modes; – determination of thermal properties of materials biological shielding models at 6 and 6.6 MW reactor power and verification of the model; – determination of thermal properties of materials

	biological shielding models at 10 MW reactor power.
List of graphic material *(with an exact indication of mandatory drawings)*	presentation

Advisors to the sections of the Master Thesis *(with indication of sections)*	
Section	**Advisor**
Financial Management, Resource Efficiency and Resource Saving	Luibov Y. Spicyna
Social Responsibility	Yuriy V. Perederin

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

Assignment issued by a scientific supervisor:

Position	Full name	Academic degree, academic status	Signature	Date
Associate Professor	Artem G. Naymushin	PhD		

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0AM0I	Tereshin Ivan Andreevich		

ASSIGNMENT FOR THE MASTER THESIS SECTION

«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

Student:

Group	Name
0AM0И	Tereshin Ivan Andreevich

School	School of Nuclear Science & Engineering	**Department**	Division for Nuclear-Fuel Cycle
Educational level	Master	**Specialization**	14.04.02 Nuclear Science and Technology

Initial data for the section «Financial Management, Resource Efficiency and Resource Saving»:	
1. The cost of scientific research resources: material, technical, energy, financial, informational and human	*Budget of research not higher than 260000 rubles*
2. Norms and standards for spending resources	*Supervisor' salary – 36174 rubles per month; engineer' salary – 18426 rubles per month; electricity costs – 3.85 rub per 1 kW*
3. The system of taxation used, tax rates, volumes of payments, discounts and loans	*Contributions for social funds are 30.2 % totally; overhead costs are 30 %.*
Problems to research, calculate and describe:	
1. Assessment of the commercial potential of engineering solutions	*Comparative analysis with other researches in this field; SWOT-analysis*
2. Planning of research and constructing process and making schedule for all periods of the project	*Calculation of working hours for project; creation of the time schedule of the project;*
3. Requirement for investments	*Costs calculations*
4. Budgeting an engineering project	*Creation of the project budget*
5. Calculation of resource, financial, social, budgetary efficiency of an engineering project and potential risks	*Integral indicator of resource efficiency for the developed project*
Graphic materials	
1. Competitiveness analysis *2. SWOT matrix* *3. Gantt chart* *4. The budget for scientific and technical research* *5. Assessment of Integral indicator of resource efficiency for the project*	

Assignment date	

Consultant:

Position	Name	Academic degree	Signature	Date
Associate Professor Division for Social Sciences and Humanities School of Core Engineering Education	Spicyna Luibov Yurievna	PhD		

Student:

Group	Name	Signature	Date
0AM0И	Tereshin Ivan Andreevich		

Task for section
«Social responsibility»

To student:

Group	Full name
0AM0I	Tereshin Ivan Andreevich

School	School of Nuclear Science & Engineering	Department	Division for Nuclear-Fuel Cycle
Educational level	Master	Specialization	14.04.02 Nuclear Science and Technology

Topic of research work:

Influence of increasing of IRT-T reactor power on intensity of biological shielding heating	
Initial data for the section «Social responsibility»:	
1. Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application	Distribution of heat release and temperatures in the biological shielding of the IRT-T reactor. Application area: safety of nuclear reactor
The list of subjects to study, design and develop:	
1. Legal and organizational issues to provide safety: – special (specific for operation of objects of investigation, designed workplace) legal rules of labor legislation; – organizational activities for layout of workplace.	– Labor Code of the Russian Federation of December 30, 2001 N 197-FZ (as amended on 01.03.2022); – State standard 55710-2013; – State standard 50948-2001; – State standard 12.0.003-2015; – State standard 12.1.038-82.
2. Work Safety: 2.1. Analysis of identified harmful and dangerous factors; 2.2. Justification of measures to reduce probability of harmful and dangerous factors.	Harmful and dangerous factors: – deviation of microclimate indicators; – exceeding the noise level; – insufficient illumination of the working area; – increased level of electromagnetic radiation; – psychophysiological factors; – danger of exposure to electric current; – fire and explosion hazard.
3. Safety in emergency situations:	– the most likely emergency situation at the workplace is a fire; – also possible: electric shock and falling from the height of your own growth.

Date of issuance of the assignment according to the schedule	

Assignment issued by:

Position	Name	Academic degree	Signature	Date
Associate Professor	Perederin Yuriy Vladimirovich	PhD		

Assignment accepted for execution by a student:

Group	Name	Signature	Date
0AM0I	Tereshin Ivan Andreevich		

TOMSK POLYTECHNIC UNIVERSITY
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School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Science and Technology
Specialization: Nuclear Power Engineering
Level of education: Master degree program
Nuclear Fuel Cycle Division
Period of completion: spring semester 2021/2022 academic year

Form of presenting the work:

Master Thesis

SCHEDULED ASSESSMENT CALENDAR
for the Master Thesis completion

Deadline for completion of Master's Graduation Thesis:	06.06.2022

Assessment date	**Title of section (module) / type of work (research)**	**Maximum score for the section (module)**
02.02.2022	Development of research assignment	
28.02.2022	Literature Review	
21.03.2022	Preparation of the model of the IRT-T reactor in MCU-PTR software	
25.04.2022	Preparation and verification of the biological shielding model of the IRT-t reactor in Solidworks Flow Simulation	
11.05.2022	Preparation of the results and report submission	
30.05.2022	Defense preparation	

COMPILED BY:
Scientific supervisor:

Position	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Associate Professor	Artem G. Naymushin	PhD		

APPROVED BY:

Program Director	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Nuclear Power Engineering	Vera V. Verkhoturova	PhD		

Abstract

The final qualification work contains 103 pages, 22 figures, 31 tables, 39 sources and 5 appendixes.

Key words: IRT-T, research reactor, biological shielding, energy release, MCU-PTR, SolidWorks Flow Simulation, thermal hydraulics. The object of study is the biological shielding of IRT-T reactor.

The aim of the work is to evaluate biological shielding part of the IRT-T reactor from the point of view of neutronic and thermohydraulic analysis under the new improved heat flux density conditions.

In process of the research MCU-PTR and SolidWorks software used for neutronic and thermohydraulic analysis correspondingly. Part of IRT-T reactor biological shielding model created. Thermal analysis of prepared SolidWorks model under new reactor power performed. As a result of the work, temperature distributions in the part of biological shielding most susceptible to heating under normal and power increase levels was obtained. Maximal temperatures of the shielding materials and maximal temperature difference in them were evaluated. Based on the results obtained, the possibility of operating the IRT-T reactor at a capacity of 10 MW was justified.

Application area: Academic, Nuclear Industries.

Contents

Introduction

Research reactors are nuclear reactors used for research, development, education and training. They produce neutrons for use in industry, medicine, agriculture and forensics, among others [1].

Nowadays, research nuclear reactors are actively used as a neutron source with high flux neutron beam around the world for a variety of purposes, including basic research in the field of physics, as well as practical applications in the field of industrial isotope production and activation analysis [2]. One of them is the IRT-T research reactor, situated in Tomsk.

The main purpose of using IRT-T is to produce neutron beams with a high neutron flux density for irradiation of various materials in experimental channels. Therefore, one of the prospective directions of modernization of this reactor is to increase the neutron flux density achieved during its operation. However, these changes are also proportional increase in the density of the gamma radiation flux, which is the main source of energy release in biological shielding. So, it is possible to achieve and exceed the operational limits for biological shielding materials. At the moment, the issue of increasing the capacity of the IRT-T reactor from 6 MW to 10 MW is being considered.

The main aim of the work is to determine the possibility of IRT-T reactor biological shielding to withstand the reactor operation at increased power from the point of thermodynamic analysis.

In order to achieve this aim, it is necessary to solve the following tasks:

– to perform an analysis of data on the modernization of nuclear reactors;

– to detail MCU reactor model for calculation of heat release density in the most heat-stressed part of biological shielding;

– to create and verify model of the most heat-stressed part of biological shielding in SolidWorks Flow Simulation;

– to make calculations in prepared models for a reactor power of 10 MW;

– analyze the data and make an appropriate conclusion.

1 Research reactors modernization

To date, significant experience has been accumulated in the modernization of research reactors, accompanied by an increase in their capacity. Based on this experience, it is possible to classify the main modernization methods used, as well as identify potential challenges.

1.1 Research reactors modernization experience

An example of the reactor modernization without significant changes in its design is the transition to the operation of VVER-440 reactors at a power level of 107 – 109 % of the nominal. The VVER-440 reactor plant of the V-213 project is designed using refined engineering coefficients of the reserve of thermal parameters, which allow, taking into account the experience of operation, to reduce conservatism and increase thermal power. The neutronic and thermohydraulic characteristics of the core of the operating power units of the B-213 project are such that the actual (calculated and measured) coefficients of uneven energy release for fuel cartridges and fuel rods are usually less than the maximum design and limit values. This factor was a real reserve for boosting power.

As a result of improvements in the design of fuel cassettes and calculation codes, fuel cycles have been developed that allow the reactor to operate at an increased thermal capacity of 105 – 112 %. A comparison of the characteristics of basic and advanced fuel cartridges is presented in Table 1.1. Currently, the power units of Lovisa NPP (Finland) are operated at increased capacity – by 109 % (1500 MW with the number of fuel cassettes in the core reduced to 313), Paks NPP (Hungary) – by 108 %, Dukovany NPP (Czech Republic) – up to 105 %, Bogunice and Mokhovce NPP (Slovakia) – up to 107 %, as well as the power units of Kola NPP [3].

Another example of increase of reactor power is start of operation of the VVER-1000 Balakovo NPP at power level of 104 % of nominal. To ensure the possibility of this mode of operation, the control and regulation facilities were upgraded, and the permissible errors and dynamic characteristics of the measuring channels were ensured. The main parameters of the second power unit of the Balakovo NPP with increasing capacity are presented in Table 1.2.

Table 1.1 – The characteristics of basic and advanced fuel cartridges of VVER-440

Fuel Assembly Parameter	Original fuel assembly	Modern fuel assembly
Construction material	Zr (Hf < 0.05 %)	Zr (Hf < 0.05 %)
Cover Material	Zr (Hf < 0.05 %)	Zr (Hf = 0.01 %)
Burnable absorber	–	UO_2–Gd_2O_3
Enrichment profiling in the plane: – horizontal – axial	 Is present Absent	 Is present Absent
The mass of the UO_2 in the fuel rod, rel. units.	1.00	1.05
Diameter of the axial perforation, rel. units.	1.00	0.86
The height of the fuel column, rel. units.	1.00	1.02
Step of fuel rods in the beam, rel. units.	1.00	1.01
External diameter of fuel rod, rel. units.	1.00	1.00
Maximum permissible fuel enrichment, %	4.40	4.60

One of the main conditions for the operation of the reactor core is the preservation of the integrity of the fuel element shells. For this purpose, the prevention of critical heat flow at all points of the core is controlled by means of the SVRK. With increasing power, the reserve before the heat exchange crisis decreases, but its minimum value does not decrease less than the regulatory 1.35.

Table 1.2 – Parameters of the second power unit of the Balakovo NPP with increasing capacity

Parameter	100 % of rated power	104 % of rated power	Routine values for 104% of rated power
Thermal power, MW	3000	3126	3120±60
Coolant, ºC:			
– heating in the reactor	29.2	30.6	32.0
– maximum heating in the loop	29.9	30.9	33.0
– maximum heating in the fuel assembly according to SVRK indications	37	38.5	43.3
– maximum temperature at the reactor inlet	287.9	289.4	290.0
Maximum coefficient of nonuniformity of energy release:			
– fuel assembles according to the indications of the SVRK	1.27	1.28	1.35
– the volume of the core according to the indications of the SVRK	1.41	1.44	1.86

Tests confirmed the possibility of stable operation of the second power unit of Balakovskaya NPP at an increased power level when all the envisaged changes are made to the operation of the reactor and turbine departments in accordance with the developed design and operational documentation. Neutronic and thermohydraulic characteristics are within the specified limits. So, when increasing the power to

104 % nominal reserve before the heat exchange crisis is not reduced less than the regulatory 1.35. The current coefficients of nonuniformity of energy release in the core volume do not exceed maximum allowed values. Underheating of the coolant and energy release in the most loaded fuel assemblies is below the permissible values [4].

Power of the liquid sodium-cooled experimental fast reactor JOYO (Japan) was also increased from 100 MW to 140 MW by forcing the flow rate of the coolant in primary and secondary circuit by 20 and 10%, respectively [5, 6].

The power of RA-3 research reactor (Argentina) was increased from 5 to 10 MW by introduction of an additional pump and heat exchanger in the primary circuit (the flow rate of the coolant increased from 950 to 1350 m^3/h, as well as an additional cooling draft-forced tower [7].

Increasing the reactor power was carried out at the VVR-SM reactor. The VVR-S research reactor with a capacity of 2 MW, built at the INP of the Academy of Sciences of the Republic of Uzbekistan, reached criticality in September 1959. The reactor used fuel assemblies with rod-type fuel rods with a diameter of 10 mm (EK-10), with fuel enriched with ^{235}U to 10%. The core of the fuel element with a diameter of 7 mm was a rod made of uranium dioxide in a magnesium matrix. The fuel element cladding is an aluminum alloy SAV-1. Fuel assemblies were placed in 52 cells.

In 1971, the RSC «Kurchatov Institute» developed a project for the reconstruction of the VVR-S based on the use of IRT-2M fuel assemblies with tubular fuel elements and 90 % enrichment of fuel. The reconstruction of the VVR-S, carried out at the end of 1971 with the replacement of the core body and the reflector, made it possible to increase its power from 2 to 10 MW. In 1979, VVR-SM began to use fuel assemblies of the IRT-3M type (Figure 1), also with fuel of 90 % enrichment. Their heat transfer surface is twice as high as the IRT-2M fuel assembles [8].

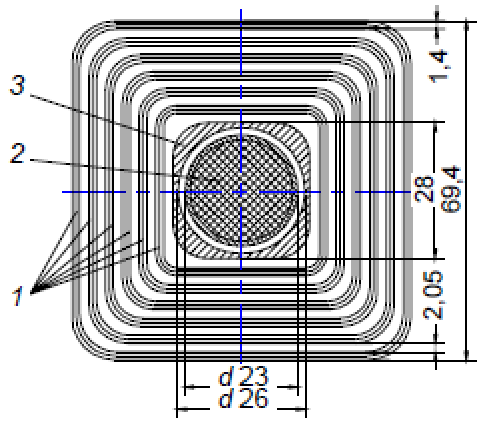

Figure 1.1 – Horizontal section of fuel assemblies IRT-3M type: 1 – fuel rods; 2 – control rod; 3 – channel

The transition of basin reactors, such as IRT-T, to a new type of fuel assemblies allowed to increase their capacity by more than 1.5 times. However, a further increase in the compactness index is limited by the minimum thickness of the fuel element cladding, which is determined by the permissible probability of fission products entering the coolant, as well as the thermomechanical resistance of fuel elements and the erosion properties of their cladding materials. In addition, a possible reduction in the inter-shaft gaps and the flow section will lead to an increase in the hydraulic resistance of the coolant path and, consequently, the power to pump it. The inability to boost the power of the pumps will cause a decrease in the flow rate of the coolant and the heat transfer coefficient, which will not be compensated by an increase in the compactness index. The introduction of additional absorbing cladding material into the core will lead to a deterioration in the physical characteristics and increase the cost of operating research reactors.

Therefore, further reserves of increasing the power of research reactors can be associated with the intensification of heat removal from the surface of fuel rods due to an increase in the heat transfer coefficient, provided that the power for pumping the coolant remains unchanged [9].

1.2 Modernization information analysis

As can be seen from the examples considered, an increase in the power of a nuclear reactor is always associated with an intensification of heat removal and reduction of thermal loads on reactor materials. At the same time, all modernization methods can be divided into three groups.

The first group includes methods of physical optimization aimed at reducing the coefficients of unevenness (profiling fuel loading, reducing its enrichment, using absorbers and burn-out additives, optimizing the position of compensating bodies, etc.).

The second group includes methods of forcing the flow rate of the coolant and its hydraulic profiling in order to increase the heat transfer coefficient, as well as lower the input temperature and increase the pressure in the circuit, i.e. essentially methods that require a global reconstruction of the heat sink system.

The third group includes improvements in fuel rod and fuel assembly designs aimed at increasing the compactness of the core [9].

1.3 The impact of increasing power on operation of biological shielding

During the fission of uranium nuclei in a nuclear reactor, the following types of particles are formed:

– fission fragments;

– instantaneous and delayed neutrons;

– beta particles and antineutrinos;

– instantaneous and delayed gamma quanta [10].

The energy released in the fission reaction is distributed among the reaction products as follows: fission fragments account for an average of 150 – 180 MeV, neutrons – 5 – 6 MeV, beta decays emit 10 – 15 MeV, and gamma quanta carry away energy approximately equal to 10 MeV.

When neutrons slow down and gamma rays weaken in the biological shielding of the reactor, a significant part of the radiation energy is converted into heat, and the main part of this heat is released in the inner layer of shielding, which has a small thickness.

In addition, the biological shielding and lower support structures of the reactor are heated as a result of heat transfer from the reactor core located in the immediate vicinity of these reactor elements. If these elements are not artificially cooled, their temperature will increase until the amount of heat removed by radiation, thermal conductivity, or convection balances the amount of heat supplied. In this case, there may be cases of destruction of structures made of insufficiently heat-resistant materials, from excessive or uneven heating, as well as due to uneven thermal expansion of materials.

The most common material for shielding of stationary nuclear reactors is various types of concrete. Along with positive properties, concrete has a disadvantage – low thermal conductivity, which makes it difficult to remove heat from it. In addition, concrete can be destroyed by heat shocks (sudden changes in temperature. Therefore, when constructing concrete protection against radiation from nuclear reactors, the question of changing the mechanical properties of concrete under the influence of temperature and radiation becomes of great importance.

In the course of research, it was found that for most types of concrete used in the biological shielding of reactors, the temperature at which there is no need to intensify its cooling or use additional heat shielding during operation does not exceed 250 °C.

At high radiation intensity, large temperature differences and, consequently, stresses can occur in the concrete, forcing special reinforcement of it. Thus, we can distinguish the following operational limits for the materials used [11]:

– maximum operational temperature equal to 250 °C;

– maximum temperature gradient equal to 2.5 °C/cm (for Portland Cement);

– maximum temperature gradient equal to 4.5 °C/cm (for heavy concrete).

2 Theoretical part

2.1 IRT-T basic features and characteristics

The IRT-T reactor (research reactor type) is a pool-type reactor in which desalinated water is used as a moderator, coolant and upper biological shielding. The main characteristics of this reactor are presented in Appendix A in Table A.1.

The layout of the main elements of the reactor is shown in the Appendix B in the Figure B.1. The reactor core is located in a pool filled with desalinated water. The core center is located at a depth of 6.5 m. The core body is made of aluminum alloy AD-1. The support grid is made of SAV-1 alloy in the form of a rectangular plate with dimensions of 940×721×85 mm. The upper core housing together with the supporting grid are mounted on a 29 mm thick stainless-steel flange. The flange is welded to the sheets of the built-in holding tank and rests additionally on 6 racks made of pipes with a diameter of 108×5 mm. The racks are welded to the bottom of the stainless-steel base plate. The lower grid for the control rods channels is welded to the base plate from above. A titanium gasket is installed between the core support spacer and the stainless-steel flange. The base plate and bottom grid of the core protect the concrete under the bottom of the tank from radiation heating. Titanium gaskets are installed at the contact points of parts made of aluminum alloys and stainless steel to prevent aluminum corrosion.

Fuel assemblies, beryllium reflector blocks, neutron trap blocks, and displacers are installed on the support grid. At the top, all these devices are spaced by special lugs on their end parts. The core housing has 56 cells for the installation of fuel assemblies and beryllium blocks. The four central cells are occupied by beryllium blocks, forming a neutron trap. In the core, IRT-3M type fuel assemblies are used – eight-pipe and six-pipe. These fuel assemblies use square tubular fuel rods with a wall thickness of 1.4 mm. The thickness of the cladding made of aluminum alloy SAV-1 is 0.5 mm each. The fuel element core is made of uranium dioxide in an aluminum matrix. Inside the eight-pipe fuel assembly, a displacer with an outer diameter of 14 mm is installed. Inside the six-pipe fuel assembly, either a channel with a control rod or an experimental channel with an outer diameter of 28 mm is installed.

The reactor core is formed by a set of 11 eight-tube and 9 six-tube fuel assemblies respectively, position of which is shown in Figure 2.1. The enrichment of fresh fuel is equal to 90 %.

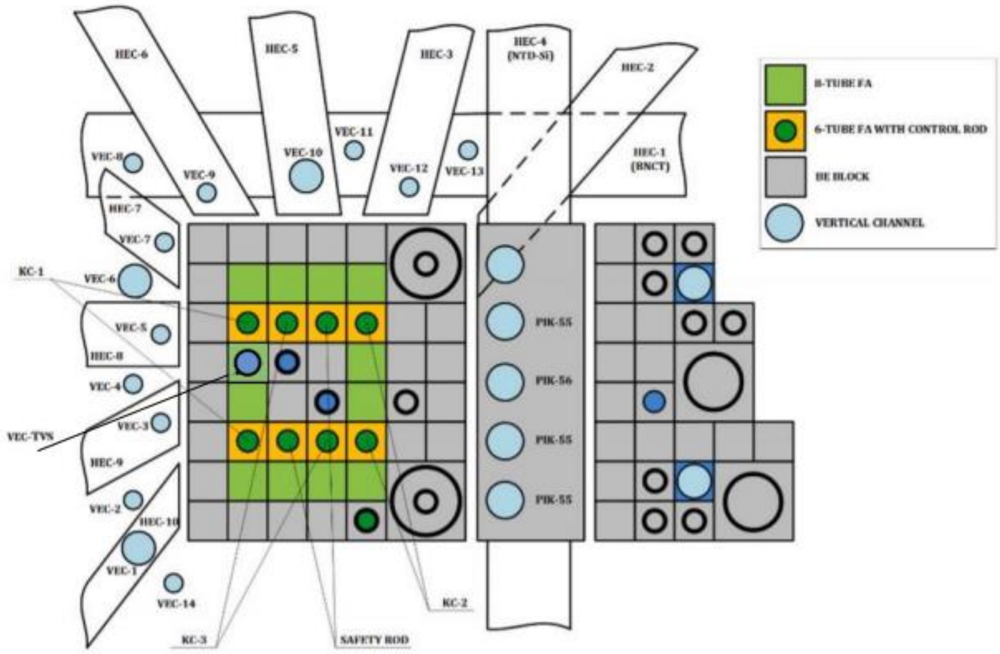

Figure 2.1 – Design of IRT-T reactor core

The side reflector if formed using beryllium blocks with a square cross-section of 69×69 mm and two beryllium blocks with a size of 138×138 mm.

There are nine control rods, place in channels if six-tube fuel assemblies and reflector: three groups of shim rods (two rods in the group) named KC-1, KC-2 and KC-3, two scram rods named AZ-1 and AZ-2, and one regulating rod named AR.

Biological shielding of the reactor in the radial direction at the core level includes water (60 mm) and heavy concrete with densities of 6.5 t/m^3 (200 mm) and 5.2 t/m^3 (1600 mm). The upper part of the radial biological shielding above the core level is made of ordinary concrete with a density of 2.3 t/m^3. Above the core, shielding is provided by a layer of water with a height of 6500 mm. Below the core, a layer of water 500 mm thick and steel plates with a total thickness of 60 mm serve as shielding.

The main technological equipment of the reactor – pipelines, primary circuit pumps, heat exchangers, holding tank, primary circuit water purification filters are located in basements with heavy concrete floors up to 600 mm thick.

The mine-storage of spent fuel assemblies is buried to the level of –1.72 m, has a side shielding of heavy concrete. On top of the fuel assembly is a layer of water 5500 mm.

The reactor cooling system ensures the removal of heat generated in fuel assemblies and other elements of the reactor both in normal operating modes at power and during shutdowns, and in emergency situations. The reactor cooling system consists of a first circuit filled with desalinated water, and a second reverse circuit where the heat is removed in the cooling tower, as well as a cooling circuit of the biological shielding heat shield.

The fuel assemblies and the reflector are cooled by pool water pumped through the fuel assemblies and the gaps between the reflector blocks by two primary-circuit centrifugal pumps operating in parallel. To avoid overflow of the pool, there is an overflow hole in the upper part of the pool. The water level is controlled.

The internal metal lining of the reactor pool is a 12X18N10T stainless steel tank. The thickness of the tank walls is 5 mm, the bottom of the tank is 10 mm. This steel is practically not subject to corrosion. Tank's length is 4.3 m, width is 8 m and depth is 7.725 m. The stainless-steel tank is placed in the former aluminum tank. The space between them is filled with a solution of Portland cement. In the area of horizontal experimental channels, a coil for cooling concrete is installed in the gap between the banks. It is connected to the reactor protection cooling system. In the upper part of the pool, the gap between the banks is used as a ventilation manifold to evenly remove air from the space between the flooring and the water, for which there are holes in the tank along the perimeter.

To drain water from the pool, there is a drainage pipe that works on the principle of a siphon. One end of the pipe is lowered to the bottom of the tank, the second reaches the upper water level. To prevent accidental discharge of water from the pool, the upper end of the siphon pipe is always open the valve on the drain pipe is plugged and sealed.

To exclude the overflow of water from the pool into the channels of special ventilation of the above-reactor space, there is an overflow device in the tank with the output of the pipeline to the special sewerage system.

The lower part of the tank at a distance of 420 mm from the bottom is covered with 14 mm thick stainless-steel sheets. Thus, a combined holding tank with a volume of 3.8 m^3 was created. Its sheets are supported by 15 racks of pipes with a diameter of 108 mm and a sheet with a thickness of 14 mm, mounted along the longitudinal axis of the tank. Natural circulation valves are installed in the sheets of the holding tank.

The pool water, having passed the active zone from top to bottom, enters the combined holding tank, from where it enters the external holding tank with a volume of 24 m^3 with internal partitions extending the path of water movement through a suction pipeline with a diameter of 410 mm. The purpose of the holding tank is to weaken the induced activity of water by short-lived isotopes.

Water from the holding tank is pumped into five heat exchangers. The material of the pumps is titanium alloys, the heat exchangers are stainless steel. The maximum pressure generated by the pumps is 0.4 MPa. In parallel with the main pumps, an emergency cooling pump is installed with power supply from the rectifier and in parallel from the batteries.

Leakage of water from the first circuit to the second circuit in the case of depressurization of the heat exchange tubes is excluded due to the fact that a higher pressure is maintained in the second circuit: in the first 0.23 MPa, in the second 0.29 MPa.

The heated water of the second circuit enters the cooling tower, where the heat is discharged into the atmosphere. The cooling tower reduces the water temperature from 30 to 20 °C (the decrease depends on the outside temperature). Emergency filling of the reactor tank with technical water is also provided from the second circuit system.

Cooling circuit of biological shielding is designed to remove heat generated in the biological shielding of the IRT-T reactor. The system is filled with demineralized water. The water heated in coils made of stainless pipes Ø 38x3 and Ø 32x3 and poured into concrete tank bottom and walls at depth 200 mm, as well as around the gates, is supplied via a pipeline Ø 50 mm to the pump type X20/31, located in the second circuit pumping room. The pump capacity is 20 m^3/h at a pressure of 0.32 MPa. A valve is installed on the suction line of the pump, and a check valve and a valve with manual control. After the pump, the demineralized water enters the T-6 water-water heat exchanger with a heat exchange surface of 1.5 m^2, where it is cooled by second-circuit technical water. Then the cooled water is fed through a pipe Ø 57x3 to the cooling coils [12].

2.2 MCU-PTR

The Monte Carlo method makes it possible to estimate the functionals of neutron and photon fluxes, including the heat release in materials, simultaneously with the evaluation of the criticality parameters. For this purpose, the contribution to the desired functional is determined in the simulation process for each collision of a particle with the nucleus.

The MCU-PTR program is designed to simulate the processes of neutron and photon transfer by analog and non-analog Monte Carlo methods, based on estimated nuclear data РОСФОНД in systems with three-dimensional geometry, taking into account changes in the isotopic composition of materials. This program allows to calculate the neutronic characteristics of research reactors or of their fragments based on the Monte Carlo method taking into account burnup of fuel, absorber in control rods, poisoning of beryllium reflector and movements of control rods. It is based on MCU-5 package which provides the possibility of full-scale modeling of cores of such reactor types as VVER, RBMK, etc., and supports parallel computing [13].

The program allows to simulate systems consisting of volumetric elements of almost arbitrary shape. The geometrical module of the program uses a combinatorial approach based on the description of complex spatial forms by combinations of simple bodies and surfaces using the operations of intersection, addition, and union. There is a certain set of types of body primitives. For each such type of body, parameters are set that completely describe the shape of a particular body and its position in space. In the geometric module, it is possible to specify lattices, which are obtained by multiplying some of the initial elements specified using combinatorics. In the NCG module, in addition to representing repeating geometric objects using grids, so-called networks are introduced. The network element is not multiplied during the input process, the trajectory inside it is calculated in the local coordinate system. Thus, the hierarchy of geometric objects is partially preserved in the counting phase. This saves a lot of memory, but requires the use of local coordinate systems in the calculation. In the NCG module, the network always consists of elements with the same external shape and tightly adjacent to each other. Coordinate transformations are reduced to shifts and do not slow down the calculation.

When describing zones by the method of combinatorial geometry, all their boundaries consist of pieces of planes or quadratic surfaces, so if there are parts with more complex boundary surfaces, they must be approximated by a very large number of zones.

The constant software support is the MDBTP50 library.

The program has a modular structure and is composed of the following modules:

– a control module that performs the functions of a monitor;

– a transport module simulating particle trajectories in the system;

– a composite physical module, designed to draw the interaction of particles with matter on the basis of the library MDBTP50;

– a geometric module simulating the straight sections of the trajectories between collisions;

– a registration module that allows you to calculate a wide range of neutron flux functionalities;

– a source module that simulates the phase coordinates of the source particles (or zero-generation neutrons when solving criticality problems);

– a hardware module that includes programs that may depend on the type of computer and operating system;

– burnup module, which allows calculating changes in the isotopic composition of reactor materials during the campaign.

The physical module of the program allows modeling collisions of particles with matter on the basis of the listed systems of constants, and it is possible to use various models of the interaction of neutrons and photons. The program allows to take into account the effects of continuous changes in the energy of the particle during collisions, as well as both the continuous and stepwise dependence of the cross sections on the energy.

When modeling neutron transport, the following effects are taken into account:

– when generating fission neutrons, it is allowed to use the fission spectrum of instantaneous and delayed neutrons.

– in the fast energy domain, the anisotropy of elastic scattering in the center-of-mass system is taken into account, and it is possible to simulate inelastic collisions taking into account the laws contained in the estimated nuclear data files.

– in the region of unsolvable resonances, the cross sections are calculated using subgroup parameters or using Bondarenko f-factors, in both cases taking into account the temperature dependence of the parameters used.

– in the region of resolved resonances, both subgroup and pointwise cross-section descriptions are allowed. The cross sections of the most important nuclides are described by an infinite number of points, since they are calculated from the resonant parameters at each energy point in the simulation. This scheme makes it possible to perform calculations directly using data on resonant parameters without preliminary preparation of cross-section tables and to evaluate temperature effects through analytical cross-section dependences on temperature.

– the simulation of collisions in the field of thermalization is carried out either in the multi-group transport approximation, or by the model of continuous energy change, taking into account the correlations between the change in energy and the angle during scattering. In both cases, the chemical bonds, the thermal motion of the nuclei, and the coherent effects for elastic scattering are taken into account.

The photon generation in (n,γ) reactions is modeled by the PHOTON submodule (according to the PHOTONS library). Modeling of the interaction of photons with matter is carried out by the PHOTON submodules (according to the PHOTONT library) or GAMMA (according to the PHOTDATA and SHELLDATA libraries).

The following effects are taken into account when modeling the photon transport in them:

– the generation of an electron-positron pair by a gamma quantum (photon) in the field of the atomic nucleus;

– scattering of a gamma-ray quantum on an electron of the medium, which (at a gamma-ray energy > 10 keV) can be considered free (Compton scattering);

– absorption of a photon by one of the electrons of an atom, followed by the departure of this electron and the emission of a series of soft photons by the remaining electrons as a result of the transition to the released lower shells (photoelectric absorption, photoelectric effect).

In the geometric module, it is possible to register particle hits in the registration areas, as well as the presence or absence of particle reflections in these areas. Registration areas are defined as material zones, registration zones, or registration objects. The registration module prints the flow values and the standard set of flow functionals, as well as their root-mean-square deviations and, on demand, the root-mean-square deviations of the variances and the asymmetry coefficients.

To output the results of the calculation of the absorbed energy due to the interaction of photons with matter, the MPHEN, ZPHEN, OPHEN maps are indicated in the general parameters section of the registration module, which determine the numbers of the registration areas (respectively, materials, zones and objects) in which the calculation is performed. In this case the result is given in eV in the registration region for one neutron born in the system [14].

2.3 SolidWorks mathematical model

SolidWorks Flow Simulation program software is applying the Navier-Stokes equation for modelling the flow (liquid or gas) direction and heat exchange. Laws of the mass, momentum and energy conservation have the following form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial\left(\rho \cdot u_i\right)}{\partial x_i}=0; \tag{2.1}$$

$$\frac{\partial\left(\rho \cdot u_i\right)}{\partial t}+\frac{\partial\left(\rho \cdot u_i \cdot u_j\right)}{\partial x_j}+\frac{\partial P}{\partial x_i}=\frac{\partial\left(\tau_{ij}+\tau_{ij}^R\right)}{\partial x_j}+S_i; \tag{2.2}$$

$$\frac{\partial\left(\rho \cdot H\right)}{\partial t}+\frac{\partial\left(\rho \cdot u_i \cdot H\right)}{\partial x_i}= \tag{2.3}$$

$$=\frac{\partial\left(u_j \cdot\left(\tau_{ij}+\tau_{ij}^R\right)+q_i\right)}{\partial x_i}+\frac{\partial \rho}{\partial t}-\tau_{ij}^R \cdot \frac{\partial u_i}{x_j}+\rho \cdot \varepsilon+S_i \cdot u_i+Q_H;$$

$$H=h+\frac{u^2}{2}, \tag{2.4}$$

where u – velocity of the medium;

ρ – density of the medium;

P – pressure of the medium;

S_i – external mass forces acting on unit of mass of the fluid;

H – full energy of the unit of mass in the medium volume;

τ_{ij} – viscous shear stress tensor;

q_i – diffusion heat flux.

These equations are supplemented by the equation of state of a gaseous medium or liquid and the dependences of density, viscosity, heat capacity and thermal conductivity on temperature. To determine the turbulent viscosity and kinetic energy of turbulent fluctuations, which enter into the equation for the viscous shear stress tensor, the two-parameter turbulence model *k–ε* is used.

Heat transfer in solid bodies is simulating with standard equation that derived from the Fourier's conduction law:

$$\frac{\partial \rho \cdot c \cdot T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_i \cdot \frac{\partial T}{\partial x_i} \right) + Q_H, \qquad (2.5)$$

where c – specific heat capacity;

T – temperature;

λ_i – heat conductivity coefficient.

Heat transfer in solid bodies is simulating with standard equation that derived from the Fourier’s conduction law:

$$Q_H = \varepsilon \cdot \sigma_0 \cdot \left(T_w^4 - T_s^4\right), \qquad (2.6)$$

where ε – emissivity factor;

σ_0 – Stefan-Boltzmann's constant;

T_w – temperature of the surface;

T_s – temperature of the environment (fluid medium).

To discretize the resulting system of differential equations, SolidWorks Flow Simulation uses the finite volume method. The object of study is presented in the form of a grid model, the cells of which are in the form of parallelepipeds (the values of independent variables are calculated at the centers of the cells, and mass, momentum, and energy flows are calculated on the faces of these cells). For each cell, linearized equations are written that describe the laws of conservation of the studied scalar physical quantity [15].

2.4 Stainless steel 12X18H10T

12KH18H10T is a high-carbon, corrosion-resistant, non-magnetic, titanium containing steel. It belongs to complex alloyed alloys of the austenite group. Due to the presence of chromium and nickel in the alloy, this steel is also called stabilized chromium nickel steel. To date, it is the most used and widespread steel of all grades of stainless steel. Due to its resistance to aggressive media (except for sulfur-containing media) it is in demand in the chemical industry – in the production of vessels operating under high pressure. Pipelines for transportation of dilute solutions of phosphoric, nitric, acetic acids, aggressive bases and salts, pipes for connection of the equipment with the increased radiation are often made of steel 12X18H10T.

The thermal conductivity and heat capacity of steel in the range from 20 to 100 °C can be assumed to be equal to $\lambda_{st} = 16.4$ W/m·K and $c_{st} = 470$ J/kg·K. The density of steel is equal to $\rho_{st} = 7900$ kg/m^3 [16, 17].

2.5 Aluminum alloy AD-1

AD-1 alloy is a technical aluminum that is only pressure-hardened. It has high anti-corrosion performance and high ductility, but its strength is low. A huge number of 10 semi-finished products are produced from technical aluminum of this brand. It is well deformed, poorly cut and perfectly amenable to all types of welding. The purity of technical aluminum guarantees its high anti-corrosion properties, so it is often used as a plating material for less corrosion-resistant high-strength aluminum and duralumin alloys. This alloy contains at least 99.3 % aluminum.

The thermal conductivity and heat capacity of AD-1 alloy in the range from 20 to 100 °C can be assumed to be equal to $\lambda_{AD} = 220$ W/m·K and $c_{AD} = 1000$ J/kg·K. The density of steel is equal to $\rho_{AD} = 2700$ kg/m^3 [18].

2.6 Portland cement and super heavy concretes

The space between them is filled with of Portland cement. According to [19], the density of rammed Portland cement can reach $\rho_{PC} = 1700$ kg/m^3. According to [20] the density of rammed Portland cement can reach, the heat capacity and thermal conductivity are equal to $\lambda_{PC} = 0.3$ W/m·K and $c_{PC} = 800$ J/kg·K.

Biological shielding of the reactor at the core level includes two types of super heavy concrete with densities of $\rho_{HC1} = 5200$ and $\rho_{HC2} = 6500$ kg/m^3.

As the main binding component for them the Portland cement was used. To achieve a high density of concrete and improve its protective properties, cast iron was chosen as a filler. The density of cast iron is equal to $\rho_{CI} = 7000$ t/m^3. The heat capacity and thermal conductivity of cast iron are equal to $\lambda_{CI} = 46$ W/m·K and $c_{CI} = 500$ J/kg·K [21].

The heat capacity and thermal conductivity of concrete can be calculated based on the formulas [22]:

$$c_i = \frac{\varphi_i \cdot c_{CI} \cdot \rho_{CI} + c_{PC} \cdot \rho_{PC} \cdot (1-\varphi_i)}{\rho_i}, \tag{2.7}$$

$$\lambda_i = \frac{\lambda_{CI} \cdot \lambda_{PC}}{\varphi_i \cdot \lambda_{PC} \cdot + \lambda_{CI} \cdot (1-\varphi_i)}, \tag{2.8}$$

where ρ_i – density of final concrete;

φ_i – volume fraction of cast iron in concrete, which can be obtained from equation:

$$\rho_i = \rho_{CI} \cdot \varphi_i + \rho_{PC} \cdot (1-\varphi_i). \tag{2.9}$$

The results of calculation of super heavy concretes properties are presented in Table 2.1.

Table 2.1 – Properties of super heavy concretes

Parameter	$\rho_{HC1} = 5200$ kg/m^3	$\rho_{HC2} = 6500$ kg/m^3
φ_i	0.660	0.906
c_i, J/kg·K	533.3	507.4
λ_i, W/m·K	0.87	2.99

3 Practical part

Due to the fact that the above operational limits applicable to concrete are associated with determining its maximum temperature, as well as the maximum temperature drop, it was decided to model only its most heat-stressed region.

3.1 Estimation of heat release distribution in biological shielding

The model of the IRT-T reactor core (Figure 3.1) is based on the design, presented in Figure 2.1. It includes 9 six-tube and 11 eight-tube fresh fuel assemblies with fuel enrichment of 90 %, safety, control rod, side beryllium reflector and HEC-4. The fuel matrix of each fuel assembly in the model is divided into 6 layers to allow tracking the altitude component of the flow.

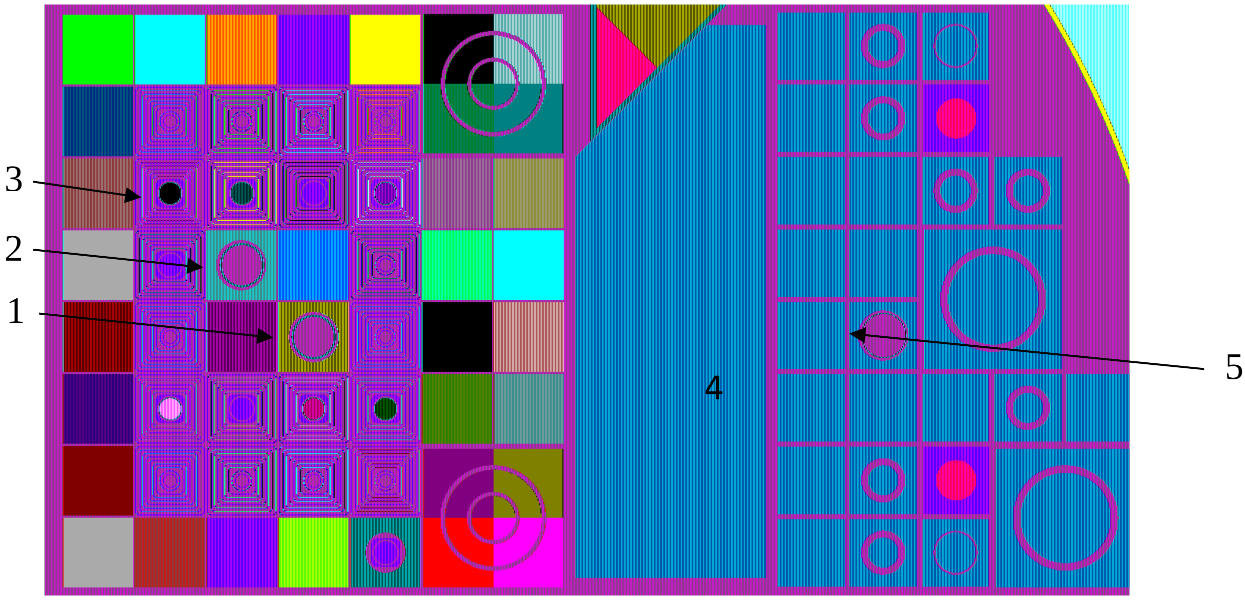

Figure 3.1 – IRT-T reactor core cross-section in MCU-PTR software:
1 – inner beryllium reflector, 2 – fuel assemblies, 3 – outer beryllium reflector, 4 – HEC-4, 5 – inner heat assembly

The first stage in the preparation of a detailed model of biological protection was to determine the form of heat release distribution in its the most stressed area.

According to [23], the shape of the gamma radiation power distribution on the shielding surface in height repeats the shape of the neutron flux density distribution in the core, which has the form:

$$\Phi = \Phi_0 \cdot \cos\left(\frac{\pi \cdot z}{H_{core}}\right), \qquad (3.1)$$

where Φ_0 – maximum neutron flux density in the core;

H_{core} – effective height of the core;

z – distance from the core center.

At the same time, the density of the gamma radiation flux has a maximum value on the protection surface and decreases with distance from it.

Taking into account the concrete temperature measurement data, it was decided to study the zones shown in Figure 3.2 and Figure 3.3.

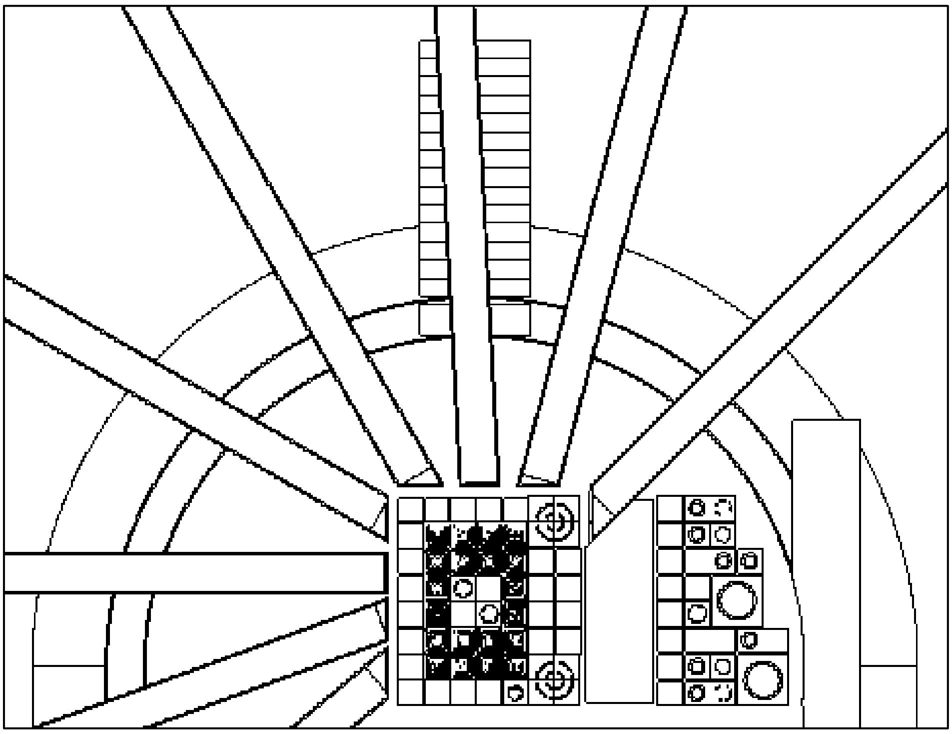

Figure 3.2 – Radial zoning of concrete at the core center level

The zones in Portland cement have a width of 30 cm, a height of 10 cm and a thickness of 8.5 cm. At the same time, the zones in heavy concrete have a height of 20 cm and a thickness of 5 cm.

The study of the distribution of the energy release density was carried out at a capacity of 6 MW.

To determine the nuclear concentrations of oxygen and hydrogen in the coolant, it is necessary to determine its density. For these purposes, the parameters of the coolant at the inlet and outlet of the core were measured and averaged.

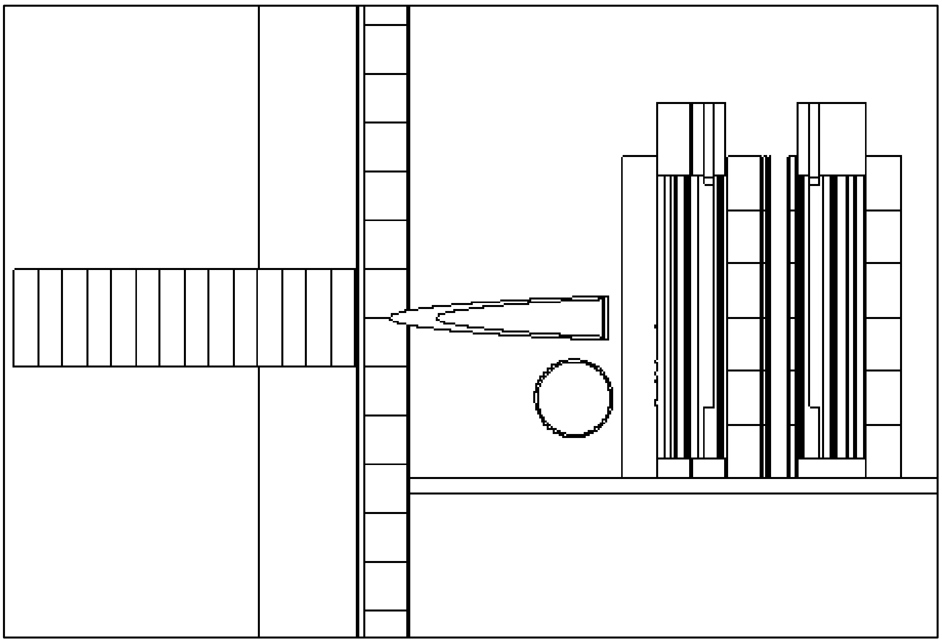

Figure 3.3 – Vertical zoning of concrete at the core center level

Table 3.1 – Parameters of the fluid in IRT-T reactor core for 6 MW calculation

Parameter	Values of measurement's			Mean value
	1	2	3	
Fluid inlet temperature, °C	39.10	39.00	39.50	39.20 ± 0.54
Fluid heating, °C	7.30	7.40	7.10	7.27 ± 0.31
Pressure difference, kPa	29.41	26.70	38.00	34.70 ± 9.38

The temperature of water at the inlet of the core was measured equal to 39.2 °C. The average water heating was 7.27 based on the measurements obtained Thus, the average water temperature can be approximately calculated as:

$$\bar{t} = 39.2 + \frac{7.27}{2} \approx 42.48 \text{ °C}.$$

The coolant pressure at the reactor core outlet is assumed to be 133 kPa. Pressure drop at the core is equal to 34.7 kPa. Then the average pressure in the core is:

$$\bar{p} = 133 + \frac{34.7}{2} = 150.35 \text{ kPa}.$$

Then the density and the concentration of isotopes of the coolant are equal to:

$$\bar{\rho}\left(\bar{t}, \bar{p}\right) = 0.9913 \text{ g/cm}^3$$

$$N_H = 2 \cdot \frac{\overline{\rho}\left(\bar{t}, \overline{p}\right) \cdot N_A}{18} = 2 \cdot \frac{0.9913 \cdot 6.02 \cdot 10^{23}}{18} = 6.63 \cdot 10^{22} \text{ cm}^{-3}$$

$$N_O = \frac{\overline{\rho}\left(\bar{t}, \overline{p}\right) \cdot N_A}{18} = \frac{0.9913 \cdot 6.02 \cdot 10^{23}}{18} = 3.315 \cdot 10^{22} \text{ cm}^{-3}$$

The obtained values of the volumetric energy release density in the zones of Portland cement are presented in Table 3.2. The numbering of zones by height is carried out from the lower to the upper zone.

Table 3.2 – Distribution of energy release density in Portland cement zones by height

Zone	Heat release density, mW/cm^3
1	4.7 ± 0.8
2	5.8 ± 0.7
3	9.2 ± 1.1
4	10.6 ± 1.2
5	15.7 ± 1.6
6	18.4 ± 1.8
7	17.4 ± 1.4
8	15.9 ± 1.6
9	10.5 ± 0.9
10	9.5 ± 0.9
11	6.6 ± 0.6
12	4.4 ± 0.6

Based on the results obtained, an approximate form of the distribution of the energy release density in Portland cement in height is obtained, which is shown in Figure 3.4. As you can see, the shape of the resulting graph is close to the cosine, as expected.

The obtained values of the volumetric energy release density in the zones at core center level are presented in Table 3.3. The numbering of zones is carried out from the shielding surface to the depth.

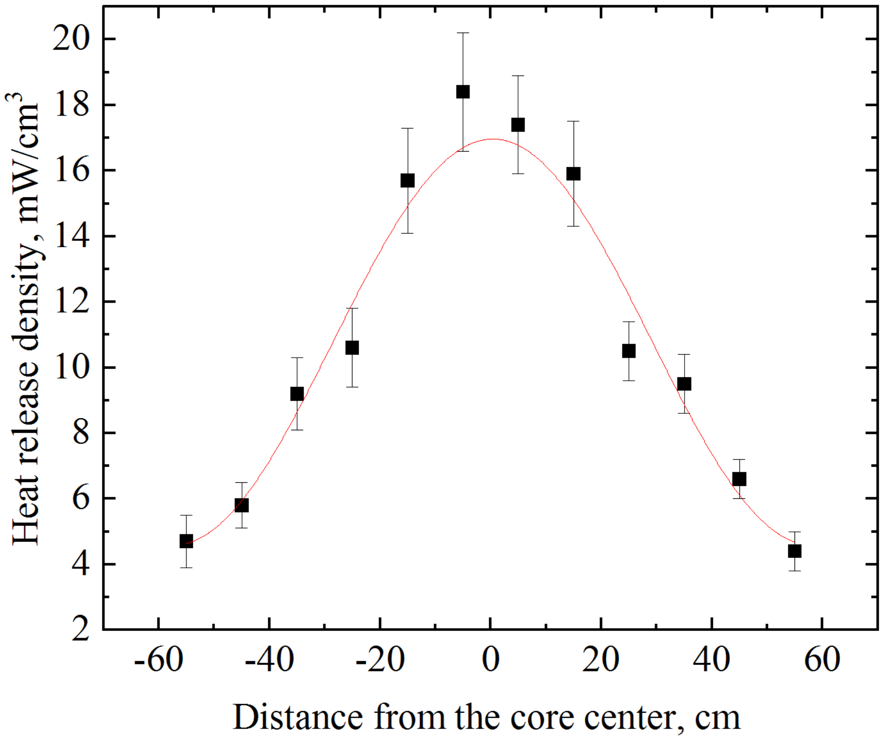

Figure 3.4 – Distribution of energy release density in Portland cement by height

Table 3.3 – Distribution of energy release density in shielding materials by depth

Zone	Heat release density, mW/cm^3
1	18.40 ± 1.80
2	9.91 ± 1.11
3	6.90 ± 0.70
4	5.90 ± 0.70
5	5.60 ± 1.30
6	4.30 ± 1.30
7	3.40 ± 0.8
8	1.9 ± 0.4
9	1.8 ± 0.50
10	1.8 ± 0.6
11	0.55 ± 0.07
12	1.20 ± 0.40
13	1.00 ± 0.5
14	0.57 ± 0.25

As you can see, the energy release density decreases with distance from the radiation source according to the exponential law. At the same time, deviations from the ideal form of the exponent can be explained by the processes of activation of iron isotopes by neutrons and the formation of a secondary gamma radiation front.

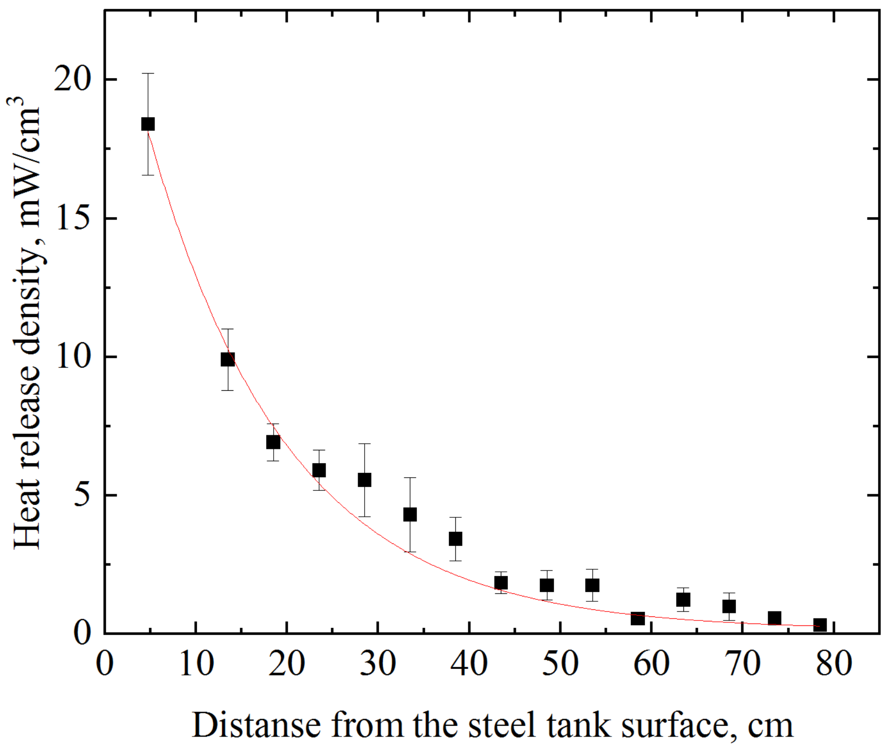

Figure 3.5 – Distribution of energy release density in shielding materials by depth

Taking into account the results obtained, the available computing power, as well as the fact that it is necessary to find only the maximum temperatures of materials, it was decided to use the following variant of the zoning of side biological shielding:

– the inner part of the side biological shielding includes a steel tank, Portland cement, aluminum tank, 2 zones of concrete $\rho_{HC2} = 6500\,\text{kg/m}^3$ and 4 zones of concrete $\rho_{HC1} = 5200\,\text{kg/m}^3$ with a thickness of 10 cm.

– the inner part of the side biological shielding includes 6 sectors;

– the height zoning includes 6 zones with a height of 20 cm symmetrically located relative to the level of the center of the active zone

The cross section of the resulting model at the level of the core center is shown in the Figure 3.6.

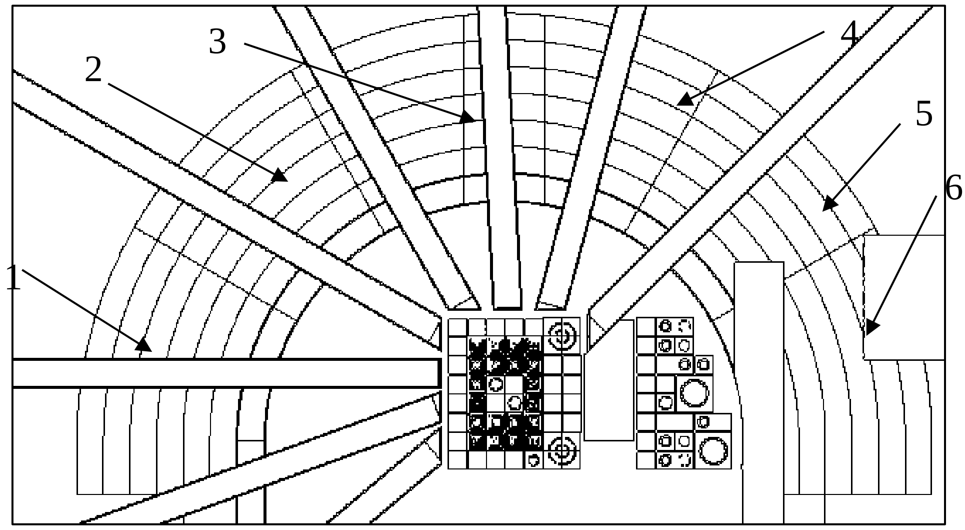

Figure 3.6 – The cross section of the resulting model at the level of the core center

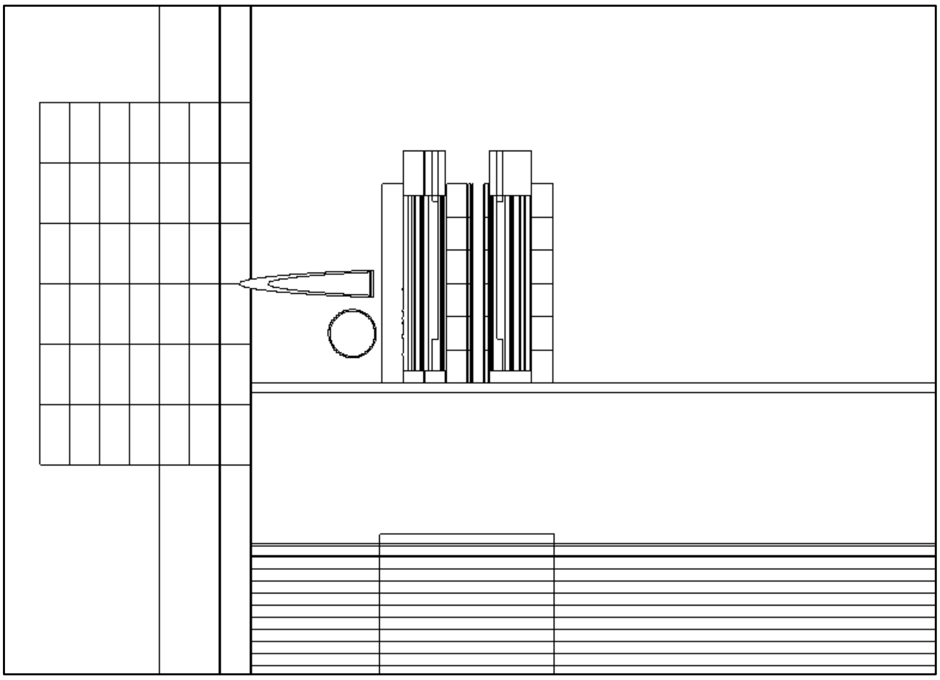

Figure 3.7 – The longitude cross section of the resulting model at the level of the core center

Additionally, zones were created for calculation of heat release in the biological shielding of the reactor bottom. They include layers of steel, Portland cement, aluminum, as well as 10 layers of concrete with a density $\rho_{HC1} = 5200\,\text{kg/m}^3$ of 4 cm thick. To highlight an especially heat-stressed area, each layer includes a zone directly located under the core and the remaining part. The numbering of sectors in the description of the calculation results is also shown in the Figures 3.6 and 3.7.

3.4 SolidWorks biological shielding model

Preparing a model of the entire reactor is an extremely energy-intensive and, in this case, inefficient modeling trajectory. Due to the fact that the subject of our interest is the maximum temperature in biological protection materials, it was decided to model the processes in the part most susceptible to heating.

The biological shielding model used is shown in the Figure 3.8.

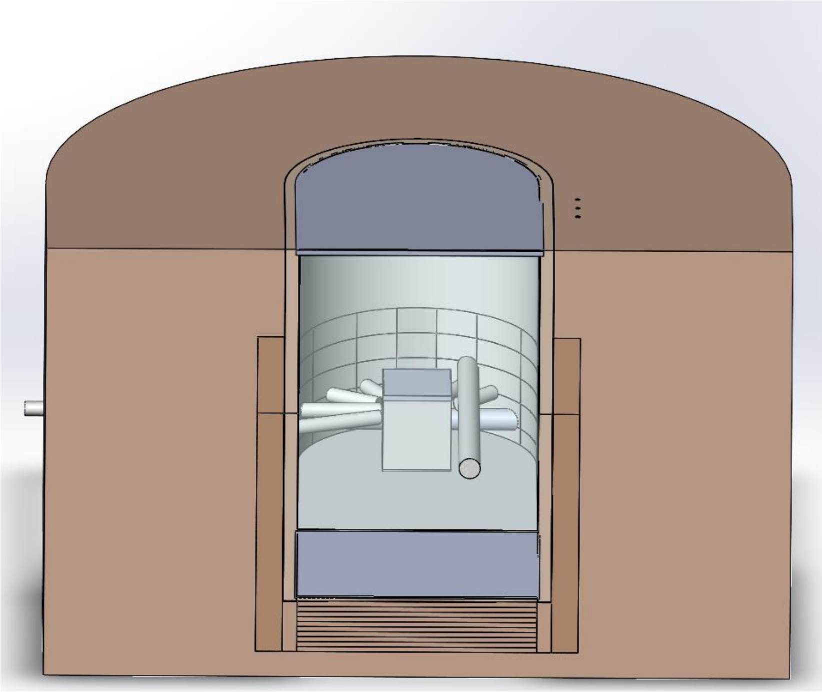

Figure 3.8 – SolidWorks biological shielding model

It includes a part of steel and aluminum tanks with Portland cement in the space between them, as well as super heavy concrete. Also, in this model there is a steel sheet with elements forming a holding capacity, as well as a simulator of the volume of the core. The side reflector is excluded from this model due to the weak influence on the cooling process from the side of the primary circuit. The scope of biological shielding also includes elements corresponding to the MCU-PTR model, such as horizontal experimental channels, as well as HEC-1 protection.

In accordance with the drawings obtained in the archive, a system of coil pipes was integrated with biological shielding, shown in the Figure 3.9.

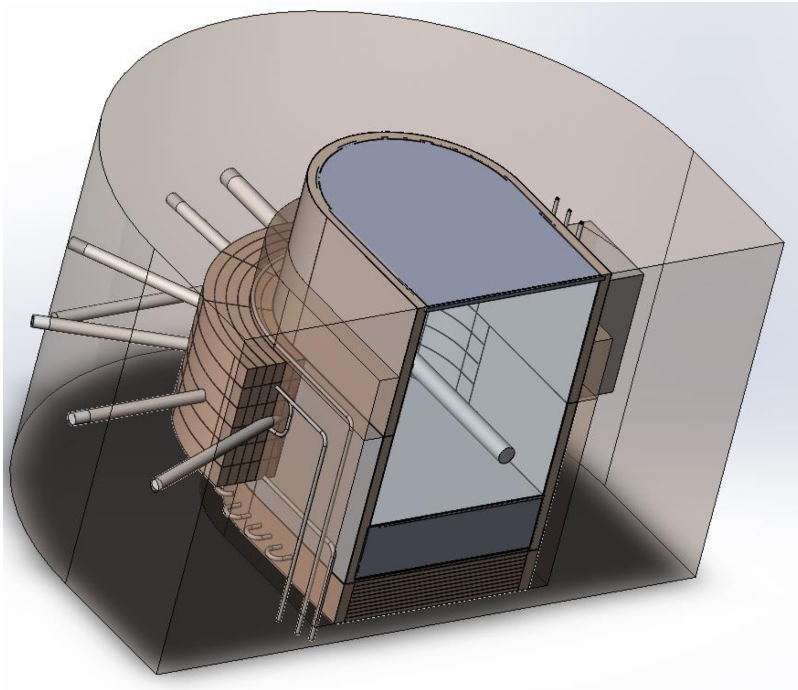

Figure 3.9 – The system of coil pipes

Due to the fact that not all surfaces of this model have air cooling, it was decided to perform the calculation within the framework of solving an internal problem. To solve this problem, it was necessary to form closed flow areas and establish boundary conditions.

With the help of plugs and an additional simulator of the water layer, 5 flow subdomains were formed. The first subdomain of the flow (Figure 3.10) simulates the vertical drop of the primary circuit coolant to the core. The boundary conditions for this area are the flow rate of the coolant at the entrance to the bank, as well as the temperature and pressure at the entrance to the core.

The second subdomain of the flow (Figure 3.11) simulates the flow of the coolant through the holding tank. The boundary conditions for this region are the pressure and temperature of the coolant at the outlet of the core, as well as the flow rate of the coolant at the outlet of the flow subdomain.

The other three subdomains correspond to the three loops of the coil pipes system. The boundary conditions for these areas are the pressure and temperature at the inlet and the flow rate at the outlet.

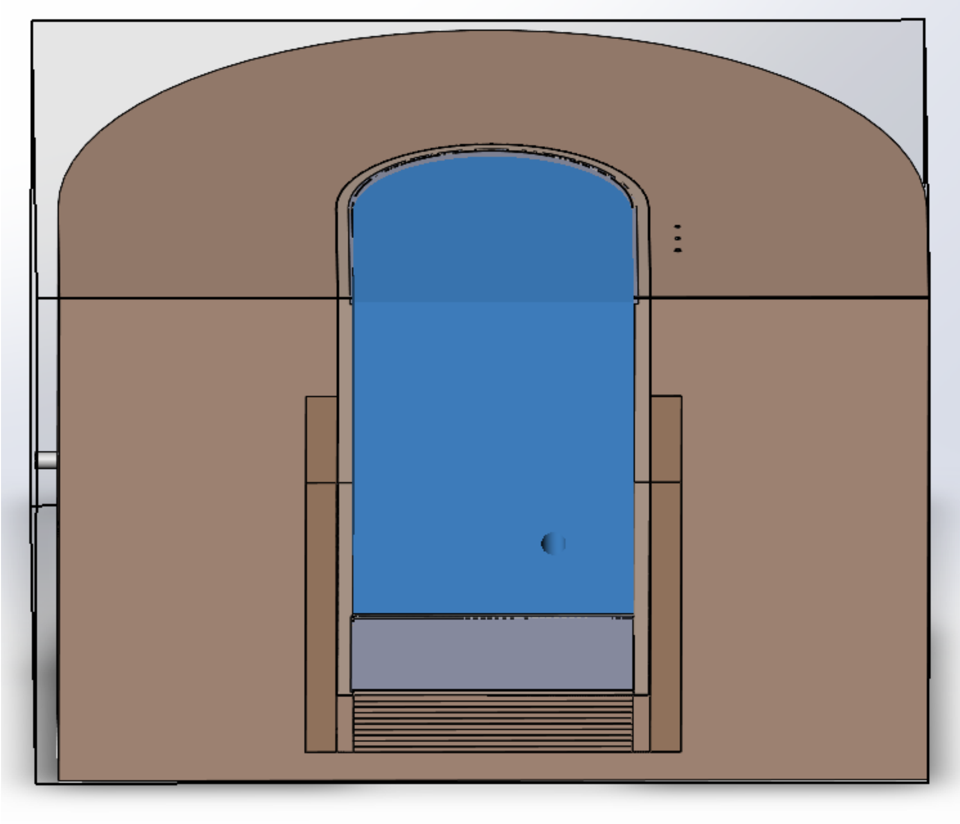

Figure 3.10 – Subdomain of the flow for simulates the drop of the primary circuit coolant to the core

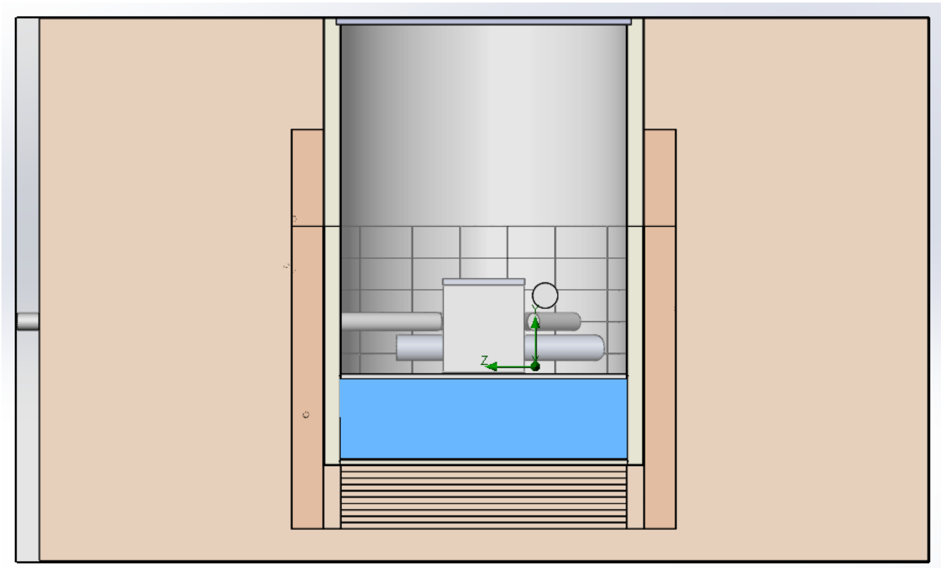

Figure 3.11 – Subdomain of the flow simulates the flow of the coolant through the holding tank

Common boundary conditions for all calculations include:

– primary circuit coolant flow rate $Q_1 = 0.19$ m^3/s;

– total pressure at the entrance to the core $p_{c1} = 167.7$ kPa;

– total pressure at the outlet of the core $p_{c2} = 133$ kPa;

– total pressure at the entrance to the coil pipes $p_{c1} = 320$ kPa;

– total flow rate on the outlet of coil pipes $Q_{CP} = 5.56 \cdot 10^{-3}$ m^3/s;

– wall temperature $t_w = 23°C$ for the outer walls;

– adiabatic wall for borders with ordinary concrete.

The heat release density calculation area is constructed from the individual blocks corresponding to the calculation zones in the MCU-PTR model. Heat sources are defined as the total heat release in each individual block.

The design grid includes an automatic base grid of the 5th level with a minimum clearance of 0.005 m, as well as a local grid applied to the HEKs and coil pipes.

3.4 Calculation of the 6 MW IRT-T reactor in MCU-PTR

To calculate the energy release in biological protection at a reactor power of 6 MW, the same parameters were used as for estimating the distribution of heat release in biological protection earlier.

The calculation results are presented in Appendix C Table C.1 – C.7.

Figure 3.12 shows the distribution of energy release density in side biological shielding at the level of the core center.

As you can see, the main energy release is concentrated in the Portland cement of sectors 3 and 4 and is rapidly decreasing away from it. In sectors 2 and 5, energy release decreases in a similar way, while in zone 6, cast iron provides additional protection for the layers behind it.

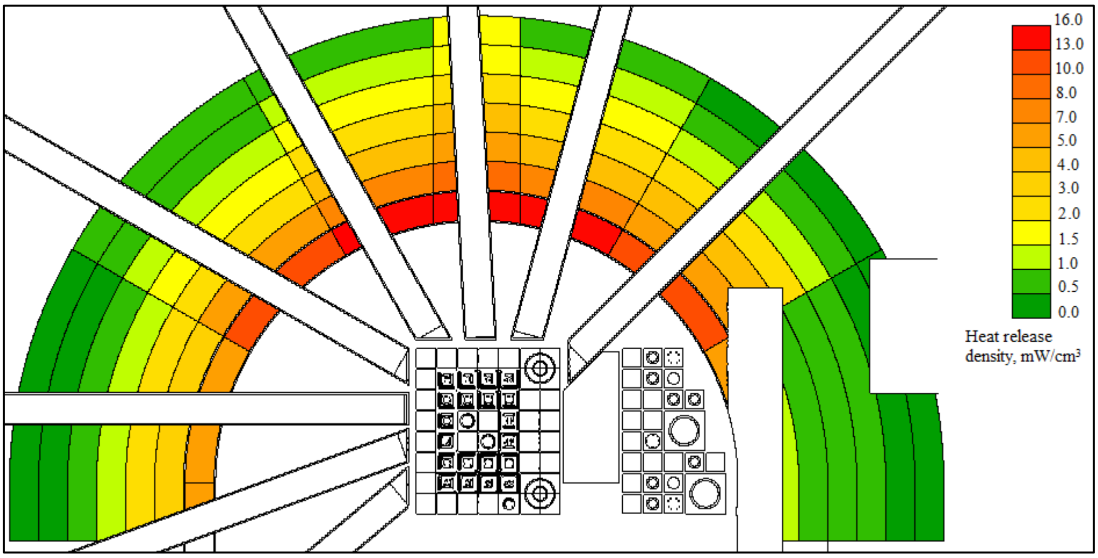

Figure 3.12 – Distribution of energy release density in biological shielding at the level of the core center at 6 MW

3.5 SolidWorks 6 MW calculation

The following additional boundary conditions were used in the calculation:

– coolant temperature at the entrance to the core $t_1 = 39.2\,°C$;

– coolant temperature at the outlet of the core $t_2 = 46.47\ °C$;

– coolant temperature at the entrance to the coil pipes $t_{CP} = 33.4\,°C$.

The obtained temperature fields are shown in the Figures 3.13 and 3.14.

As you can see, the highest temperatures are observed in Portland cement and heavy concrete with density of 6.5 t/m^3, as well as in the space under the core. The highest calculated temperature value was equal to $t_{\max} = 48 \pm 0.1\,°C$.

To verify the reliability of the temperature calculation in this zone, experimental measurements were used at the points shown in Figure 3.13. Measurements were made by sensitive elements platinum technical CHEPT-2, having a class B. Then, according to [23], the measurement error by this device is defined as:

$$\Delta t = 0.3 + 0.005 \cdot t, \tag{3.2}$$

where – temperature measurement result, °C.

The results of calculations and measurements are presented in Table 3.4

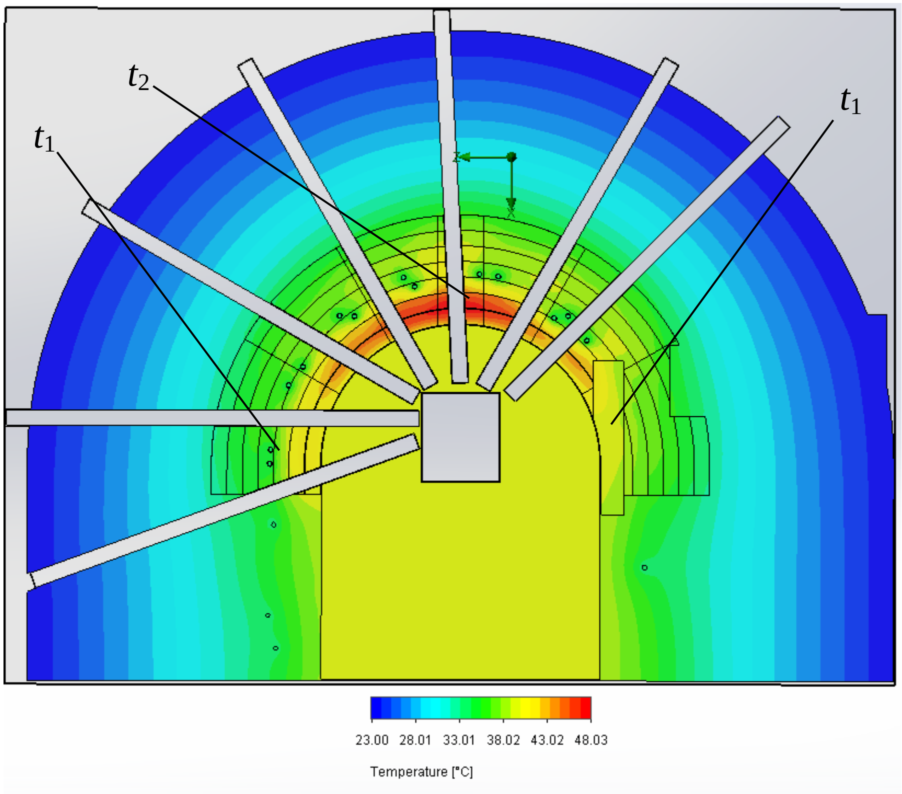

Figure 3.13 – Temperature field in the side shielding at the level of the core center at power of 6 MW

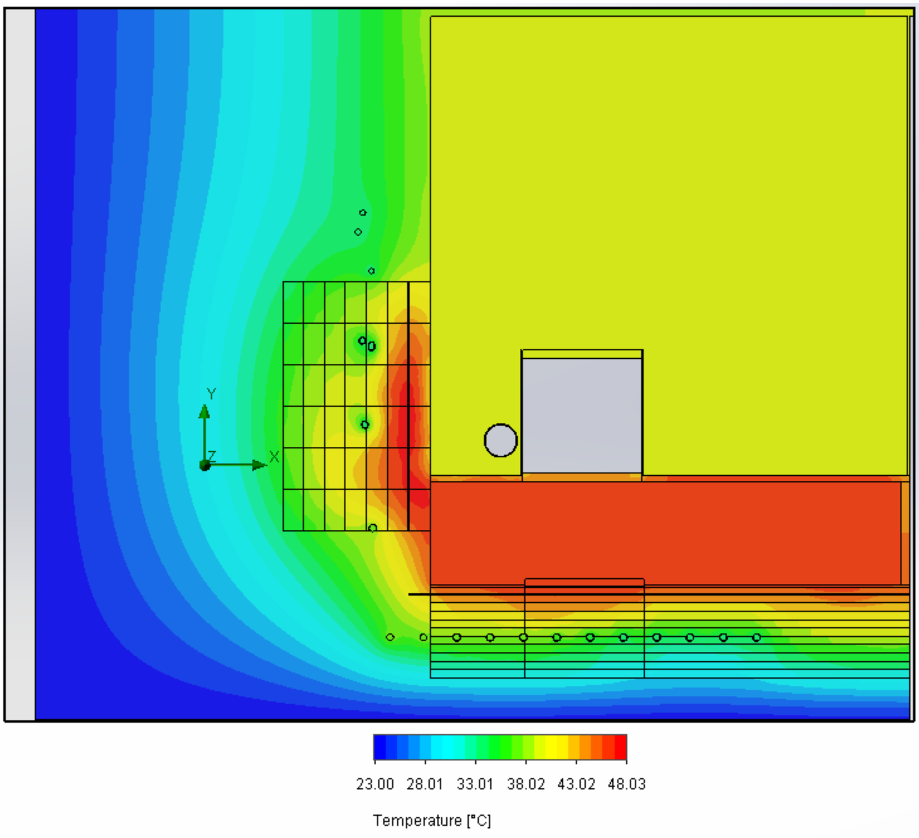

Figure 3.14 – Vertical temperature distribution at a power of 6 MW

Table 3.4 – Temperature measurement and calculation results for power of 6 MW

Parameter	Calculation	Measurement
t_1, °C	35.77 ± 0.09	34.5 ± 0.5
t_1, °C	47.39 ± 0.04	48.5 ± 0.5
t_1, °C	39.30 ± 0.02	41.4 ± 0.5

The difference between the results of calculations and measurements does not exceed 2.1 °C, which corresponds to the relative deviation in 5.1 %. The resulting difference may be due to the following factors:

– heterogeneity of the properties of real concrete;

– the approximate type of description of the heat release density distribution.

3.6 Calculation of the 6.6 MW IRT-T reactor in MCU-PTR

To further substantiate the applicability of this model for calculating maximum temperatures in materials, calculations were also made based on experimental data for a power of 6.6 MW.

The results of measuring the temperature of the coolant at the entrance to the core and its heating are presented in the Table 3.5.

Table 3.5 – Parameters of the fluid in IRT-T reactor core for 6.6 MW calculation

Parameter	Values of measurement's			Mean value
	1	2	3	
Fluid inlet temperature, °C	44.10	44.00	44.50	44.20 ± 0.15
Fluid heating, °C	8.6	8.5	8.3	8.47 ± 0.08

The temperature of water at the inlet of the core was measured equal to 44.2 °C. The average water heating was 8.47 °C based on the measurements obtained Thus, the average water temperature can be approximately calculated as:

$$\bar{t} = 44.2 + \frac{8.47}{2} \approx 48.435 \text{ °C}.$$

The coolant pressure at the reactor core outlet is assumed to be 133 kPa. Pressure drop at the core is equal to 34.7 kPa. Then the average pressure in the core is:

$$\bar{p} = 133 + \frac{34.7}{2} = 150.35 \text{ kPa}.$$

Then the density and the concentration of isotopes of the coolant are equal to:

$$\bar{\rho}(\bar{t}, \bar{p}) = 0.9888 \text{ g/cm}^3$$

$$N_H = 2 \cdot \frac{\bar{\rho}(\bar{t}, \bar{p}) \cdot N_A}{18} = 2 \cdot \frac{0.9888 \cdot 6.02 \cdot 10^{23}}{18} = 6.61 \cdot 10^{22} \text{ cm}^{-3}$$

$$N_O = \frac{\bar{\rho}(\bar{t}, \bar{p}) \cdot N_A}{18} = \frac{0.9888 \cdot 6.02 \cdot 10^{23}}{18} = 3.307 \cdot 10^{22} \text{ cm}^{-3}$$

The calculation of energy release in biological shielding was carried out in the same manner as for 6 MW. The calculation results are presented in Appendix D Table D.1 – D.7.

Figure 3.15 shows the distribution of energy release density in side biological shielding at the level of the core center.

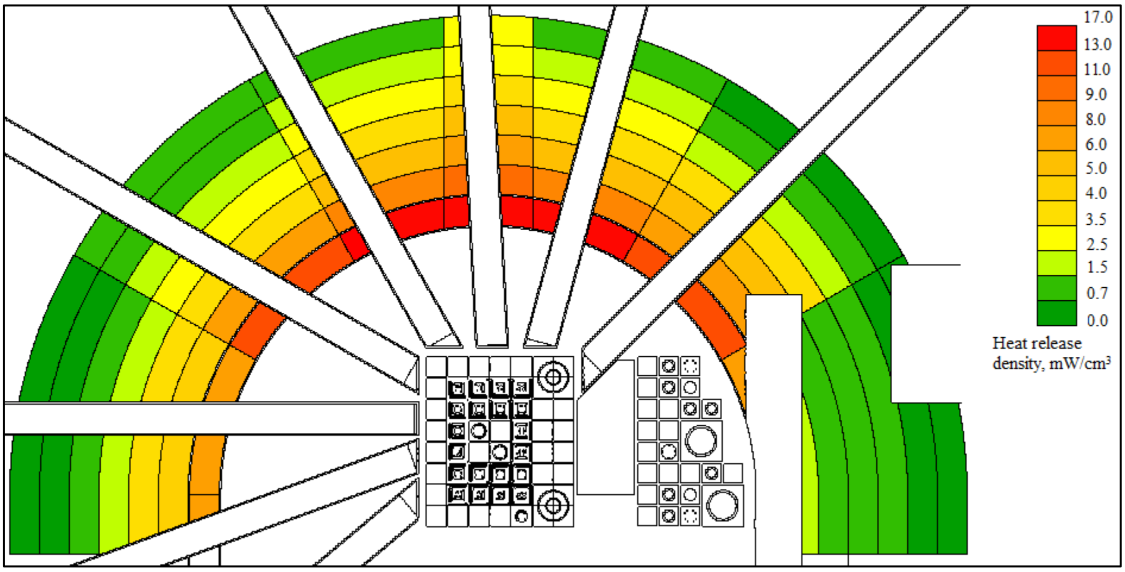

Figure 3.15 – Distribution of energy release density in biological shielding at the level of the core center at 6.6 MW

As you can see, the form of the distribution of energy release in biological shielding remains unchanged. At the same time, there is an increase in the heat release density proportional to the increase in reactor power.

3.7 SolidWorks 6.6 MW calculation

The following additional boundary conditions were used in the calculation:

– coolant temperature at the entrance to the core $t_1 = 44.2$ °C;

– coolant temperature at the outlet of the core $t_2 = 52.67$ °C;

– coolant temperature at the entrance to the coil pipes $t_{CP} = 38.4$ °C.

The obtained temperature fields are shown in the Figures 3.16 and 3.17.

As you can see, the highest temperatures are observed in Portland cement and heavy concrete with density of 6.5 t/m^3, as well as in the space under the core. The highest calculated temperature value was equal to $t_{max} = 53.69 \pm 0.18$ °C.

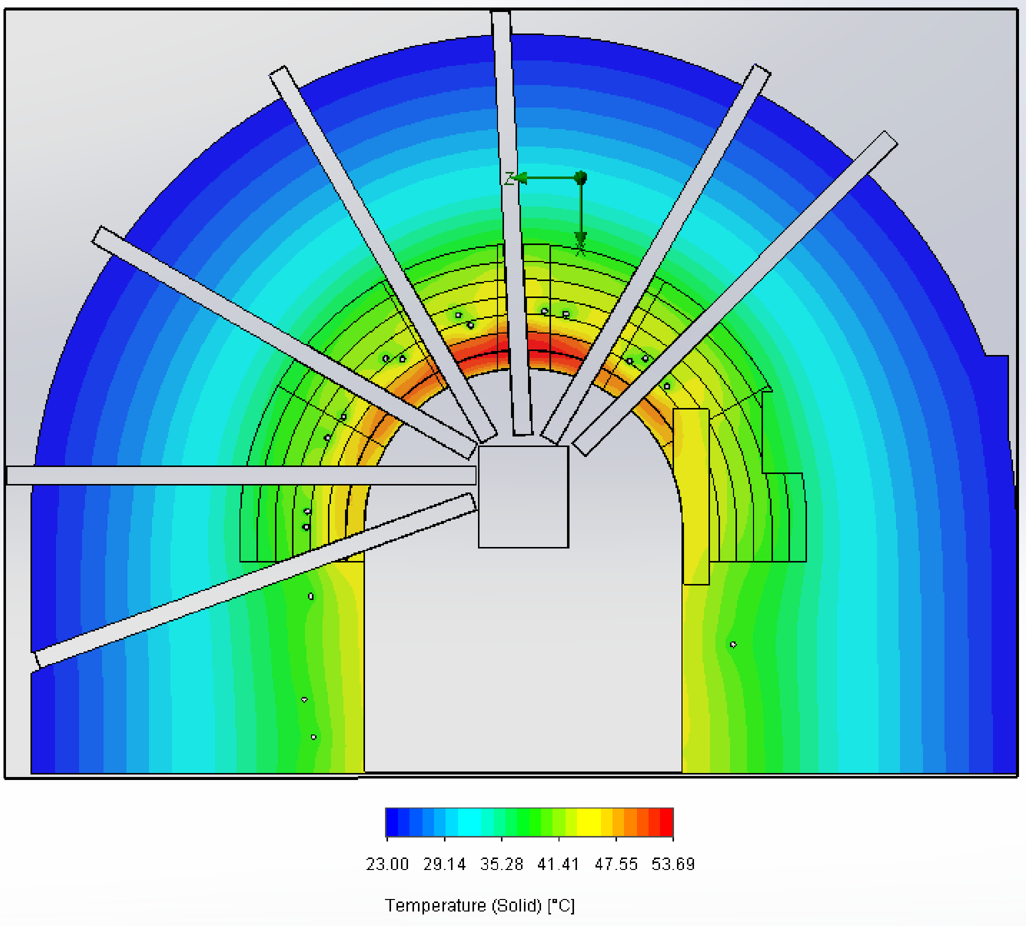

Figure 3.16 – Temperature field in the side shielding at the level of the core center at power of 6.6 MW

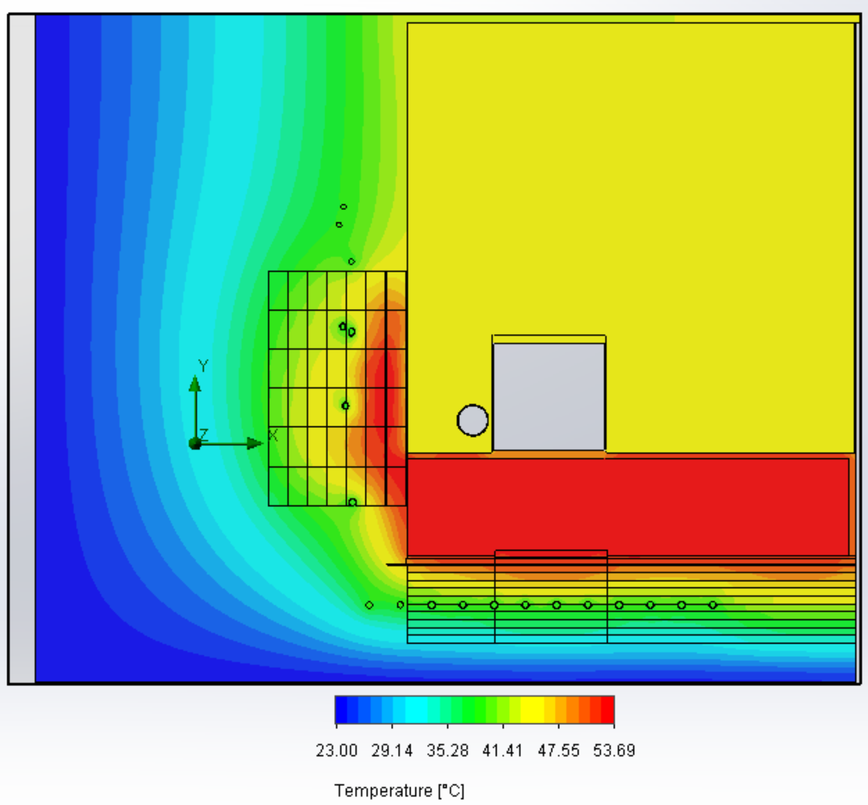

Figure 3.17 – Vertical temperature distribution at a power of 6.6 MW

The results of temperature in registration channels calculations and measurements are presented in Table 3.6

Table 3.6 – Temperature measurement and calculation results for power of 6.6 MW

Parameter	Calculation	Measurement
t_1, °C	40.74 ± 0.08	39.6 ± 0.50
t_1, °C	53.35 ± 0.15	54.10 ± 0.60
t_1, °C	44.16 ± 0.03	45.7 ± 0.50

The difference between the results of calculations and measurements does not exceed 1.54 °C, which corresponds to the relative deviation in 3.4 %, what is acceptable for our assessment.

3.8 Calculation of the 10 MW IRT-T reactor in MCU-PTR

The calculation of temperatures during reactor operation at a power of 10 MW is carried out under the worst heat exchange conditions.

Thus, the maximum value of the temperature at the entrance to the core can be 55 °C.

The average heating of the coolant in the core can be estimated as:

$$\Delta\overline{t} = \frac{P}{c \cdot Q_1 \cdot \rho} = \frac{10^7}{4200 \cdot 0.19 \cdot 1000} = 12.53 \text{ °C}.$$

Thus, the average water temperature can be approximately calculated as:

$$\overline{t} = 55 + \frac{12.53}{2} \approx 61.265 \text{ °C}.$$

The coolant pressure at the reactor core outlet is assumed to be 133 kPa. Pressure drop at the core is equal to 34.7 kPa. Then the average pressure in the core is:

$$\overline{p} = 133 + \frac{34.7}{2} = 150.35 \text{ kPa}.$$

Then the density and the concentration of isotopes of the coolant are equal to:

$$\overline{\rho}\left(\overline{t}, \overline{p}\right) = 0.9826 \text{ g/cm}^3;$$

$$N_H = 2 \cdot \frac{\overline{\rho}\left(\overline{t}, \overline{p}\right) \cdot N_A}{18} = 2 \cdot \frac{0.9826 \cdot 6.02 \cdot 10^{23}}{18} = 6.57 \cdot 10^{22} \text{ cm}^{-3};$$

$$N_O = \frac{\overline{\rho}\left(\overline{t}, \overline{p}\right) \cdot N_A}{18} = \frac{0.9826 \cdot 6.02 \cdot 10^{23}}{18} = 3.286 \cdot 10^{22} \text{ cm}^{-3}.$$

The calculation of energy release in biological shielding was carried out in the same manner as for 6 MW. The calculation results are presented in Appendix E Table E.1 – E.7.

Figure 3.18 shows the distribution of energy release density in side biological shielding at the level of the core center.

As you can see, the form of the distribution of energy release in biological protection remains unchanged. At the same time, there is an increase in the energy release density proportional to the increase in reactor power.

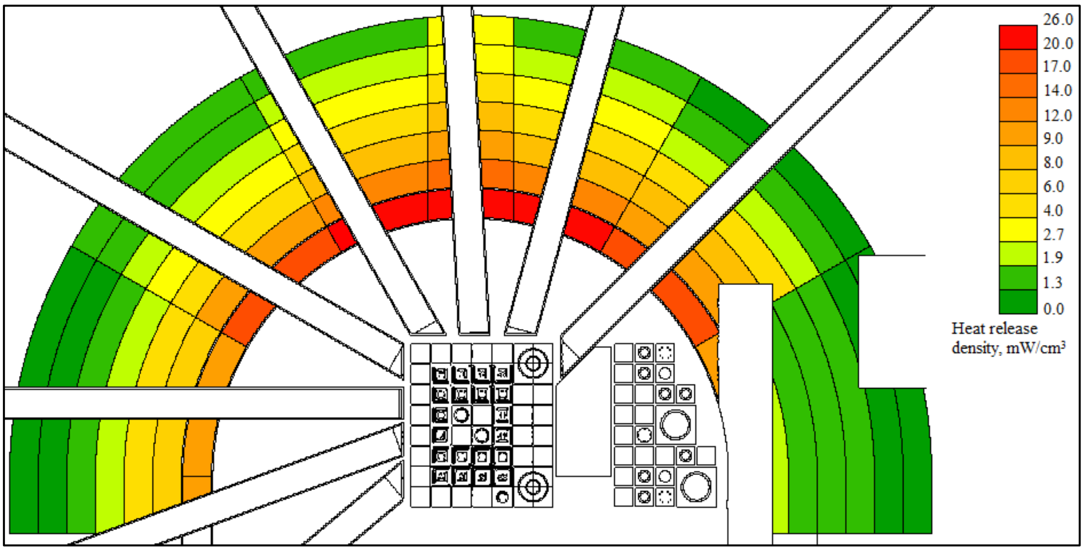

Figure 3.18 – Distribution of energy release density in biological shielding at the level of the core center at 10 MW

3.9 SolidWorks 10 MW calculation

The following additional boundary conditions were used in the calculation:

– coolant temperature at the entrance to the core $t_1 = 55\,°C$;

– coolant temperature at the outlet of the core $t_2 = 67.53\ °C$;

– coolant temperature at the entrance to the coil pipes $t_{CP} = 49.2\,°C$.

The obtained temperature fields are shown in the Figures 3.19 and 3.20.

For Portland cement, as well as for each type of concrete, maximum temperature values were calculated, as well as maximum temperature differences. The calculation results are presented in the Table 3.7.

Table 3.7 – The calculation results for the reactor power of 10 MW

Material	t_{max}, °C	Δt_{max}, °C
Portland cement	69.63 ± 0.18	0.32
Concrete 6.5 t/m^3	69.75 ± 0.15	0.25
Concrete 5.2 t/m^3	62.95 ± 0.08	0.93

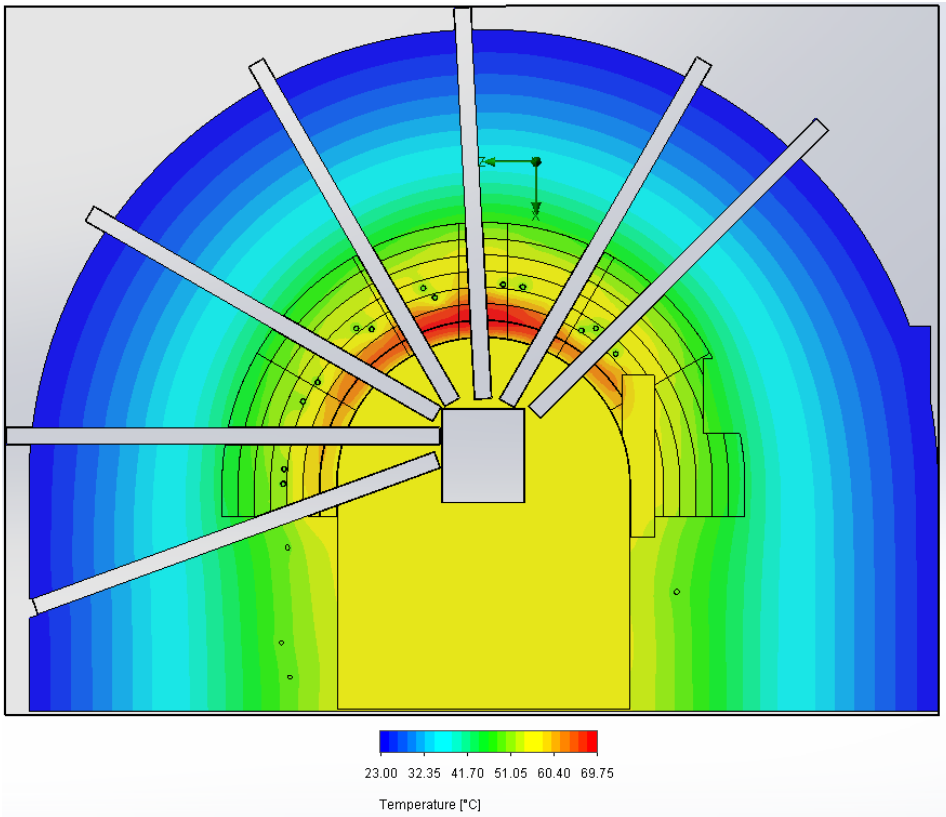

Figure 3.19 – Temperature field in the side shielding at the level of the core center at power of 10 MW

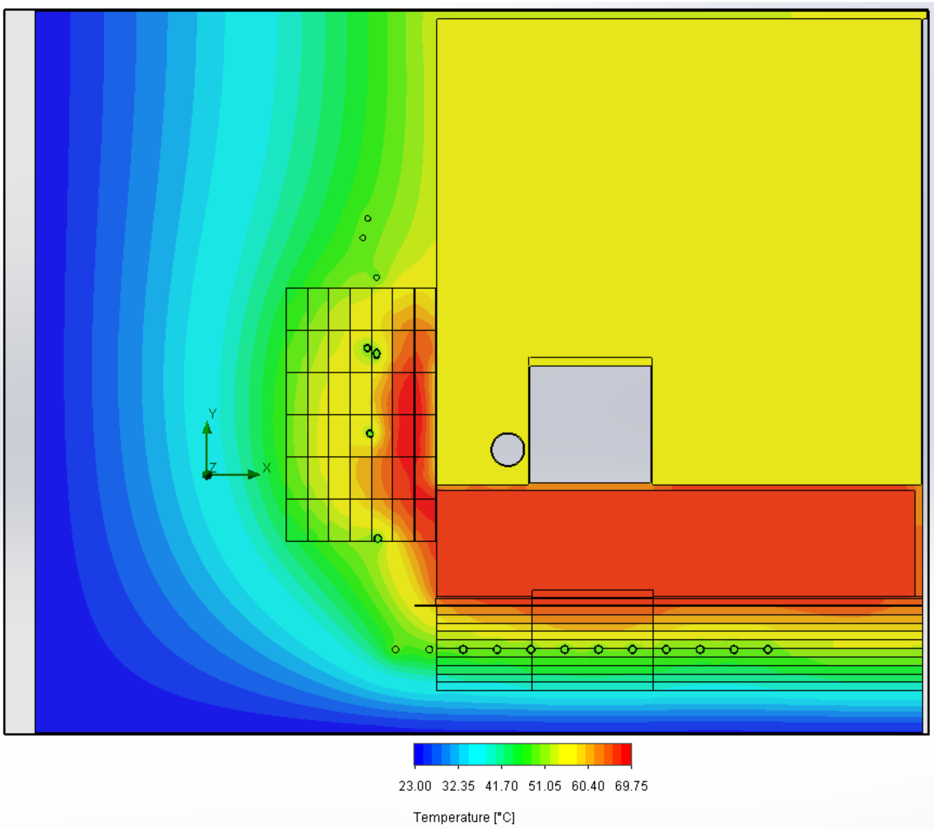

Figure 3.20 – Vertical temperature distribution at a power of 10 MW

Based on the results obtained, it can be concluded that when the reactor is operated at a capacity of 10 MW, the operational limits for biological protection materials are not exceeded.

4 Financial management, resource efficiency and resource saving

The topic of this work is «Influence of increasing of IRT-T reactor power on intensity of biological shielding heating».

The aim of this work is to determine the possibility of IRT-T reactor biological shielding to withstand the reactor operation at increased power from the point of thermodynamic analysis.

The purpose of this section discusses the issues of competitiveness, resource efficiency and resource saving, as well as financial costs regarding the object of study of Master's thesis. Competitiveness analysis is carried out for this purpose. SWOT analysis helps to identify strengths, weaknesses, opportunities and threats associated with the project, and give an idea of working with them in each particular case. For the development of the project requires funds that go to the salaries of project participants and the necessary equipment, a complete list is given in the relevant section. The calculation of the resource efficiency indicator helps to make a final assessment of the technical decision on individual criteria and in general.

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

$$C = \sum P_i \cdot W_i, \tag{4.1}$$

where C – the competitiveness of research or a competitor;

W_i – criterion weight;

P_i – point of i-th criteria.

This work includes two main stages: calculation of energy release in biological shielding materials and thermophysical calculation.

Calculation of energy release in biological shielding materials can be provided by two alternative methods:

– MCU-PTR software that was developed for calculating the research nuclear reactors of pool type (P_f);

– theoretical calculation of absorbed doses of gamma radiation used to estimate the thickness of biological shielding of various radiation sources (P_1).

In this case, the verified model of the IRT-T reactor is available only in the format for the MCU-PTR program, which allows it to be used without preliminary development and research.

Evaluation map analysis of methods these methods is presented in Table 4.1.

Table 4.1 – Evaluation card for comparison of competitive technical solutions

Evaluation criteria	Criterion weight	Points		Competitiveness	
		P_f	P_1	C_f	C_1
1	2	3	4	5	6
Technical criteria for evaluating resource efficiency					
1. Growth in User’ productivity	0.2	5	4	1	0.8
2. Convenience in operation	0.1	5	3	0.5	0.3
4. Energy efficiency	0.1	3	5	0.3	0.5
5. Reliability	0.2	5	3	1	0.8
6. Functional capacity	0.1	5	4	0.5	0.4
7. Ease of operation	0.1	3	5	0.3	0.5
Economic criteria for performance evaluation					
1. Competitiveness of the method	0.1	5	3	0.5	0.3
2. Software price	0.1	3	5	0.3	0.5
Total	1	32	30	4.4	4.1

As it can be seen the competitiveness of the MCU-PTR software C_f = 4.4 exceeds that of the theoretical calculation method, equal to C_1 =4.1. The main disadvantages the MCU-PTR software of include low energy efficiency and the complexity of mastering and using this program

The SolidWorks program was chosen for the thermophysical calculation due to the availability of the licensed version and the remaining unavailability of such an analog – Ansys program.

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.

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.

The summative matrix of SWOT analysis is presented in Table 4.2.

Table 4.2 – The summative matrix of SWOT analysis

	Strengths: S1. The relevance of the chosen theme. S2. Minimal research costs S3. Reliability of the results S4. The ability to control the calculation processes S5. Takes into account both neutron and thermophysical aspects	Weaknesses: W1. The requirement of licenses for the use of programs W2. Long time calculations. W3. High level of knowledge for performing calculations. W4. Limited number of calculated parameters.

Continuation of Table 4.2

Opportunities: O1. Possibility of verification of results based on experimental data O2. The carried out research provides a primary assessment and a basis for further development work	The results of the analysis of the interactive matrix of the project fields «Strengths and opportunities»: 1. Verification of results based on experimental data increases their reliability 2. The reliability of the results reduces the cost of further research	The results of the analysis of the interactive matrix of the project fields «Weaknesses and opportunities»: 1. The presence of licensed programs allows other researchers to verify calculations
Threats: T1. Human factor T2. The presence of competing software T3. Non-interest of third-party organizations in the application of the results of work.	The results of the analysis of the interactive matrix of the project fields «Strengths and threats»: 1. The ability to control the calculation process allows to minimize the influence of the human factor	The results of the analysis of the interactive matrix of the project fields «Weaknesses and threats»: 1. The required high level of knowledge to perform calculations and the human factor increase the likelihood of errors in calculations

SWOT analysis shows that the advantages of the developed methodology prevail over its disadvantages.

As it can be seen, the required high level of knowledge to perform calculations and the human factor increase the likelihood of making mistakes in calculations. At the same time, comparison of the calculation results with experimental data and the possibility of calculations by other researchers using the same licensed software can significantly reduce the influence of these factors on the research results.

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 presented in Table 4.3.

Table 4.3 – Stakeholders of the project

Project stakeholders	Stakeholder expectations
Division for Nuclear-Fuel Cycle of TPU	A set of models for calculating the thermophysical parameters of biological shielding and determining the possibility of its operating at increased reactor power

Purpose and results of the project are presented in Table 4.4.

Table 4.4 – Purpose and results of the project

Purpose of project:	Possibility justification of biological shielding operating at increased reactor power
Expected results of the project:	Heat release and temperature distribution in biological shielding materials
Criteria for acceptance of the project result:	Verification of models based on experimental data
Requirements for the project result:	Calculation error less than 20 %

4.3.1 The organizational structure of the project

At the current stage it is important to decide who will be in the workgroup of this project, to define roles for each participant and to assign the functions for each participant. Besides, there should be considered working hours. This information is represented in Table 4.5.

Table 4.5 – Project workgroup

№	Participant	Role in the project	Functions	Labor time, hours
1	A.G. Naymushin	Supervisor	Student control	120
2	I.A. Tereshin	Engineer	Doing research work	672
Total				792

4.3.2 Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members. Information about them is represented in Table 4.6.

Table 4.6 – Project limitations

Factors	Limitations / Assumptions
Project's budget	260000 rubles
Source of financing	National Research Tomsk Polytechnic University
Project timeline:	02.02.2022-30.05.2022
Date of approval of plan of project	07.02.2022
Completion date	30.05.2020

4.4 Schedule of the project

As part of the planning of a research project, it is necessary to build a timetable and a calendar schedule for the project. The timetable is shown in Table 4.7. Scientific advisor and an engineer are the main contributors to the report.

Table 4.7 – Timetable of the project

№	Job title	Duration, working days	Start date	Date of completion	Participants
1	Development of research task	1	02.02.2022	03.02.2022	Supervisor Engineer
2	Drafting and approving the research task	2	04.02.2022	07.02.2022	Supervisor
3	The choice of research direction	5	08.02.2022	14.02.2022	Supervisor Engineer
4	Selection and study of materials on the topic	10	15.02.2022	28.02.2022	Engineer
5	Calendar planning of the work	3	01.03.2022	03.03.2022	Supervisor, Engineer
6	Performing calculations and analyzing the received data	41	04.03.2022	29.04.2022	Engineer
7	Summarizing and evaluating results	2	30.04.2022	03.05.2022	Supervisor, Engineer
8	Detailed report writing	3	04.05.2022	08.05.2022	Engineer
9	Checking the correctness of the report on the state standard	2	09.05.2022	11.05.2022	Supervisor Engineer
10	Preparations to the defense of the thesis	13	12.05.2022	30.05.2022	Engineer

A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule. 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 4.8 – 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	Development of research task	Supervisor Engineer	1												
2	Drafting and approving the research task	Supervisor	2												
3	The choice of research direction	Supervisor Engineer	5												
4	Selection and study of materials on the topic	Engineer	10												
5	Calendar planning of the work	Supervisor Engineer	3												
6	Performing calculations and analyzing the received data	Engineer	41												
7	Summarizing and evaluating results	Supervisor Engineer	2												
8	Detailed report writing	Engineer	3												
9	Checking the correctness of the report on the state standard	Supervisor Engineer	2												
10	Preparations to the defense of the thesis	Engineer	13												

– Supervisor, – Engineer

4.5 Scientific and technical research budget

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.

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;

– basic salary;

– additional salary;

– labor tax;

– overhead costs;

– other direct costs.

4.5.1 Material costs of scientific research

Material costs includes the costs of purchasing all types of materials, components and semi-finished products necessary to perform research work.

The calculation of material costs may be also carried out according to the formula:

$$C_m = (1 + k_t) \cdot \sum_{i=1}^{m} P_i \cdot N_{consi}, \tag{4.2}$$

where m – the number of types of material resources consumed in the performance of scientific research;

N_{consi} – the amount of material resources of the *i*-th species planned to be used when performing scientific research;

P_i – the acquisition price of a unit of the *i*-th type of material resources consumed;

k_t – coefficient taking into account transportation costs, $k_t = 0.05$.

Prices for material resources can be set according to data posted on relevant websites on the Internet by manufacturers (or supplier organizations).

Material costs, required for this research are shown in Table 4.9.

Table 4.9 – Material costs

Name of position	Quantity, pcs	Price per unit, rub	Sum, rub
A4 size printer paper	1	350	350
Printer Cartridge	1	2700	2700
Total:			3203

Energy costs are calculated by the formula:

$$C_{el} = P_{el} \cdot N_{el} \cdot F_{eq}, \quad (4.3)$$

where P_{el} – power rates, P_{el} =5.8 rub./kWh;

N_{el} – power of equipment, $N_{el} = 0.6$ kW;

F_{eq} – equipment usage time, $F_{eq} = 792$ hours.

Then:

$$C_{el} = P_{el} \cdot N_{el} \cdot F_{eq} = 5.8 \cdot 0.6 \cdot 792 = 2756 \text{rub.}$$

The total material costs are equal to:

$$C_{mtot} = C_m + C_{el} = 3203 + 2756 = 5959 \text{ rub.}$$

4.5.2 Costs of special equipment

This point includes the costs associated with the acquirement of special equipment (instruments, stands, devices and mechanisms) necessary to carry out work on a specific topic.

In this work, we used special software packages for thermal and neutronic calculations, as well as equipment (laptop) for carrying out the above procedures. Due to the fact that the MCU-PTR and SolidWorks programs used in the work with the Flow Simulation module are officially licensed for use by the University for educational purposes, they are not taken into account in the cost calculation.

Besides, there was used a personal computer with cost 39500 rubles, which is less than 40000 rubles, hence depreciation of hardware is not necessary.

Costs of special equipment, required for this research are shown in Table 4.10.

Table 4.10 – Costs of special equipment

Name of position	Quantity of equipment	Price per unit, rub.	Total cost of equipment, rub.
Personal computer	1	39500	39500

4.5.3 Calculation of the basic and additional 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 is calculated according to the following formula:

$$S_b = S_a \cdot T_w, \tag{4.4}$$

where S_b – basic salary per participant;

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

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

The average daily salary is calculated by the formula:

$$S_a = \frac{S_m \cdot M}{F_v}, \tag{4.5}$$

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;

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

Monthly salary is calculated by formula:

$$S_m = S_{base} \cdot k_{reg}, \tag{4.6}$$

where S_{base} – base salary, rubles;

k_{reg} – regional rate, $k_{reg} = 1.3$.

Base salary calculation for the scientific advisor and for an engineer is presented in Table 4.11.

Table 4.11 – Basic and additional salary calculation

Perfomers	S_{base}, rub.	k_{reg}	S_m, rub.	S_a, rub.	T_w, days	S_b, rub	S_{add}, rub
Supervisor	36174	1.3	47026	2098	15	31470	3147
Engineer	18426	1.3	23954	1069	82	87658	8766

Additional salaries include 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 % of the base salary of workers:

$$S_{add} = k_{extra} \cdot S_b, \tag{4.7}$$

where S_{add} – additional salary, rubles;

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

S_b – base salary, rubles.

Additional salaries calculation for the scientific advisor and for an engineer is presented in Table 4.11.

4.5.4 Contributions in non-budget funds

Social security pays (so-called labor 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:

$$S_{soc} = k_b \cdot \left(S_b + S_{add}\right), \tag{4.8}$$

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 30.2 %.

Results of calculation for social funds are presented in Table 4.12.

Table 4.12 – Contributions in non-budget funds

	Supervisor	Engineer
Basic salary, rub.	31470	87658
Additional salary, rub.	3147	8766
Coefficient for non-budget contributions, %	30.2	
Total, rub.	39574	

4.5.5 Calculation of 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 is calculated according to the formula:

$$S_{ov} = k_{ov} \cdot \left(S_b + S_{add}\right), \tag{4.9}$$

where k_{ov} – overhead rate, $k_{ov} = 0.3$

Results of calculation for overhead costs are presented in Table 4.13.

Table 4.13 – Contributions in non-budget funds

	Supervisor	Engineer
Basic salary, rub.	31470	87658
Additional salary, rub.	3147	8766
Overhead rate	0.3	
Total, rub.	39312	

4.5.6 Budgeting of project costs

Budgeting of project costs, which is a lower limit for scientific-technical production costs is presented in Table 4.14.

Table 4.14 – Budgeting of project costs

Cost item	Amount, rubles
Material costs	5959
Costs of special equipment	39500
Basic salary	119128
Additional salary	11913
Contributions in non-budgetary funds	39574
Overhead costs	39312
Total	255386

4.6 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 integral financial measure of development is defined as:

$$I_f^p = \frac{F_{pi}}{F_{\max}}, \qquad (4.10)$$

where I_f^p – integral financial indicator of current project;

Φ_{pi} – price for i-th variant of execution;

Φ_{max} – maximum cost of execution of a research project (including analogs).

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 $I_f^p = 1$.

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

$$I_m^a = \sum_i^n a_i \cdot b_i^a, \; I_m^p = \sum_i^n a_i \cdot b_i^p, \qquad (4.11)$$

where I_m^p – an integral indicator of resource efficiency of project;

I_m^a – an integral indicator of resource efficiency of options;

a_i – the weight coefficient of the i-th parameter;

b_i^a, b_i^p – the score of the i-th parameter for the analog and development, set by an expert method on the selected rating scale;

n – the number of comparison parameters.

The calculation of the integral indicator of resource efficiency for MCU-PTR software and theoretical calculation of absorbed doses is presented in the form of Table 4.15.

Table 4.15 – Comparative evaluation of the characteristics of the project execution options

Criteria	Parameter weighting factor	MCU-PTR software	Theoretical calculation
Growth in User' productivity	0.2	5	4
Convenience in operation	0.20	5	3
Energy efficiency	0.20	3	5

Continuation of Table 4.15

Reliability	0.25	5	4
Time consumption	0.15	4	5
Total	1	22	21

The integral indicator of the development efficiency is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_{fin}^{p} = \frac{I_{m}^{p}}{I_{f}^{p}},\ I_{fin}^{a} = \frac{I_{m}^{a}}{I_{f}^{a}}, \qquad (4.12)$$

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

$$E_{av} = \frac{I_{fin}^{p}}{I_{fin}^{a}}. \qquad (4.13)$$

Thus, the effectiveness of the development is presented in Table 4.16.

Table 4.16 –Efficiency of development

№	Indicator	Project	Analog
1	Integral financial indicator	1	1
2	Integral resource efficiency indicator	4.45	4.15
3	Integral efficiency indicator	4.45	4.15

Comparative effectiveness of the project:

$$E_{av} = \frac{I_{fin}^{p}}{I_{fin}^{a}} = \frac{4.45}{4.15} = 1.07.$$

Comparing the values of integrated performance indicators allows us to understand and choose a more effective solution to a technical problem in terms of financial and resource efficiency.

4.7 Conclusions on financial management part

In this section, the economic aspects and resource efficiency of this study are evaluated. The analysis of competitive technical solutions of scientific research was carried out, in which it was found out that the methodology chosen in the study it is the most preferred due to the best convenience in operation, reliability and functional capacity. The conducted SWOT analysis showed that the advantages of the used methods prevail over its shortcomings, and the identified threats are manageable.

In the course of the work:

– a Gantt chart is constructed, which clearly illustrates the time spent for the implementation of scientific research. The total number of days during which the engineer worked was 82, and the total number of days during which scientific advisor worked – 15;

– the cost of scientific research has been determined and the main items of expenditure have been identified. The cost budget of this research work amounted to 255386 rubles; the main item of expenditure is salaries for supervisor and engineer.

– the value of the integral indicator of resource efficiency was 4.45, while for analogue this indicator is 4.15 which indicates the greatest effectiveness of the chosen research methodology.

5 Social responsibility

In this final qualifying work, the main thermal parameters of the IRT-T reactor biological shielding are calculated, namely, the maximal temperature and temperature gradient in biological shielding material. The calculation is based on a previously verified model in the SolidWorks program, the energy release for which was obtained using the MCU-PTR software. The development can be used for further operation of the IRT-T reactor.

Since the study was implemented using a computer, the purpose of this section is to analyze compliance with sanitary norms and rules in the process of working on a project using this technical means. Measures to protect the employee from the negative impact of the environment are considered. Harmful and dangerous factors that negatively affect human health when working with the relevant elements are investigated. Ways to reduce the impact of harmful factors to acceptable limits are being studied. And also, possible emergency situations and actions that the student must perform in the event of an emergency are considered.

The object of study is the biological shielding of the IRT-T reactor. Since the study is carried out using various software packages, the object of study in this section is also the student’s work area, including a desk, personal computer, keyboard, computer mouse and chair, as well as the room in which this work area is located.

5.1 Legal and organizational issues of security

Labor protection and safety regulations are introduced in order to prevent accidents, ensure safe working conditions for workers and are mandatory for workers, managers, engineering and technical workers.

The main law regulating the labor relations of an employee and an employer, as well as labor standards, is the Labor Code of the Russian Federation [24]. According to article 5 of which the regulation of labor relations is carried out by: labor legislation and other regulatory legal acts containing labor law norms.

According to Article 91 of the Labor Code of the Russian Federation, the normal working time may not exceed 40 hours per week.

Also, according to the Labor Code of the Russian Federation [24], every employee has the right to:

− workplace that meets the requirements of labor protection;

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

− refusal to perform work in case of danger to his life and health due to violation of labor protection requirements, except for the following cases;

− provision of means of individual and collective protection;

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

− an extraordinary medical examination in accordance with medical recommendations with the preservation of his place of work and average earnings during the examination;

− guarantees and compensations established in accordance with this Code, a collective agreement, an agreement, a local regulatory act, an employment contract, if he is engaged in work with harmful and (or) dangerous working conditions.

5.2 Analysis of harmful and dangerous factors

In the course of their work, a person may be exposed to dangerous and harmful production factors. In the absence of protective measures against these factors, the risk of injury or sudden deterioration in the well-being of employees increases, as well as the risk of developing chronic diseases. Therefore, in order to ensure a high level of worker safety, it becomes necessary to consider factors specific to a particular production and take measures to reduce their negative impact.

The research process is associated with direct interaction with a personal computer, therefore, harmful and dangerous factors include:

– deviation of microclimate indicators;

– exceeding the noise level;

– insufficient illumination of the working area;

– increased level of electromagnetic radiation;

– psychophysiological factors;

– increased value of voltage in the electrical circuit;

– fire and explosion hazard.

5.2.1 Deviation of microclimate indicators

The microclimate of industrial premises is the conditions of the internal environment of the premises (combinations of temperature, humidity, air velocity) that affect the thermal state of a person and determine working capacity, health and labor productivity. To ensure the safe production of works, it is necessary to comply with the requirements defined by [25]. Table 5.1 shows the optimal norms.

Table 5.1 – Optimal microclimate norms in the work area

Season of the year	Temperature, °C	Relative air humidity, %	Air speed, m/s,
Cold	22-24	40-60	0.1
Warm	23-25	40-60	0.1

The microclimate if the most significant factor, especially the temperature and humidity of the air, since high temperature and humidity have a significant impact on a person’s ability to work, his susceptibility decreases and the number of errors increases. With significant deviations of the environmental parameters from the norm, the employee may experience hypothermia or overheating. With hypothermia, the body temperature decreases, blood vessels narrow, the work of the cardiovascular system is disrupted, and you increase the likelihood of colds. When an employee overheats, his pulse, breathing quickens, weakness, headache appears, and body temperature rises. To minimize the impact of the factor, a ventilation and air conditioning system is used. Also, when working in the premises, daily wet cleaning and systematic ventilation should be carried out after each hour of work.

Providing the necessary microclimate in the room is also carried out by air circulation. So, for a workplace in auditorium 321 of the TPU 10th building, designed for 12 seats, there is about 10 m^3 of air volume per engineer with a full landing (since the volume of the entire room is 120.9 m^3). Natural air circulation is carried out in the room through an easily opened window opening, as well as a doorway. According to [2], the air circulation in the classroom should be at least 20 m^3/h per seat with an air exchange rate of at least 2. Then the minimum air flow in this room will be equal to:

$$G = V \cdot K_{air}, \tag{5.1}$$

where V – volume of the room, m^3;

K_{air} – air exchange rate, h^{-1}.

$$G = V \cdot K_{air} = 120.9 \cdot 2 = 241.8 \text{ m/h}.$$

The obtained value corresponds to the minimum circulation threshold for the classroom of a higher education institution [25]. To maintain this level of air flow, the «VO-4M250B» fan [26] is best suited.

5.2.3 Exceeding the noise level

Noise in the workplace has an irritating effect on the employee, increases his fatigue, and when performing tasks that require attention and concentration, it can lead to an increase in errors and an increase in the duration of the task. Prolonged exposure to noise causes hearing loss of the employee up to his complete deafness.

Table 5.2 shows the permissible noise levels in the classroom according to [27].

Table 5.2 – Values of the permissible noise levels

Sound pressure levels (Db) in octave bands with average geometric 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

When working on a PC in all classrooms, the noise level at the workplace should not exceed 55 dBA.

To protect an employee from the effects of noise and vibration, it is necessary to eliminate their source or reduce its impact on people. To do this, it is necessary to carry out organizational and technical measures to protect personnel from noise and vibration:

– elimination of the cause of noise or vibration;

– rational planning of the premises;

– the use of isolation from external sources of vibration;

– automation of the process in places where vibrating machines work;

– the use of personal protective equipment (PPE) [28].

5.2.4 Insufficient illumination of the working area

Light sources can be both natural (the sun) and artificial objects (light bulbs). Lack of lighting can develop nearsightedness and astigmatism in an employee. In the rooms where the work is being carried out, it is necessary to provide an artificial lighting system from fluorescent fluorescent lamps or incandescent lamps.

According to [29], the following illumination standards are applied in computer classes of educational institutions: illumination E = 300 lx, uniformity of illumination U_0 is not less than 0.60, the pulsation coefficient K_p is not more than 15 %. The number of lamps required to provide the required level of illumination can be determined by the formula:

$$N = \frac{E \cdot S \cdot K}{U \cdot n \cdot \Phi_l}, \qquad (5.1)$$

where E is the required illumination equal to 300 lx;

S is the area of the cabinet, S = 40.3 m^2;

K is the margin factor, taking into account the decrease in illumination during operation, K=1.15;

U is the utilization factor;

n is the number of lamps in the lamp;

Φ_l is the luminous flux of one lamp.

The utilization factor *U*, equal to the reciprocal of the safety factor for an office space, is equal to 0.711.

Luminaires type LPO-71-4×18 – 552, which is used in room 321 of 10th academic building, contains four lamps of LD–18, which have the luminous flux of 880 lm for each one. Then:

$$N = \frac{E \cdot S \cdot K}{U \cdot n \cdot \Phi_l} = \frac{300 \cdot 40.3 \cdot 1.15}{0.71 \cdot 4 \cdot 880} = 5.56 \approx 6.$$

In order to avoid insufficient illumination of the workspace, the estimated number of lamps is rounded up to the whole side. Thus, the required number of lamps in room 321 of the 10th academic building is 8 pieces. The requirements for the number of lamps during the research work were met.

5.2.5 Increased level of electromagnetic radiation

In this work, the impact of electric and magnetic fields (most often, biological impact) is possible only in the case of the research process – as a result of working with a PC. The most sensitive to electric and magnetic fields are cardiovascular (pain in the heart area, hypotension), nervous (appearance of autonomic dysfunctions, great irritability, increased fatigue and impaired higher nervous activity), immune (impaired immunogenesis), endocrine (adrenaline production increases, pituitary gland activity decreases) and reproductive systems. The biological effect of electric and magnetic fields under conditions of long-term exposure can accumulate, as a result of which the development of long-term consequences of degenerative processes in the central nervous system, neoplasms, and hormonal diseases is possible. Maximal permissible levels of electric and magnetic fields created by the personal computer are presented in Table 5.3 [30].

Table 5.3 – Maximum permissible levels of electric and magnetic fields

Name of parameters	Frequancy	Value of parameter
Electric field strength	5 Hz – 2 kHz	25 V/m
	2 kHz – 400 kHz	2.5 V/m

Continuation of Table 5.3

Magnetic flux density	5 Hz – 2 kHz	250 nTl
	2 kHz – 400 kHz	25 nTl

During the work, the parameters defined according to the table were not exceeded.

There are a number of recommendations, following which you can reduce the negative impact of computer technology:

– if several computers or laptops are constantly in the same room, then they should be placed around the perimeter of the room, leaving the center free, since the sides and back of the monitor generate much more harmful radiation.

– turn off the computer after the end of work: the longer it works, the more radiation it generates, and releases a significant amount of harmful substances into the environment.

– the use of a special protective film.

– systematic dusting, wet cleaning and the use of ionizers [31].

5.2.6 Psychophysiological factors

Neuropsychiatric overload is divided into:

– mental overstrain, including caused by information load;

– overstrain of analyzers, including caused by information load;

– monotony of work – emotional overload [32].

Overstrain of the visual analyzers can lead to fatigue and disruption of the contractile function of the eye muscles. Nervous and emotional stress can be caused by responsibility for the work performed, high requirements for the quality of the work performed, the complexity of the work, especially in conditions of time shortage. Nervous and emotional stress can disrupt the functional state of the cardiovascular and central nervous system.

To reduce the impact of neuropsychiatric overload, the limits of the duration of breaks are established. Table 5.4 shows the recommended rational work and rest regime for people of intellectual labor with an 8-hour working day for the morning shift [33].

Table 5.4 – Rational regime of work and rest for persons of intellectual labor with an 8-hour working day

№	Break	Time of the event	Duration		Filling the break
			Group 1	Group 2	
1	Scheduled break	After 2 hours from the start of work	5 – 7 min.	7 – 10 min.	A set of physical exercises for coordination, accuracy and speed of movements and concentration of attention
2	Meal break	After 4 hours from the start of work	30 min.	60 min.	Lunch in the dining room, rest
3	Scheduled break	After 6 hours from the start of work	5 – 7 min.	10 – 15 min.	Psychological relief
4	Micropause	Individually as needed	20 – 40 s.	40 c – 3 min.	Micropauses of active recreation

According to [33], the first group includes average workers, and the second group includes workers with a high degree of labor intensity with pronounced nervous and emotional stress, a significant amount of information load, a high degree of responsibility for the work of the technological process, working around the clock. During the research work, a rational work regime was applied, corresponding to the 1st group.

5.2.7 Danger of exposure to electric current

Since in the course of the study, work was carried out with electrical appliances that are under voltage, such as a display, a system unit, a multifunctional unite and peripheral input/output devices, there is a danger of electric shock to the employee. The possibility of electric shock to a person may arise from direct accidental contact with live parts that are under voltage, during work or repair of equipment, when touching non-live parts (in case of a violation of the insulation of live parts), and also in the case of a short circuit of a high-voltage power supply of a computer or monitor.

Regarding the danger of electric shock to people, premises include:

1) premises without increased danger, in which there are no conditions that create increased or special danger;

2) premises with increased danger, characterized by the presence of one of the following conditions that create increased danger:

– dampness or conductive dust;

– conductive floors (metal, earth, reinforced concrete, brick, etc.);

– high temperature;

– the possibility of simultaneous human contact with metal structures of buildings connected to the ground, technological devices, mechanisms, etc., on the one hand, and to metal enclosures of electrical equipment (open conductive parts), on the other;

3) particularly dangerous premises characterized by the presence of one of the following conditions that create a special danger:

– special dampness;

– chemically active or organic medium;

– two or more conditions of increased danger at the same time [34].

Working room 321 belongs to category 1, since it does not contain excessive dampness or conductive dust, the floors of the room do not conduct electricity, the temperature does not exceed the set room value, and there is no possibility of closing the circuit by simultaneously touching the metal structures of the building connected to the ground, technological devices, mechanisms, etc., on the one hand, and to metal cases of electrical equipment (open conductive parts) – on the other [34].

According to the Order of the Ministry of Labor dated December 15, 2020 N 903n [35] employees and other visitors to room 321 for electrical safety can be classified as group I, since they are non-electrotechnical personnel (does not apply to electrical and electrotechnological personnel).

Measures to ensure electrical safety of electrical installations include:

– disconnection of voltage from current-carrying parts on which or near which work will be carried out, and taking measures to ensure that it is impossible to supply voltage to the place of work;

– hanging posters indicating the place of work; – grounding of the housings of all installations through the zero wire;

– coating of metal surfaces of tools with reliable insulation;

– unavailability of current-carrying parts of the equipment (enclosure of electric-reflecting elements, current-carrying parts) [36].

5.2.8 Fire and explosion hazard

A fire in an office can lead to irreversible consequences (loss of valuable information, damage to property, injuries and death of people), so it is necessary:

– to identify and eliminate all causes of a fire;

– to analyze the plan of measures to eliminate the fire in the building; building evacuation plan.

According to the fire safety standards NPB 105-03 [37], premises with personal computers are classified as category B3 (fire hazardous) and should be located in buildings of I or II degree of fire resistance.

The most probable classes of fires in rooms with computer equipment are «A» (combustion of solid substances with accompanying smoldering) and «E» (ignition of electrical installations).

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

Organizational measures provide for proper operation of equipment, proper maintenance of buildings and territories, fire-fighting 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, norms in the design of buildings, when installing electrical wires and equipment, heating, ventilation, lighting, proper placement of equipment.

Operational measures include timely preventive inspections, repairs and tests.

Regime measures include the establishment of rules for the organization of work, and compliance with fire protection measures.

To prevent a fire in an organization, it is necessary first of all to implement primary fire safety measures, such as:

– cleaning of the entire territory from combustible garbage;

– use of non-combustible materials in construction;

– creation of fire-resistant barriers, with the help of metal doors, capital walls;

– equipment of shields with fire-fighting equipment;

– installation of automatic means of fire notification and extinguishing;

– electrical wiring must be kept in full working order and periodically checked.

In case of an emergency, it is necessary to:

– stop working;

– inform the management (on duty);

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

– take measures to eliminate the accident in accordance with the instructions [38].

5.3 Emergency safety

Emergency situations violate the normal working conditions of employees of enterprises and have a serious impact on the functioning of organizations affected by emergencies in general. Therefore, in many places where a person can be overtaken by danger, in particular at enterprises, a set of measures is being developed to help prevent the occurrence of an emergency.

When conducting any scientific research, unforeseen emergencies may arise. By the nature of their occurrence, emergencies can be divided into natural, man-made, ecological, biological, social and anthropogenic. Technogenic emergencies can have the most significant impact on the researcher's work.

Probable emergencies that may occur during the work are:

– fires in the building;

– electric shock;

– fall from the height of your own growth.

A fire in the building where the study is being conducted may occur if the rules of operation of one or another equipment used during the study are violated.

Electric shock may occur as a result of breakdown of electrical equipment caused by violation of operating conditions.

Fall from the height of your own growth may occur if the coefficient of friction of the floor surface does not correspond to the established by SP 29.13330.2011 [39].

Measures to prevent emergency and emergency situations, as well as actions in case of their occurrence are presented in Table 5.5.

Table 5.5 – Emergency situations at the workplace, measures to prevent them and actions in case of their occurrence

Emergency situation	Prevention measures	Emergency response
Fire	1. check the condition of electrical devices and heating devices; 2. comply with fire safety rules in accordance with the requirements of regulatory documentation; 3. conduct training and instructing employees, practice fire extinguishing skills	1. in case of fire, call 01, 101, 112; 2. use powder and carbon dioxide fire extinguishers as extinguishing agents
Electric shock	1. to prevent damage to the insulation of current-carrying parts of electrical installations; 2. to carry out routine inspections of electrical damage; 3. to observe the permissible distance between insulators and wires;	1. turn off the voltage on the damaged installation; 2. fence off the place, put up signs; 3. if there are victims, provide first aid and call an ambulance by phone 112, 103

Continuation of Table 5.5

	4. to comply with safety and technical operation rules; 5. to train and instruct workers; 6. to install protective grounding.	
Fall from the height of your own growth	1. Timely cleaning of the audience, the release of passages from obstructing objects. 2. Timely detection of the appearance of defects in the floor covering, reporting this to the relevant services of the organization. 3. Fencing hazardous areas (temporary and permanent protective fences), including during cleaning of premises. 4. Use of anti-slip coatings if it is impossible to reduce the slipperiness of the floors.	1. At the time of the fall, group up (press your head to your chest, hands to your body) and land on your side, rolling, softening the impact on the floor surface. 2. Do not try to save things that you carry in your hands. 3. Examine yourself for injuries. In case of sharp pains – do not move and do not allow anyone to move you, call an ambulance by phone 103.

5.4 Conclusions on the section

In the chapter were considered and analyzed following dangerous and harmful factors of room 321 of the TPU 10th building:

– deviation of microclimate indicators [25];

– exceeding the noise level [27, 28];

– insufficient illumination of the working area [29];

– increased level of electromagnetic radiation [30];

– psychophysiological factors [33];

– danger of exposure to electric current [34, 36];

– fire and explosion hazard [37, 38].

Workroom 321 is assigned to:

– on electrical safety to category 1 (premises without increased danger) [35];

– on fire safety to category «B3» [37].

It was also found that microclimatic conditions are observed through the use of heating and air conditioning systems. The illumination in the workplace and noise levels are within the permissible limits of the norm [27, 29]. The probability of electric shock is minimized. The room is equipped according to the requirements of electrical safety [36] and fire and explosion safety [38]. Thus, it can be concluded that the workplace meets the standards of protection from harmful and dangerous factors.

In the final part of the section, measures are considered to prevent the most likely emergency and emergency situations, namely, a fire, an accident with electrical equipment and fall from the height of your own growth that may occur during the work. Also, a set of measures necessary in case of occurrence of these emergency situations.

Conclusion

In the thesis, the result of the analysis of the existing experience of modernization of nuclear reactors is presented. All modernization methods can be included in three main groups: methods of physical optimization, methods of increase the heat transfer coefficients and improvements in fuel rod and fuel assembly designs. the potential possibility of increasing the reactor power without making significant changes to its design is also shown.

Operational limits of materials used in biological shielding of the reactor are identified:

– maximum operational temperature equal to 250 °C;

– maximum temperature gradient equal to 2.5 °C/cm (for Portland Cement);

– maximum temperature gradient equal to 4.5 °C/cm (for heavy concrete).

The research reactor of the Tomsk Polytechnic University IRT-T is considered, the main design features and technical characteristics of the reactor and its cooling system are given.

The distribution of energy release density in the most heat-stressed area of biological protection has been studied. The change in the energy release density with distance from the source has an exponential form, while the height distribution repeats the shape of the neutron flux density distribution, symmetrical with respect to the center of the core and described by the cosine. Based on this study and experimental data, the model of the IRT-T reactor in MCU-PTR was detailed.

A model of the most heat-stressed part of biological shielding in SolidWorks Flow Simulation has been prepared and verified for the reactor power of 6 MW and 6.6 MW. The relative deviation of the calculation results of the concrete temperature from the readings of the measurement channels did not exceed 5.1 %.

The calculation of the maximum values of temperature and temperature difference of biological protection materials for the reactor power of 10 MW was carried out:

– the maximum temperature of Portland cement is t_{PC} = 69.63 ± 0.18 °C and the maximum temperature gradient is equal to Δt_{PC} = 0.32 °C/cm;

– the maximum temperature of concrete with density of $\rho_{HC1} = 5200$ kg/m^3 is equal to t_{HC1} = 62.95 ± 0.08 °C/cm and the maximum temperature gradient is equal to Δt_{HC1} = 0.25 °C;

– the maximum temperature of concrete with density of $\rho_{HC2} = 6500$ kg/m^3 is equal to t_{HC2} = 69.75 ± 0.15 °C and the maximum temperature gradient is equal to Δt_{HC2} = 0.93 °C/cm.

Based on the results obtained, it can be concluded that when the reactor is operated at a capacity of 10 MW, the operational limits for biological shielding materials are not exceeded.

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Appendix A

(obligatory)

Table A.1 – Main characteristics of the IRT-T reactor

Parameter	Value
Thermal power, MW	6
Core heat transfer surface, m^2	29.6
Core volume, m^3	59.3
Maximum energy density, kW/l	227
Maximum heat flux density, kW/m^2	427
Pressure drop at the core, m of water column	3.4
Average coolant velocity in fuel assembly gaps, m/s	2.88
Coolant mass flow rate, t/h	900
Temperature of the coolant at the inlet to the core, °C	30÷55
Maximum calculated fuel element surface temperature, °C	77
Surface boiling start temperature, °C	123

Appendix B

(obligatory)

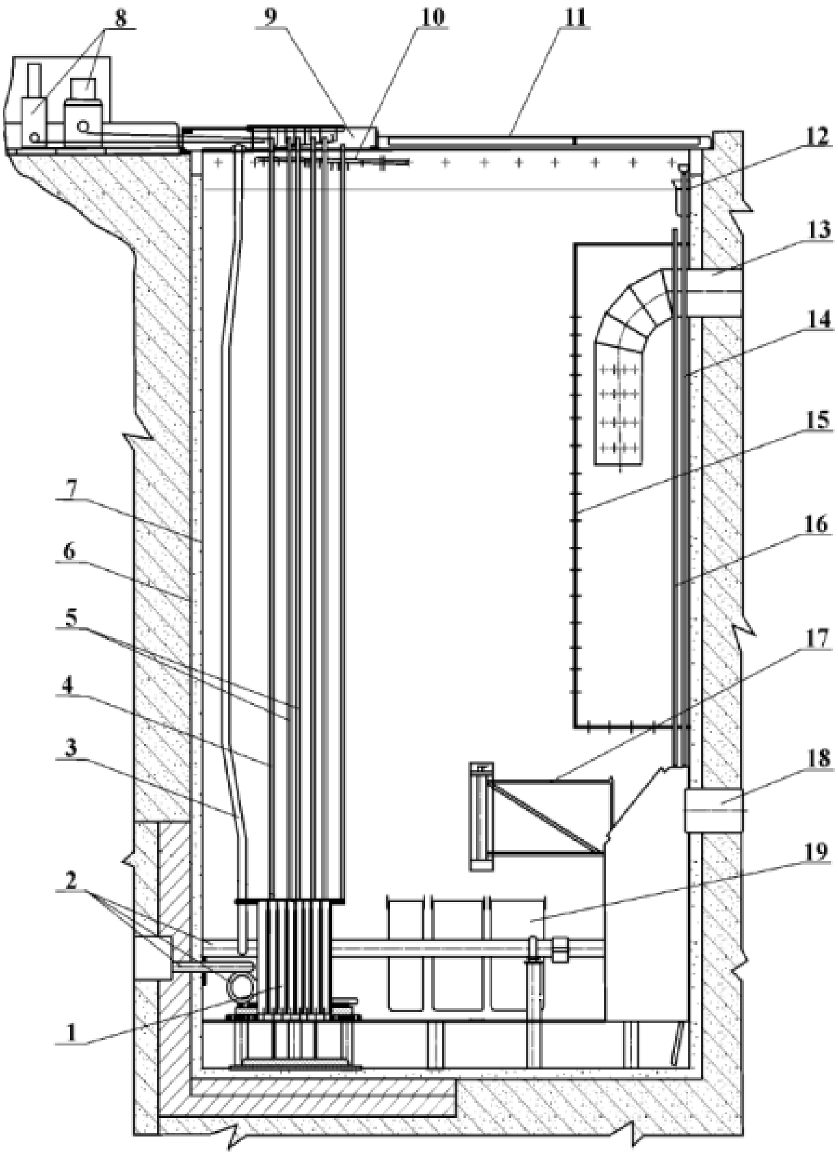

Figure B.1 – Longitudinal section of the IRT-T reactor:
1 – reactor core; 2 – horizontal experimental channels; 3 – vertical experimental channels; 4 – channel with a control rod; 5 – central experimental channels; 6 – aluminum tank; 7 – stainless steel tank; 8 – control rod drive mechanism; 9 – control and safety system site; 10 – sprinkler; 11 – transparent flooring; 12 – overflow funnel;13 – delivery piping; 14 – emptying pipe; 15 – distribution tank; 16 – pipe for breaking the syphon ;17 – fuel assemblies transportation device; 18 – intake pipe; 19 – temporary storage of fuel assemblies

Appendix C

(obligatory)

Table C.1 – Heat release in Sector 1 at 6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.51	27.37	2.45	124.68	112.79	12.14	7.08	3.38	2.77
2	8.18	46.91	6.08	36.34	20.85	24.34	13.18	4.31	5.31
3	10.45	68.63	8.75	50.50	30.62	25.10	19.89	10.31	5.67
4	9.25	70.28	6.82	53.18	41.58	25.97	13.48	8.01	7.44
5	6.15	54.42	5.53	47.67	26.55	14.23	8.90	6.08	5.24
6	3.84	30.53	7.54	24.22	21.49	12.42	7.94	3.96	2.74

Table C.2 – Heat release in Sector 2 at 6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.45	41.10	4.37	26.72	14.96	13.08	8.96	8.10	3.99
2	7.44	70.65	5.46	42.92	24.97	24.93	10.09	7.78	6.35
3	8.39	97.57	11.55	64.23	44.06	30.40	18.79	12.75	10.14
4	8.94	106.86	12.61	56.03	29.85	24.22	18.37	11.89	11.46
5	7.85	73.11	8.12	42.17	24.78	20.57	11.70	8.52	4.14
6	3.62	48.69	4.09	26.35	20.36	19.49	8.23	5.93	4.22

Table C.3 – Heat release in Sector 3 at 6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.73	33.11	3.88	20.25	10.34	16.99	10.83	7.54	4.33
2	7.10	65.27	4.30	39.68	20.27	22.37	10.83	7.12	7.29
3	8.70	88.08	7.02	55.32	29.39	25.30	14.15	9.24	7.63
4	9.66	86.02	10.45	53.55	29.49	26.19	15.67	9.85	9.76
5	5.55	51.43	4.42	30.37	18.21	19.18	11.51	9.78	8.04
6	4.57	33.50	2.71	20.25	12.14	12.01	8.03	8.27	5.95

Table C.4 – Heat release in Sector 4 at 6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	9.54	69.72	9.03	57.24	34.21	28.99	16.92	16.41	8.24
2	12.75	139.81	14.39	85.01	61.25	38.92	27.41	17.07	9.64
3	15.65	164.58	19.75	121.11	75.20	44.15	34.59	17.72	16.85
4	22.26	180.29	21.51	114.57	78.64	55.58	38.51	26.37	15.62
5	13.56	130.04	11.31	81.51	66.20	42.66	29.60	21.30	14.62
6	5.56	83.81	9.43	55.30	35.43	27.46	23.15	10.42	9.63

Table C.5 – Heat release in Sector 5 at 6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	4.50	42.34	5.98	29.58	24.11	15.83	8.93	7.84	7.42
2	7.17	88.85	9.23	50.81	32.89	22.86	14.41	8.37	6.38
3	8.11	98.26	8.72	56.33	37.45	26.40	18.59	12.70	11.48
4	7.42	81.17	10.13	48.14	38.06	33.20	20.43	13.55	8.30
5	5.89	74.05	6.26	39.28	27.75	20.36	14.81	10.53	6.22
6	2.78	43.99	5.47	23.60	20.05	12.82	9.83	7.79	4.65

Table C.6 – Heat release in Sector 6 at 6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	2.09	26.78	1.48	21.84	16.01	8.65	6.20	5.61	3.94
2	2.59	38.80	3.78	22.15	16.55	14.68	9.56	4.26	1.71
3	3.51	29.17	-	10.73	16.93	15.73	14.44	6.23	1.86
4	3.34	25.33	-	8.28	13.67	13.06	12.14	3.79	2.53
5	1.69	22.77	-	7.41	13.30	12.81	11.87	3.40	1.20
6	1.55	21.96	2.34	15.52	9.75	9.49	8.06	3.22	1.38

Table C.7 – Heat release in bottom biological shielding at 6 MW

Layer	Heat release, W	
	The most stressed	Remaining part
Steel tank	24.33	100.76
Portland cement	57.44	187.24
Aluminum tank	27.47	72.72
Concrete 1	59.78	198.59
Concrete 2	62.91	177.30
Concrete 3	34.21	135.21
Concrete 4	29.65	110.93
Concrete 5	23.42	100.19
Concrete 6	20.94	83.67
Concrete 7	19.32	70.80
Concrete 8	12.34	56.60
Concrete 9	9.36	39.98
Concrete 10	8.38	37.32

Appendix D

(obligatory)

Table D.1 – Heat release in Sector 1 at 6.6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.86	30.11	2.70	27.15	14.07	13.35	7.79	3.72	3.04
2	9.00	51.61	6.69	39.98	22.94	26.77	14.50	4.74	5.85
3	11.50	75.49	9.63	55.55	33.68	27.60	21.88	11.34	6.24
4	10.18	77.30	7.51	58.50	45.73	28.57	14.83	8.81	8.18
5	6.77	59.86	6.08	52.44	29.20	15.66	9.79	6.69	5.76
6	4.22	33.58	8.29	26.64	23.64	13.66	8.74	4.36	3.02

Table D.2 – Heat release in Sector 2 at 6.6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.79	45.21	4.81	29.39	16.46	14.38	9.86	8.91	4.39
2	8.18	77.71	6.00	47.21	27.46	27.42	11.10	8.56	6.98
3	9.23	107.32	12.71	70.66	48.47	33.44	20.67	14.03	11.15
4	9.83	117.54	13.87	61.64	32.83	26.64	20.21	13.08	12.61
5	8.64	80.42	8.93	46.39	27.25	22.63	12.87	9.38	4.56
6	3.98	53.56	4.50	28.98	22.40	21.44	9.06	6.52	4.65

Table D.3 – Heat release in Sector 3 at 6.6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.73	33.11	3.88	20.25	10.34	16.99	10.83	7.54	4.33
2	7.10	65.27	4.30	39.68	20.27	22.37	10.83	7.12	7.29
3	8.70	88.08	7.02	55.32	29.39	25.30	14.15	9.24	7.63
4	9.66	86.02	10.45	53.55	29.49	26.19	15.67	9.85	9.76
5	5.55	51.43	4.42	30.37	18.21	19.18	11.51	9.78	8.04
6	4.57	33.50	2.71	20.25	12.14	12.01	8.03	8.27	5.95

Table D.4 – Heat release in Sector 4 at 6.6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	10.49	76.69	9.93	62.97	37.63	31.89	18.61	18.06	9.06
2	14.02	153.79	15.83	93.51	67.38	42.81	30.15	18.78	10.60
3	17.21	181.04	21.72	133.22	82.72	48.56	38.05	19.49	18.54
4	24.48	198.32	23.66	126.02	86.50	61.14	42.37	29.00	17.18
5	14.92	143.04	12.44	89.66	72.82	46.93	32.56	23.43	16.08
6	6.11	92.19	10.37	60.83	38.98	30.21	25.47	11.46	10.59

Table D.5 – Heat release in Sector 5 at 6.6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	4.96	46.58	6.57	32.54	26.52	17.42	9.82	8.63	8.17
2	7.88	97.74	10.15	55.89	36.18	25.15	15.85	9.21	7.02
3	8.92	108.09	9.59	61.97	41.20	29.04	20.45	13.97	12.63
4	8.16	89.28	11.14	52.96	41.86	36.52	22.48	14.90	9.13
5	6.48	81.45	6.89	43.21	30.52	22.40	16.30	11.58	6.85
6	3.06	48.39	6.02	25.96	22.05	14.10	10.81	8.57	5.11

Table D.6 – Heat release in Sector 6 at 6.6 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	2.30	29.45	1.63	24.02	17.61	9.51	6.82	6.17	4.34
2	2.85	42.68	4.16	24.37	18.20	16.15	10.52	4.69	1.88
3	3.86	32.08	-	11.80	18.63	17.31	15.88	6.85	2.05
4	3.68	27.86	-	9.11	15.03	14.36	13.35	4.17	2.79
5	1.86	25.05	-	8.15	14.63	14.09	13.05	3.74	1.32
6	1.70	24.16	2.57	17.07	10.72	10.44	8.86	3.54	1.52

Table D.7 – Heat release in bottom biological shielding at 6.6 MW

Layer	Heat release, W	
	The most stressed	Remaining part
Steel tank	26.76	110.8393
Portland cement	63.18	205.9637
Aluminum tank	30.22	79.98778
Concrete 1	65.76	218.4538
Concrete 2	69.20	195.0317
Concrete 3	37.63	148.7345
Concrete 4	32.61	122.0213
Concrete 5	25.76	110.2044
Concrete 6	23.03	92.03226
Concrete 7	21.25	77.88267
Concrete 8	13.57	62.26421
Concrete 9	10.29	43.97802
Concrete 10	9.22	41.04732

Appendix E

(obligatory)

Table E.1 – Heat release in Sector 1 at 10 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	5.85	45.62	4.09	41.13	21.32	20.23	11.80	5.63	4.61
2	13.63	78.19	10.13	60.57	34.76	40.56	21.97	7.18	8.86
3	17.42	114.39	14.59	84.17	51.03	41.83	33.15	17.18	9.45
4	15.42	117.13	11.37	88.63	69.29	43.28	22.46	13.35	12.39
5	10.26	90.69	9.21	79.45	44.24	23.72	14.83	10.13	8.73
6	6.39	50.88	12.56	40.36	35.82	20.70	13.24	6.60	4.57

Table E.2 – Heat release in Sector 2 at 10 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	5.75	68.50	7.28	44.53	24.94	21.79	14.94	13.50	6.65
2	12.40	117.75	9.10	71.54	41.61	41.54	16.81	12.97	10.58
3	13.98	162.61	19.25	107.06	73.44	50.67	31.31	21.26	16.90
4	14.90	178.10	21.01	93.39	49.74	40.36	30.62	19.82	19.10
5	13.09	121.85	13.54	70.28	41.29	34.29	19.50	14.20	6.91
6	6.04	81.15	6.82	43.91	33.94	32.48	13.72	9.88	7.04

Table E.3 – Heat release in Sector 3 at 10 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	6.21	55.18	6.46	33.74	17.23	28.31	18.05	12.57	7.21
2	11.84	108.79	7.17	66.14	33.78	37.29	18.05	11.87	12.16
3	14.51	146.80	11.70	92.21	48.99	42.17	23.58	15.40	12.71
4	16.09	143.37	17.41	89.25	49.15	43.66	26.12	16.42	16.26
5	9.26	85.71	7.37	50.62	30.35	31.97	19.19	16.29	13.40
6	7.62	55.83	4.52	33.74	20.23	20.02	13.38	13.79	9.92

Table E.4 – Heat release in Sector 4 at 10 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	15.90	116.19	15.05	95.41	57.02	48.31	28.20	27.36	13.73
2	21.25	233.01	23.98	141.68	102.09	64.87	45.68	28.46	16.06
3	26.08	274.31	32.91	201.84	125.33	73.58	57.65	29.53	28.08
4	37.10	300.48	35.85	190.94	131.07	92.64	64.19	43.94	26.03
5	22.60	216.73	18.84	135.84	110.34	71.10	49.33	35.50	24.37
6	9.26	139.69	15.71	92.16	59.06	45.77	38.59	17.37	16.04

Table E.5 – Heat release in Sector 5 at 10 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	7.51	70.57	9.96	49.31	40.18	26.39	14.88	13.07	12.37
2	11.95	148.09	15.38	84.69	54.82	38.10	24.01	13.96	10.63
3	13.52	163.77	14.53	93.89	62.42	43.99	30.99	21.17	19.13
4	12.36	135.28	16.88	80.24	63.43	55.33	34.06	22.58	13.83
5	9.82	123.41	10.44	65.47	46.25	33.94	24.69	17.55	10.37
6	4.64	73.32	9.12	39.34	33.42	21.36	16.38	12.98	7.74

Table E.6 – Heat release in Sector 6 at 10 MW, W

Zone by height	Steel	Portland cement	Aluminum	ρ = 6.5 t/m^3		ρ = 5.2 t/m^3			
				1	2	1	2	3	4
1	3.49	44.63	2.47	36.40	26.68	14.42	10.33	9.34	6.57
2	4.31	64.66	6.30	36.92	27.58	24.47	15.94	7.10	2.85
3	5.85	48.61	-	17.88	28.22	26.22	24.06	10.38	3.10
4	5.57	42.21	-	13.80	22.78	21.76	20.23	6.32	4.22
5	2.82	37.95	-	12.34	22.16	21.35	19.78	5.67	1.99
6	2.58	36.60	3.90	25.87	16.25	15.82	13.43	5.37	2.31

Table E.7 – Heat release in bottom biological shielding at 10 MW

Layer	Heat release, W	
	The most stressed	Remaining part
Steel tank	40.54	167.94
Portland cement	95.73	312.07
Aluminum tank	45.79	121.19
Concrete 1	99.64	330.99
Concrete 2	104.85	295.50
Concrete 3	57.01	225.36
Concrete 4	49.41	184.88
Concrete 5	39.03	166.98
Concrete 6	34.90	139.44
Concrete 7	32.20	118.00
Concrete 8	20.57	94.34
Concrete 9	15.59	66.63
Concrete 10	13.96	62.19