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
Теплогидравлический расчёт 1-го контура реактора ИРТ-Т

УДК 621.039.55:621.039.517

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Томск – 2022 г.

TOMSK POLYTECHNIC UNIVERSITY — ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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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 thesis
Computational thermal hydraulic simulation of the IRT-T 1st circuit

UDC 621.039.55:621.039.517

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Section “Social Responsibility”

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

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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
0АМ0И	Artem Alexandrovich Rybachenko

Topic of research work:

Computational thermal hydraulic simulation of the IRT-T 1st circuit	
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.)*	– thermal power 6 [MW]; – mass flow rate 720 [m^3/h]; – coolant – water; – coolant temperature in core 55 [°C]; – geometry of IRT-T first circuit; – power measuring and control equipment.
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).*	– study of the existing power control system at IRT-T; – analysis of suitable equipment for thermal power control; – creation of a calculation model of the primary circuit in the Ansys Fluent program;

	– assessment of the deviation of the programmatically specified power from that determined by the values at the control points; – analysis of the suitability of the selected power control equipment.
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	31.01.2022

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

Position	Full name	Academic degree, academic status	Signature	Date
Associated Professor Division of Nuclear Fuel Cycle of Nuclear Science and Engineering School	Yuriy Borisovich Chertkov	PhD		

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0АМ0И	Artem Alexandrovich Rybachenko		

ASSIGNMENT FOR THE DIPLOMA PROJECT SECTION
«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

For a student:

Group	Full Name
0АМ0И	Artem Alexandrovich Rybachenko

School	Nuclear Science and Engineering	**Department**	Nuclear Fuel Cycle
Educational level	Master degree	**Specialization**	14.04.02 Nuclear Science and Technology / Nuclear Power Engineering

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 equal to 197 thousand rubles:* *The material costs: 4 thousand rubles, the basic salary: 110 thousand rubles, the additional salary 11 thousand rubles, the labor tax: 36 thousand rubles, the overhead: 36 thousand rubles.*
2. Norms and standards for spending resources	*Supervisor’ salary – 76 thousand rubles per month; engineer’ salary – 28 thousand rubles per month.*
3. The system of taxation used, tax rates, volumes of payments, discounts and loans	*Coefficient of incentive bonuses 25%, coefficient of incentives for the manager for conscientious work activity 10%; contributions for social funds are 30,2% totally.*
Problems to research, calculate and describe:	
1. Assessment of the commercial potential of engineering solutions	*Assessment of project competitive power and SWOT-analysis.*
2. Planning of research and constructing process and making schedule for all periods of the project	*Formation of plan and schedule of thesis:* *– definition of the structure of work;* *– determination of the labor intensity of work;* *– development of the Gantt chart.*
3. Budgeting an engineering project	*Creation of the project budget:* *– materials cost;* *– additional salary;* *– labor tax;* *– overhead costs;* *– formation of budget costs.*
Graphic materials	
1. Market segmentation map *2. Competitive power of the project* *3. SWOT matrix* *4. Project schedule* *5. Gantt chart* *6. Project budget* *7. Comparative characteristics of the project*	

Date of issuance of the assignment for Master Thesis completion according to the schedule	31.01.2022

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

Position	Full Name	Academic degree, academic status	Signature	Date
Associate Professor Division for Social Sciences and Humanities School of Core Engineering Education	Lubov Yurievna Spicyna	PhD		

Assignment accepted for execution by a student:

Group	Full Name	Signature	Date
0АМ0И	Artem Alexandrovich Rybachenko		

ASSIGNMENT FOR THE DIPLOMA PROJECT SECTION
«SOCIAL RESPONSIBILITY»

For a student:

Group	Full Name
0АМ0И	Artem Alexandrovich Rybachenko

School	Nuclear Science and Engineering	Department	Nuclear Fuel Cycle
Education level	Master degree	**Specialization**	14.04.02 Nuclear Science and Technology / Nuclear Power Engineering

Topic of Master Thesis:

Computational thermal hydraulic simulation of the IRT-T 1st circuit	
Initial data for the section "Social Responsibility":	
1. Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application	– first circuit of IRT-T reactor.
Problems to research, 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;	– GOST 23000-78. The "man-machine" system. Control panels. General ergonomic requirements; – GOST 21889-76. The "man-machine" system. Operator's chair. General ergonomic requirements.
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	– indoor climate; – quality of illumination; – ionizing radiation; – noise.
3. Ecological safety:	– analysis of the impact of the object of study on the atmosphere, hydrosphere, lithosphere.
4. Safety in emergency situations:	– selection of possible emergencies during the operation of the object under consideration and the procedure for actions during them.

Date of issuance of the assignment for Master Thesis completion according to the schedule	31.01.2022

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

Position	Full name	Academic degree, academic status	Signature	Date
Associated Professor Division of Nuclear Fuel Cycle of Nuclear Science and Engineering School	Yuriy V. Perederin	PhD		

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0АМ0И	Artem Alexandrovich Rybachenko		

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)

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)
31.01.2022	*Assignment accepted*	
14.02.2022	*IRT-T design and power control system studying*	
28.02.2022	*Development of research procedure*	
21.03.2022	*Creation of model geometry and mesh*	
28.03.2022	*Computational analysis of the reactor thermal hydraulic*	
04.04.2022	*Obtained data analysis and processing*	
11.04.2022	*Making conclusion*	
30.05.2022	*Thesis writing*	
03.06.2022	*Thesis submission*	

COMPILED BY:
Scientific supervisor:

Position	Full name	Academic degree, academic status	Signature	Date
Associate Professor	Yuriy. B. Chertkov	PhD		

APPROVED BY:

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

ABSTRACT

Master’s thesis contains 88 pages, 28 figures, 24 tables, 47 references, 3 appendixes.

Key words: Research reactor, IRT-T, Ansys Fluent, thermal hydraulic, power control.

Research objects: Primary circuit of IRT-T reactor, process parameters control system.

Goal of research – verification of the implementation and possible improvement of the thermotechnical method for controlling the thermal power of the IRT-T reactor.

Research tasks: simulation of reactor first circuit, assessment of the possibility of thermal monitoring of reactor power, assessment of the financial side of the work; social, legal and environmental issues are considered.

Obtained data make it possible to judge about possibility of implementing a thermotechnical method of power control. Understand some features of the power distribution in the reactor tank and choose the most suitable places for installing control sensors.

Field of application: thermal physics, nuclear industry.

The economic efficiency/significance of the work is high.

Table of contents

Introduction

In accordance with the requirements of the regulations for the safe operation of reactor installations the thermal power of the reactor is one of the main controlled parameters, which determine the limits and conditions for their safe operation. At the same time the thermal power of the reactor is also the main parameter for determining the technical and economic performance in general (for example, the possibility of operating at an increased level of nominal power).

For example, for power reactors there are up to five methods for determination of the reactor power, each of which with its own weighting factor is included in the determination of the average power. These methods are based on the conversion of radiation energy and temperature difference into the thermal power of the reactor. Methods based on the temperature difference of the coolant at the inlet and outlet of the circuits can be summarized for simplicity as thermotechnical or thermal.

IRT-T – thermal research reactor – Tomsk. This is a pool-type medium-flux reactor with a thermal power of 6 MW located in Tomsk. The power of the reactor was increased after reconstruction in 1977-1984. Over the past decades work has been underway to up the reactor power to 10-12 MW. A change in the main characteristics of the reactor entails the need to improve all the reactor instrumentation and first of all the reactor power control systems.

Thermal power control at the IRT-T reactor is following according to the readings of the ionization chambers. Conversion of the neutron flux density into a current is caused by help of three fission chambers (FC) KN 012 and one ionization chambers (IC): KNK-53, the values of which are converted into the thermal power of the reactor which provides operational information about the state of the reactor.

Determining the reactor power from the readings of the IC located in its reflector has features that don't allow obtain reliable results. These features are associated with unbalanced load of fuel in the reactor and position changing of the control rods that affect the neutron flux incident on the IC. This due to the fact that at constant neutron power of the reactor (readings of the IC) the thermal power of the reactor can vary within 10-15 %.

The presence of one control method isn’t acceptable in terms of the reliability of the obtained values. IRT-T is equipped with all the necessary detectors and sensors for determining the thermal power by thermotechnical methods according to the temperature of the core, heat exchangers of the primary and secondary circuits. Some of this instrumentation is even included in the reactor control and protection system (CPS), but the possibility of using it as a means of power control wasn’t initially planned.

As part of testing the possibility of power control by the thermal method, the following facts was obtained. According to the IC the power of the reactor after reaching its nominal power is 6 MW, while the thermal method can give values in a range of 6-7 MW and even higher. The task develops of analyzing the existing system in order to verify for thermal method and improve it.

The master's thesis is concerned with the work on the thermal hydraulic calculation of the primary circuit of the IRT-T reactor in order to verify the implementation and possible improvement of the thermotechnical method for the thermal power control of the IRT-T reactor. The numerical calculation was performed in the ANSYS Fluent program using the finite volume method. The data obtained make it possible to judge the possibility of implementing a thermotechnical method of power control, understand some features of the power distribution in the reactor tank and choose the most suitable places for installing sensors.

The relevance of the work is to improve the power control of the operating thermal reactor. Firstly, it increases its safety and efficiency, and secondly, it is can be done by instrumentation system already working in reactor.

To achieve this goal, the following tasks were performed:

– review of relevant literature on the selected topic was done;

– structure of the IRT-T reactor and instrumentation system were studied;

– calculation method was chosen;

– computational model of the first circuit of reactor was prepared for calculation in the Ansys Fluent program;

– assessed the suitability of the existing system and proposed ways to improve it;

– assessment of resource efficiency and resource saving was done;

– issues related to industrial safety and labor protection are considered.

1 Literature review

1.1 Research reactors of IRT type. Features of IRT-T

Construction and operation experience of pressurized water reactors has proven their advantage over other types: simplicity of design, ease of experimentation, relatively low cost, low operating costs and safety in operation. Pressurized water research reactors also provide significant neutron fluxes at quiet operating conditions. Due to this, pressurized water research reactors are most widely used [1].

IRT - thermal research reactor. These are serial water-cooled pool-type reactors. The first IRT reactor was launched at the Institute of Atomic Energy. I.V. Kurchatov in 1957. Total of 9 reactors were built [1].

Thermal Research Reactor - Tomsk (IRT-T). A 6 MW medium-flow reactor of a pool type, with water as a coolant and an upper biological shield, and beryllium as a reflector. It was brought into operation in 1967, modernized in 1984 and in 2004-2005, it was created as a training and research nuclear reactor. Students of technical specialties of Tomsk Polytechnic University (TPU) have laboratory practice at the reactor. Being a powerful source of neutrons and gamma radiation, it allows conducting scientific researches in the geological and geochemical field, the production of neutron-transmutation doped silicon, and the production of radiopharmaceuticals [2].

Use of fuel assemblies of the IRT-3M type makes it possible to obtain a compact core with high neutron leakage into the reflector. Beryllium as a reflector material makes it possible to provide a high density and a wide energy spectrum of thermal neutrons in experimental channels [3].

1.2 Reactor power control

The operation of reactors requires operational control over the thermal power of the reactor. Control lay on the in-core instrumentation system (ICIS) [4]. The main purpose of the system is to ensure the safe and economical operation of the reactor in the power range by collecting, processing and presenting information to the operator about the state of the core and the primary circuit. Information about the total thermal power of the reactor, the distribution of energy release over the volume of the core, the temperature and heating of the coolant in the 1st circuit and etc. is visualized with a sufficient degree of accuracy for operator [5].

The procedure for monitoring the reactor power, fuel burnup in fuel assemblies, and, consequently, programs for partial fuel refueling, etc., are based on measurements of the neutron and thermal powers of the reactor in different versions, as well as the energy release fields in the reactor.

The reactor power monitoring procedure: fuel burnup in fuel assemblies and, consequently, programs for partial fuel refueling and etc. are based on measurements of the neutronic and thermal powers of the reactor in different options, as well as the energy release fields in the reactor.

The system provides control over the neutronic and thermal hydraulic parameters of the coolant. ICIS for power control uses two methods: energy conversion of radiation and temperature signals [6].

1.2.1 Conversion of ionizing radiation energy into reactor power

To register ionizing radiation are used methods based on the interaction of radiation with matter: gamma and neutron induced reactions. Fission chambers (FC), ionization chambers (IC), direct charge detectors (DCD), electron emission neutron detectors (END), and thermal neutron detectors (TND) are usually used as detectors [4, 5].

Let’s show in detail operation of the IC and FC as the detectors used on the IRT-T. Ionization chambers and fission chambers register charged particles, they can register neutrons and gamma rays. When they interact with the substance of the screen (solid or gaseous) charged particles are created.

Gamma radiation creates electrons by the photoelectric effect, the Compton effect and the formation of electro-positron pairs. These electrons are registered due to the ionization they cause.

Neutrons can be registered as a result of a nuclear reaction accompanied by the emission of charged particles registered by detector. As the reaction (n, α) and (n, f)

are most often used, the screen substance is B^{10} and U^{235} respectively. The IC scheme is shown in Figure 1.

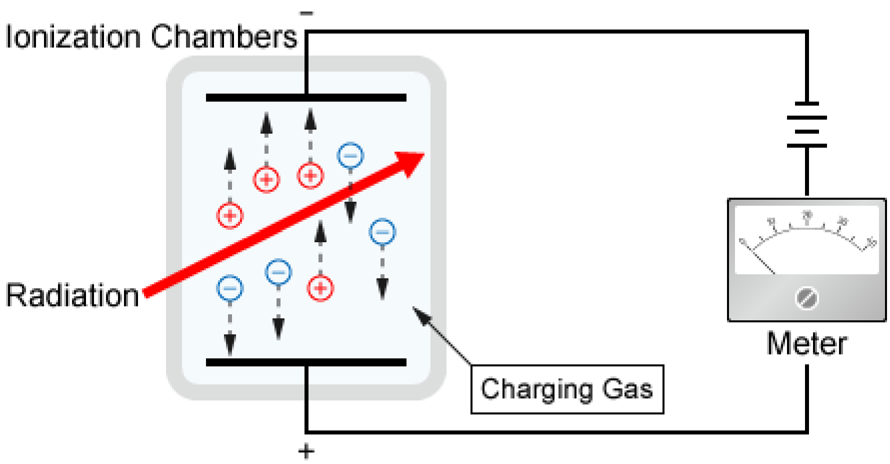

Figure 1 – Visualization of ion chamber operation

For registration of secondary particles (α-particles, β-particles, fission fragments) ability of charged particles to ionize gases is used. Pairs of ions formed as a result of gas ionization in the interelectrode space. Then particles are separated by the applied potential difference and an electric current appears in the circuit that is proportional to the degree of gas ionization and hence the radiation intensity. The current in the chamber circuit also depends on the applied voltage (Figure 2).

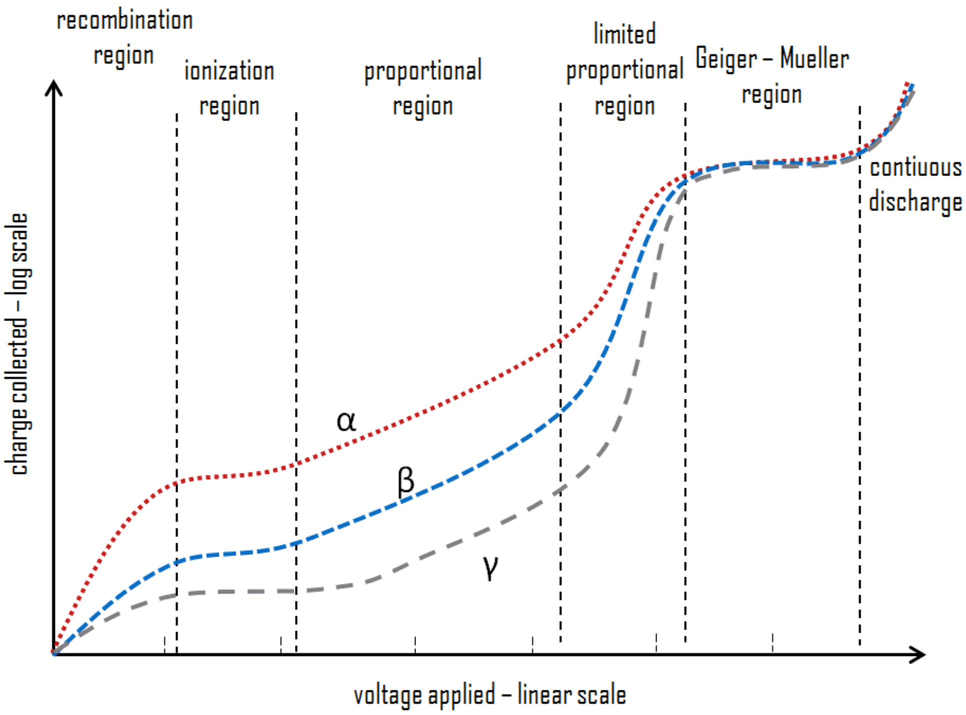

Figure 2 – Current-voltage curve of ion chamber

Compensated IC are used for neutrons registration in the presence of a gamma radiation. A draw of such a detector is shown in Figure 3. Unlike usual IC compensated one has two volumes. In one volume screen with a neutron-sensitive layer and in the other without. The chamber registers a current proportional to the neutron flux density.

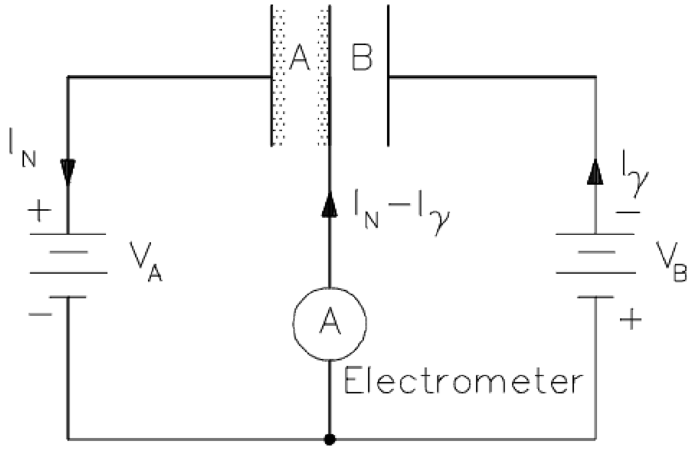

Figure 3 – Compensated ion chamber

1.2.2 Conversion of temperature into reactor power

Two types of temperature sensors are used in ICIS: thermocouples (TC) and thermal resistance (TR) [4].

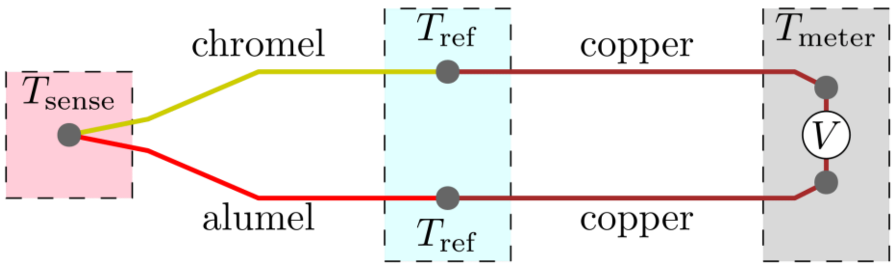

Figure 4 – Visualization of thermocouple operation

Thermocouple (Figure 4) is a temperature measuring device. Operation procedure based on the thermoelectric effect (Seebeck effect). EMF occurs between dissimilar soldered conductors due to the temperature difference between them. The result is a signal that can be registered. The hot junction of the thermocouple is placed at the measurement site.

To determine the absolute temperature, it is necessary to know the temperature of the cold junction. The thermocouple is made of a cable with a magnesia cover, its service life is several years.

The reading error is determined by the gamma heating of the hot junction under irradiation and by the current in the wires due to beta emission. Also, the temperature distribution along the length of the thermocouple and the inhomogeneity of cautery electrode alloys has affect. In addition, radiation transformations of electrode materials occur under irradiation which increases the measurement errors.

Thermal resistance is a sensitive element, the principle of which is that the electrical resistance of the element increases with increasing ambient temperature and vice versa (Figure 5).

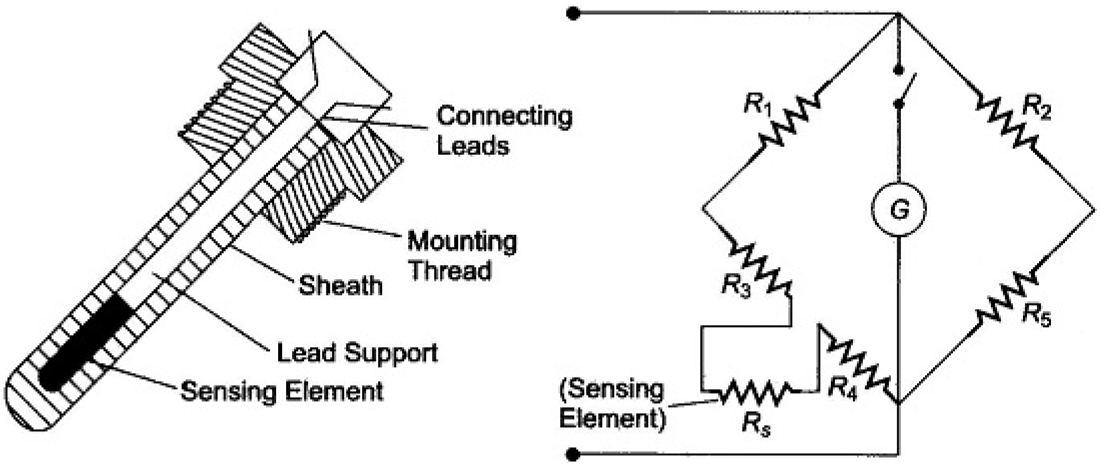

Figure 5 – Visualization of resistance temperature detector operation

Compared with TR, which are also used for in-reactor control, TC have the following advantages: greater operational reliability and metrological characteristics are more stable under irradiation.

TC don’t require an external power source, are simple in design and technologically advanced in manufacturing. At the same time, TCs also have a number of significant disadvantages: lower measurement accuracy compared to TR and a smaller output electrical signal; the need to compensate temperature of the cold junction of the TC, which increases the measurement error.

In this regard, in the ICIS system, TCs are used under severe conditions inside the reactor vessel for mass measurements of the coolant temperature at the outlet of the fuel assemblies, as well as the coolant temperature in the whole volume. TRs are used to make accurate measurements under less severe conditions. For example, all TCs of the primary circuit are calibrated by TRs that are installed on the cold and hot lines of the circulation loops.

1.3 Improvement of power control methods at nuclear reactors

The development and improvement of methods for monitoring the thermal power of reactors doesn’t stop today. In Russia this task is formulated in the development strategy of nuclear energy in one of the three main tasks: “Maintaining the safe and efficient operation of operating NPPs and their fuel infrastructure” [7].

The papers [8, 9] present the results of such works. These works aren’t new, but their goals and applied methods are still relevant today.

For example, in 2008 a study was made for the MIR.M1 research reactor, where the need to take into account all components of the energy release was substantiated: the mutual influence of photon and neutron radiation created by the working fuel assemblies of the reactor and experimental fuel elements. Automated installation for gamma-scanning of irradiated fuel rods has been designed and built to study the distributions of energy release and fission fragments. The implementation of the techniques made it possible to reduce the errors in determination of the thermal power of fuel elements and fuel burnup during tests in the reactor and improve the representativeness of researches and increase the safety of tests and operation of the reactor [8].

Another example is [9]. An attempt is made in the paper to make an initial approximation of the classification of the error components for the methods used in the ICIS for calculating the thermal power of the reactor and their estimates based on the accumulated experimental data during startups and commissioning phases.

Estimating the reactor power according to the readings of different measurement channels is a classic method for estimating the reactor power, each reading is accompanied by its weighting factor (1), the coefficients take into account the deviation from the nominal power, this is due both to the imperfection of thermodynamic systems and to random, systematic and dynamic errors in determining these quantities.

$$W_{core} = \frac{K_1 \cdot W_{IC} + K_2 \cdot W_{DCD} + K_3 \cdot W_{1C} + K_4 \cdot W_{2C}}{K_1 + K_2 + K_3 + K_4}, \text{kW}, \tag{1}$$

where: W_{core} – average power of core, kW;

W_{IC} – average power by reading of ion chambers, kW;

W_{DCD} – average power by reading of direct charge detectors, kW;

W_{1C} – average power of the first circuit, kW;

W_{2C} – average power of the second circuit, kW;

K_1, K_2, K_3, K_4 – weight coefficients that take into account the measurement error of the quantity by this method.

As a result, method was proposed for estimating weight coefficients in determining the weighted average thermal power.

1.4 Numerical simulation of hydrodynamics and thermal hydraulics in nuclear reactors

Modeling the thermal physics of reactors by software has long been a common practice. There are many software packages such as OpenFoam, SolidWorks, Ansys Fluent or CFX, ATHLET etc. All of them provide a set of tools for modeling the hydrodynamics, heat transfer, and thermal hydraulics of various objects. In relation to reactors, these can be fuel assemblies, fuel rods or entire cores [10].

One example is the work [11]. The paper investigates the occurrence of corrosion on fuel assemblies of a PWR reactor due to the deposition of impurities. The calculation was done of the distribution of corrosion in assemblies and its effect on thermal-hydraulic parameters, for example, on water overheating and subsequent surface boiling.

The work [12] is devoted to determining the presence of hot spots (places of overheating) of the IRT-5000 nuclear reactor in order to determine the critical heat flux ratio. A study on a reactor similar to the IRT-T is of practical use for the current calculation.

The calculation in [14] was done to determine the hydraulic effects in the gaps of IRT-3M fuel assemblies. The results make it possible to separate each gap in the FA model in accordance with the currently used model for calculating neutron fluxes by the Monte Carlo method. The results of this work can be used to determine the allowable power of studies of the IRT type.

2 Preparation of reactor first circuit thermal hydraulic simulation

As it was said at the beginning, the work is devoted to the thermal hydraulic calculation of the IRT-T primary circuit in order to verify and improve the thermal method of the thermal power control of the reactor. To achieve this goal the following tasks were performed.

The structure of the primary circuit of the reactor was studied in order to determine the structural elements that will be modeled in the calculation model; the power control at the reactor was studied in order to identify the location of the instrumentation, its composition and operation mode. This determines what conditions formed the calculation methodology.

In the section devoted to the method of work the requirements for the calculation model are substantiated step by step: the geometry and mesh of the model are demonstrated, the requirements for the mesh are given; calculation configuration is shown.

2.1 Research object

2.1.1 IRT-T primary circuit design

The simulation object is the first circuit of the reactor, namely the primary circuit (without including experimental channels and other equipment). It consists of [14]:

– reactor tank;
– biological shield concrete;
– flow pipeline;
– distribution vessel;
– core;
– natural circulation valves;
– decay vessel;
– suction pipeline;
– external decay vessel;
– four circulation pumps;

– emergency cooling pump;

– collector, inlet and outlet pipelines of heat exchangers and pumps;

– drainage pipelines;

– pipeline fittings;

– four heat exchangers.

All of the above structural elements and equipment are shown in Figures 6-8.

In this work calculation model of a reactor was created including the tank geometry (the volume inside the steel tank), distribution vessel, core, decay vessel, flow and suction pipelines. The choice of elements is determined to their function in the operation of the primary circuit – heating the coolant, supply and output of the coolant, influence on the flow of the coolant. This is a sufficient set of elements, which made it possible to study the distribution of coolant and energy in the primary circuit.

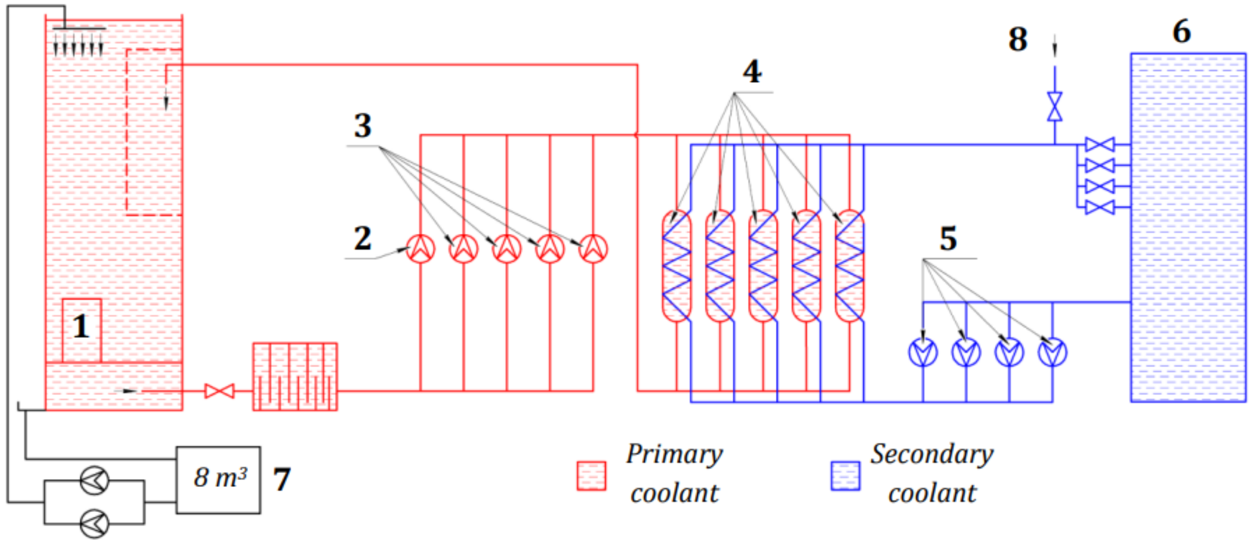

Figure 6 – Cooling scheme of IRT-T:

1 – core; 2 – emergency cooling pump; 3 – primary coolant pumps; 4 – heat exchangers; 5 – secondary coolant pumps; 6 – cooling stack; 7 – collection and fault isolation system; 8 –industrial water

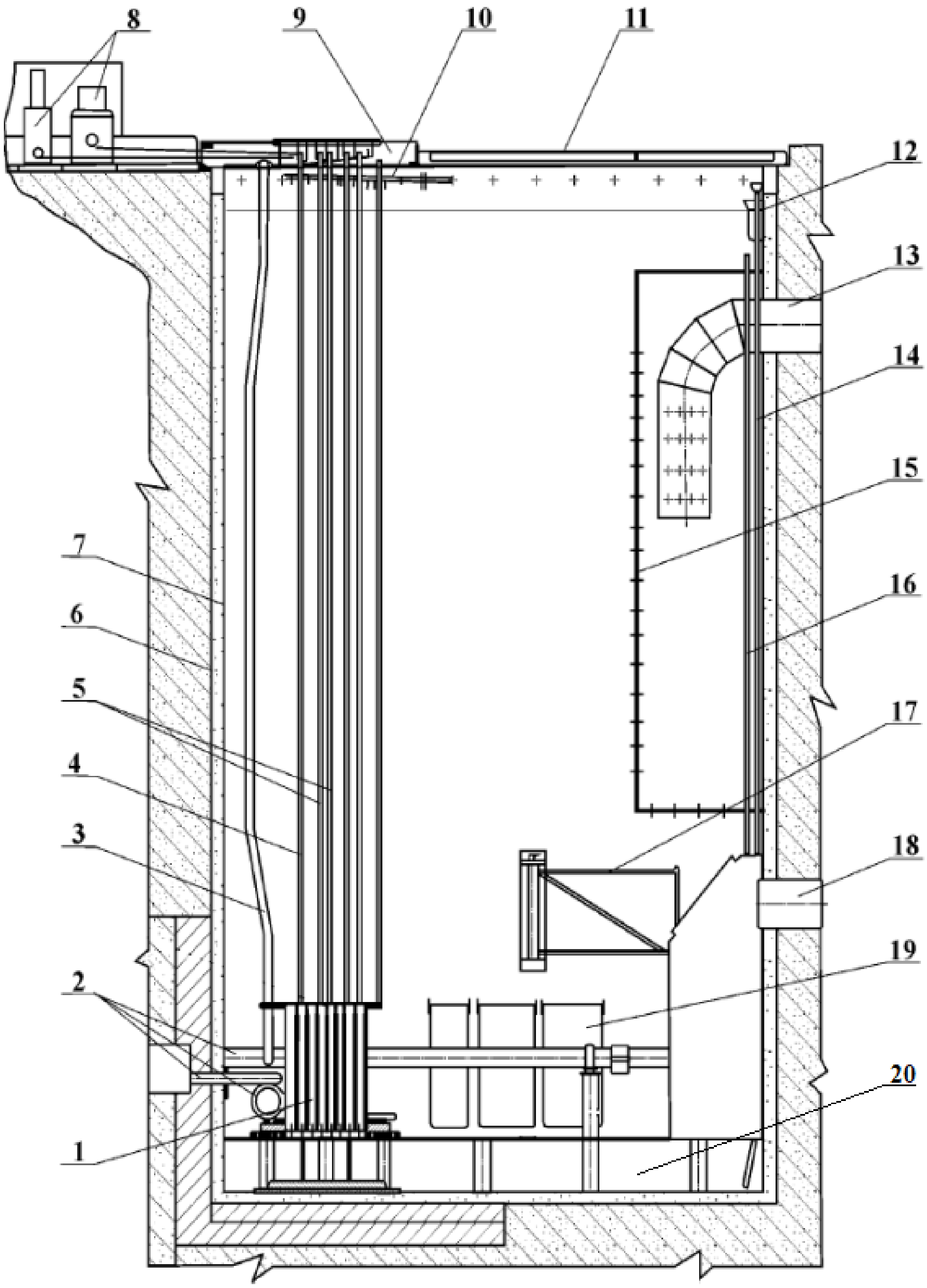

Figure 7 – Vertical section of IRT-T:

1 – core; 2 – horizontal experimental channels; 3 – vertical experimental channels; 4 – control rods channels; 5 – central experimental channels; 6 – aluminum tank; 7 – stainless steel tank; 8 – actuators of control rods; 9 – control rods platform; 10 – sprinkler; 11 – transparent floor; 12 – overflow funnel; 13 – flow (inlet) pipe; 14 – emptying pipe; 15 – distribution vessel; 16 – siphon break pipe; 17 – handler; 18 – suction (outlet) pipe; 19 – temporary storage for FA; 20 – inner decay vessel

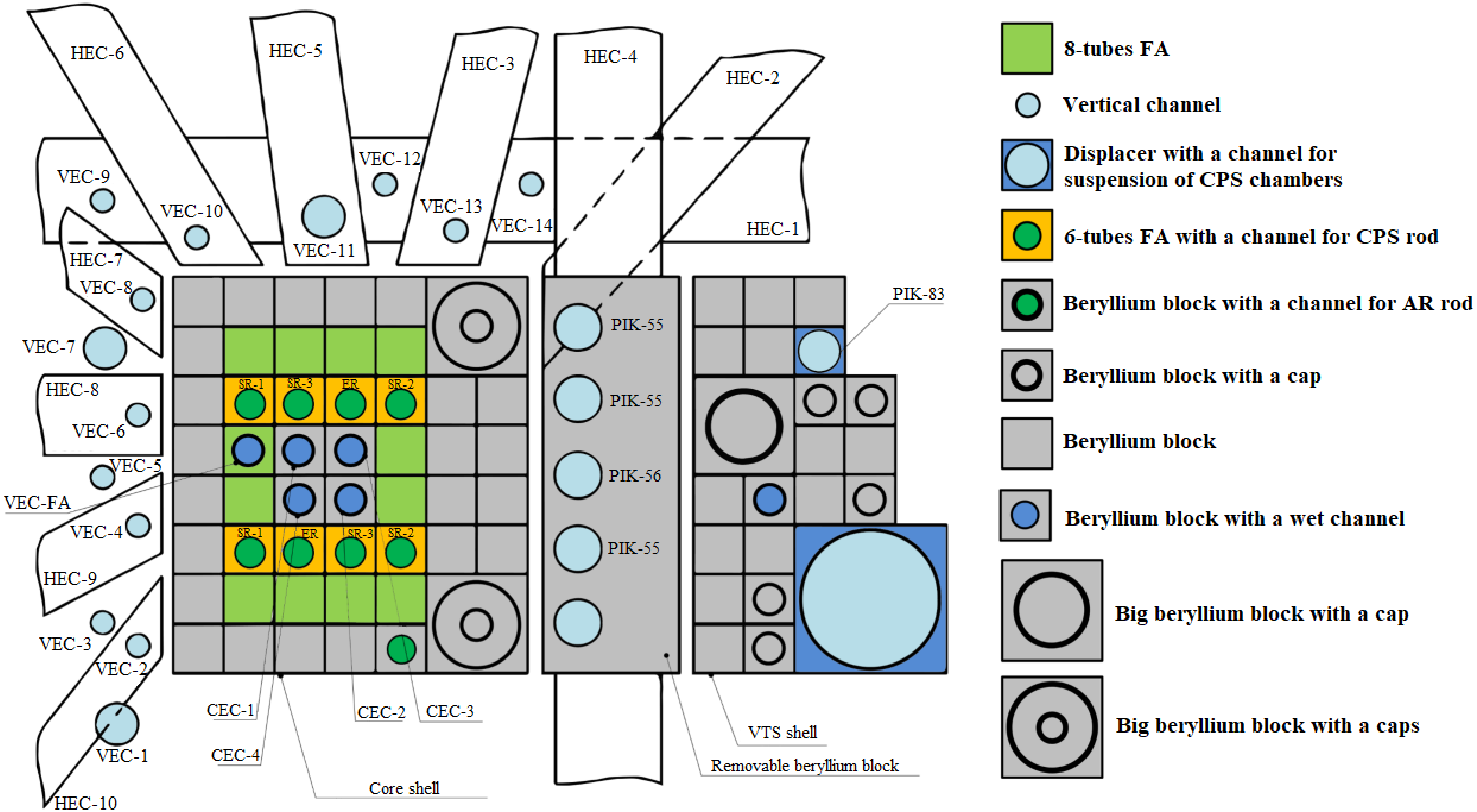

Figure 8 – Cartogram of the core and experimental equipment of IRT-T

The first element that houses the core and all auxiliary equipment and elements is the steel tank of the reactor. This is a container made of polished stainless-steel grade 12X18H1OT (In Russian, AISI 304 analogue). Tank length – 4,3 m, width – 1,8 m, depth – 7,725 m, tank volume - 56 m^3. The thickness of the walls of the tank is 5 mm, the bottom of the tank is 10 mm. The coolant level in the tank is about 7,3 m.

The coolant enters the reactor tank through flow pipeline Ø 350x5 mm, first entering the distribution vessel. It is made of perforated steel sheets 5 mm thick. Tanks create a zone after which the flow is uniformly distributed inside the tank, improving heat transfer.

Core is located at a depth of 6,5 m. The core is assembled in a vessel made of AD-1 (АД-1 in Russian) aluminum alloy, support spacer grid made of SAV-1 (САВ-1 in Russian) aluminum alloy is installed at the bottom of the vessel. It contains fuel assemblies and reflector blocks, a total of 56 elements with a 7x8 mesh.

Through a stainless-steel flange, the vessel is welded to the top sheet of the decay vessel. Also, the vessel is attached to the bottom of the tank by six posts Ø 108x5 mm.

After passing through the core, coolant enters the decay vessel. The top sheet of the vessel rests on 15 posts (similar to those of core vessel) and is separated by a steel sheet along. The purpose of the vessel is to increase the coolant transit time to reduce the induced activity of the coolant.

Then through the suction pipeline Ø 350x5 mm coolant leaves the reactor tank.

2.1.2 Power control by readings of ionization chambers

The reactor power control system provides:

– power level measurement;

– measurement of the power rate (period).

We are interested in the first component of the system – measurement of the power level.

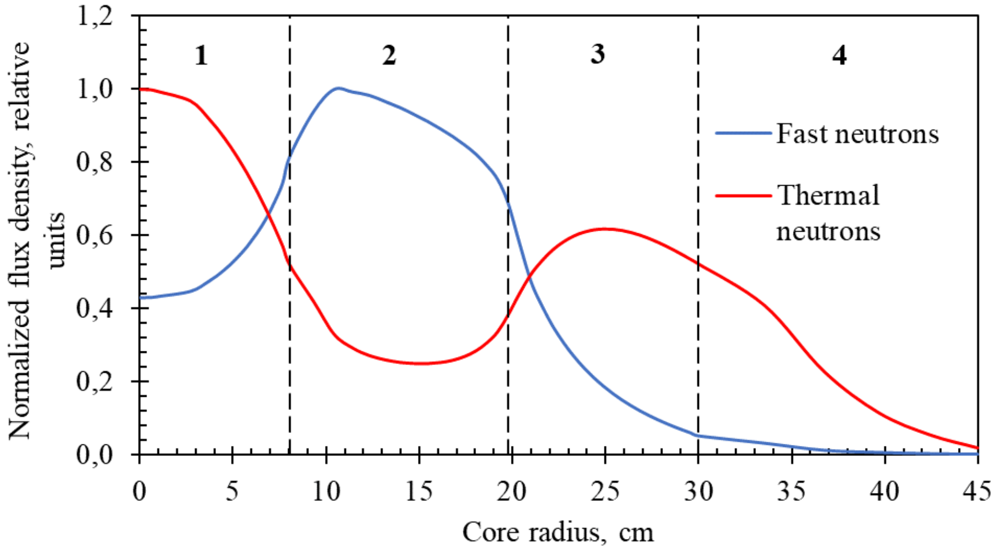

Figure 9 – Flux density distribution radially:

1 – neutron trap; 2 – FA; 3 – side reflector; 4 – water

Way of the reactor power control is the readings of the IC current. In accordance with the principle used in power reactors, chambers should be located around the reactor, since the neutron flux is nonuniform along the radius and height of the reactor. ICs are installed behind the core and register a flux proportional to the flux in the core. Figure 9 shows the radial distribution of neutrons in the IRT-T reactor.

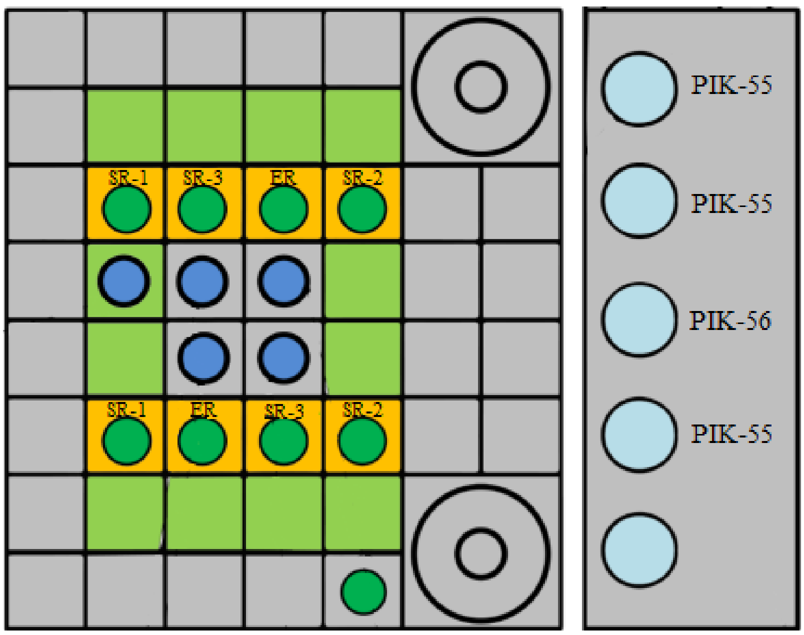

Figure 10 – Position of ionization chambers

Four regular neutron detectors are located along one of the sides of the reactor (on the right side) (Figure 10) in the wet channels of the beryllium assembly. These are 3 PIK 55 neutron detection assemblies with KN 012 fission chambers and one assembly PIK 56 with a KNK 53M ionization chamber with gamma compensation each. The power is controlled through 4 channels (chambers), 3 channels with shim rods (SR) from the PIK 55 signals and one channel for the automatic regulator (AR) from the PIK 56 signals [15].

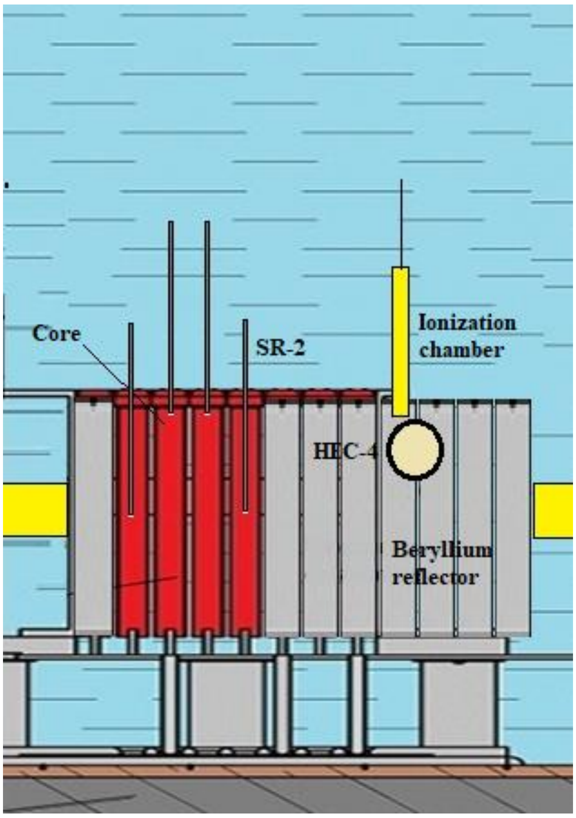

Figure 11 – Position of ionization chamber relative to height of core

Reactor power is raising to the nominal power level and maintaining practically only by the readings of PIK 56 assembly. Power raising in automatic regime using a power selector, on which a predetermined current level is set. Power maintenance consists in maintaining the current level of this power control channel constant. Physically this corresponds to keeping the neutron flux density constant at the location of this IC [16]. Maintaining the chamber current at a constant level led to the fact that the neutron flux in this region is saving, but the actual thermal power of the IRT-T reactor core will change from run to run and during each run.

The detector assemblies are putted above the core (Figure 11), the ICs located in this way register fast neutrons generated on the periphery of the right side of the core. If the distribution of neutrons is symmetrical with respect to the center of the reactor, then the readings of the chambers are proportional to the real thermal power of the reactor. Reactor operates in the mode of partial refueling, so the distribution of neutrons over the core changes in each new run. The position of SRs and AR (immersion depth) is also not constant. This introduces disturbances in the neutron field and the power distribution along the height, which also leads to change in the readings of the cameras located nearby. Thus, the neutron flux recorded by the chambers is proportional not to the flux of the entire reactor, but only to its periphery, taking into account the introduction of disturbances by the control rods.

Therefore, maintaining constant current of the power control channel, partial refueling, influence of control rods and the location of the chamber's assemblies on the periphery leads to the fact that the real thermal power may not correspond to the readings of the chambers. This can be clearly seen in Figure 12.

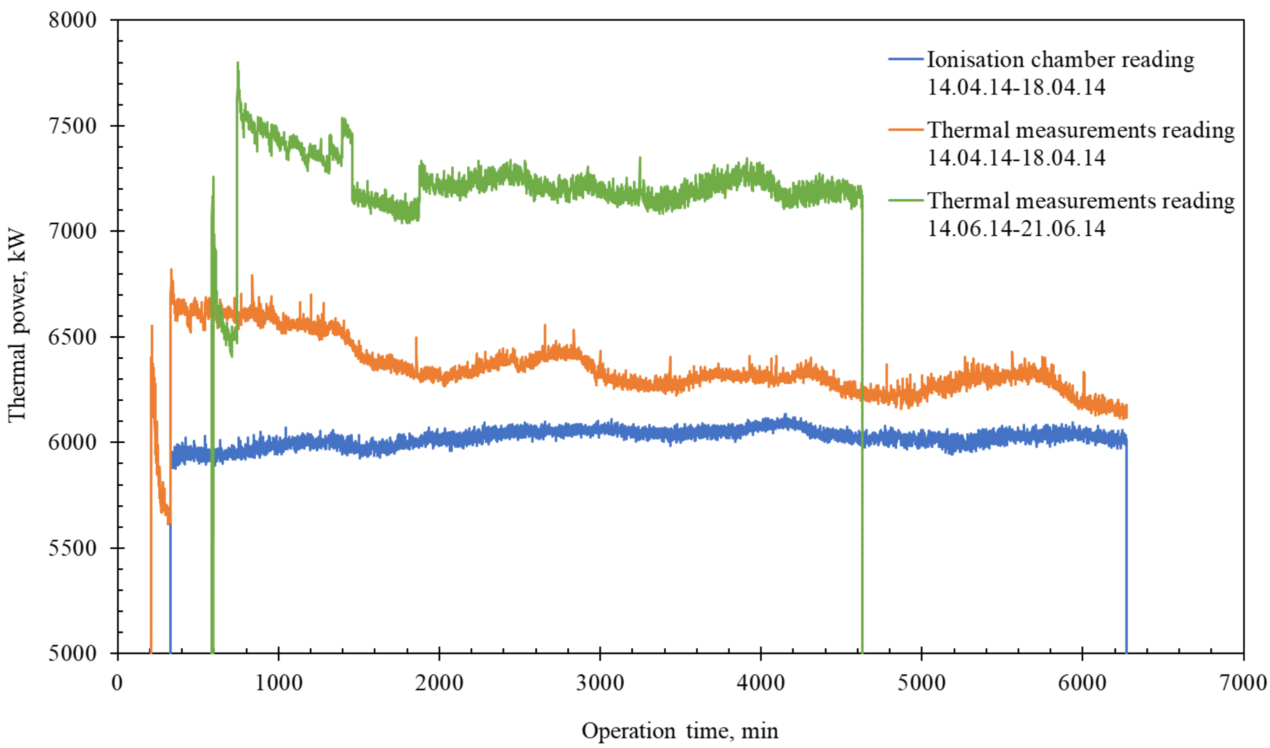

Figure 12 - Reactor power measurement during operation

2.1.3 Power control by thermotechnical method

Regular power control at IRT-T is accomplished through only readings of ionization chambers. At the same time, nuclear reactors are characterized by the presence of another method – thermotechnical, i.e. by changing the temperature of the coolant after passing through the core or in the case of multi-circuit schemes by changing the temperature in each of the circuits. Measuring devices are installed at IRT-T to measure all the parameters necessary for this method, however, only a part of these sensors is included in the reactor CPS, but there is no set of sensors that would be part of the CPS and determine the power by the thermal method.

The thermal power of the IRT-T reactor can be determined from the heating of the coolant passing through the core. The evaluation of thermal power is based on the formula that relates the mass flow rate of water to the specific heat capacity of water and the change of temperature at the inlet and outlet of the core (2) or the difference of the enthalpies of water at the inlet and outlet of the core (3).

$$N_{th} = Q_m \cdot C_p \cdot (T_{out} - T_{in}), \mathrm{kW}, \quad (2)$$

$$N_{th} = Q_m \cdot (h_{out} - h_{in}), \mathrm{kW}. \quad (3)$$

where: Q_m – mass flow rate, m^3/s;

C_p – heat capacity of water, kJ/K·kg;

T_{out}, T_{in} – temperature of water after and before reactor core, K;

h_{out}, h_{in} – specific enthalpy of water after and before reactor core, kJ/kg.

These formulas (2, 3) are applicable both for the first circuit and for the second one.

From formulas (2, 3) it follows that to determine the thermal power, sensors are needed to control the following quantities:

– coolant flow rate;
– coolant temperature at the inlet and outlet;
– pressure (for enthalpy).

Heat capacity and enthalpy are determined from tabular values.

Sensors suitable for this purpose are presented in table 1. The following equipment can be used for this purpose (table 1). The sensors included in the CPS operate according to the Majority principle 2 out of 3.

Table 1 – Instrumentation suitable for thermal method of power control [14]

Parameter	**Device**	**Part of CPS?**
Coolant flow rate	Orifice DK 6	Yes
	Metran 150	Yes
Coolant temperature	TSPU-2222	No
	ChEPT-2	Yes
Pressure	Metran 150	Yes

To measure the flow rate of the primary coolant flow measuring units are installed, which include:

– ring chamber orifice DK 6 (ДК 6 in Russian);
– differential pressure transducer Metran 150DD (“Метран 150ДД” in Russian);
– universal millivoltmeter IRT-1730U/M (ИРТ-1730У/M in Russian).

Orifice DK 6 is installed on the pressure pipeline Dy 350, designed with angular annular slots (rings) for pressure extraction [17] (Figure 13).


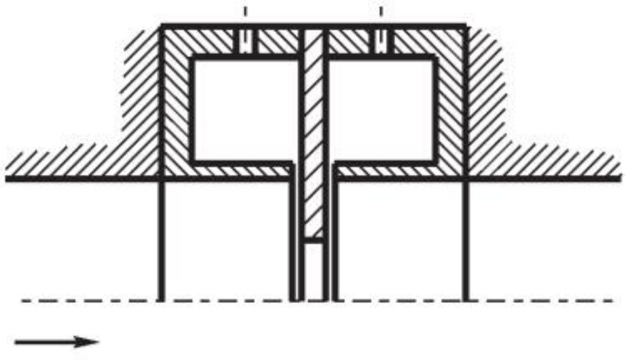

Figure 13 – Pipeline orifice DK 6

The orifice creates a local flow constriction (Figure 14), the static pressure of the flow after the orifice is less than before it and in accordance with the Bernoulli law

(5) and the continuity equation (5), the coolant flow rate (6) is determined from the pressure difference (Venturi effect).

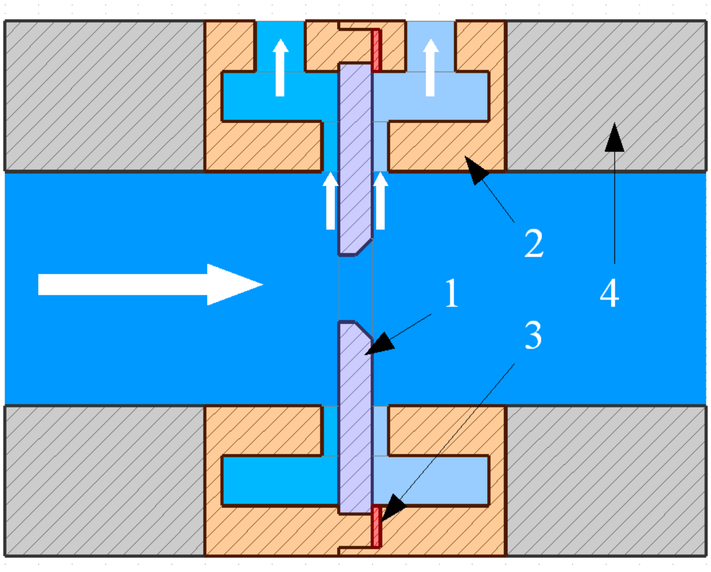

Figure 14 – Orifice operating principle:
1 – orifice; 2 – ring chamber; 3 – seal; 4 – tube

$$P_1 + \frac{1}{2} \cdot \rho \cdot V_1^2 = P_2 + \frac{1}{2} \cdot \rho \cdot V_2^2 = \text{const}, \text{Pa}, \tag{4}$$

where: $P_{1,2}$ – static pressure before and after diaphragm, Pa;

ρ – density of water, kg/m^3;

$V_{1,2}$ – velocity of water before and after diaphragm, m/s.

$$Q_m = \rho \cdot V_1 \cdot S_1 = \rho \cdot V_2 \cdot S_2 = \text{const}, \text{kg/s}, \tag{5}$$

where: $S_{1,2}$ – cross section area before and after diaphragm, m^2.

$$Q_m = C \cdot S_2 \cdot \sqrt{2 \cdot \rho \cdot (P_1 - P_2)}, \text{kg/s}, \tag{6}$$

where: C – orifice flow coefficient, dimensionless.

Metran-150 pressure sensors (Figure 15) are designed to measure gauge pressure, absolute pressure, differential pressure, hydrostatic pressure. To measure the flow rate of the flow pipeline, the sensor operates in the differential pressure mode. Two impulse tubes from different ends of the chamber are brought into the chamber and based on the pressure difference sensor generates a current signal in the range of 0÷4 mA for millivoltmeter.

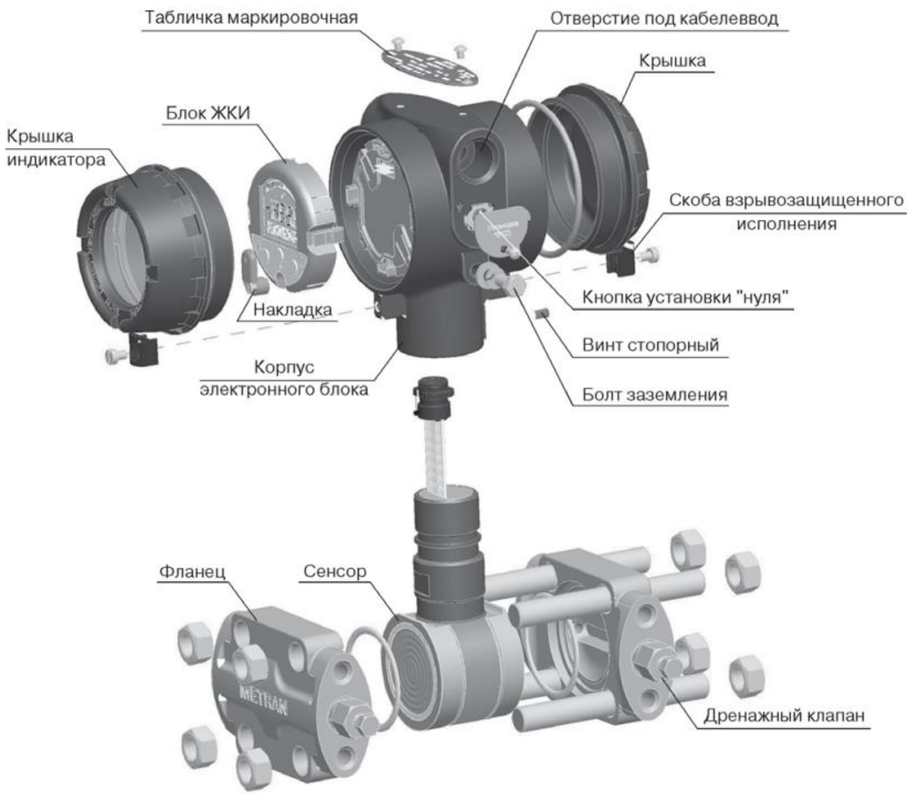

Figure 15 – Scheme of Metran 150

Technological meter-regulator (universal millivoltmeter) IRT 1730U/M (Figure 16) is designed to measure and control temperature and other non-electric quantities converted into electric signals of DC strength and voltage.

Figure 16 – Millivoltmeter IRT 1730U/M

The pressure in the differential mode of the sensor is measured in the range from 0,25 to 6,3 kPa. Error of pressure drop measurement is $\pm 0{,}1\%$ [18]. The measurement error of the millivoltmeter is $\pm 0{,}2\%$ [19]. Flow measurement limits from 0 to 1250 m^3/h [14]. The measurement error of the coolant flow rate is $\pm 0{,}22\%$.

The measurement error of a multicomponent measuring chain (Metran 150 - IRT 1730U/M) is determined by the geometric sum of the errors (6).

$$\sigma_{\Sigma} = \sqrt{\sum_{i=1}^{m} \sigma_i^2} \quad (7)$$

The temperature of coolant in the primary circuit is measured by sensors on the flow and suction pipelines and in the tank volume near the core.

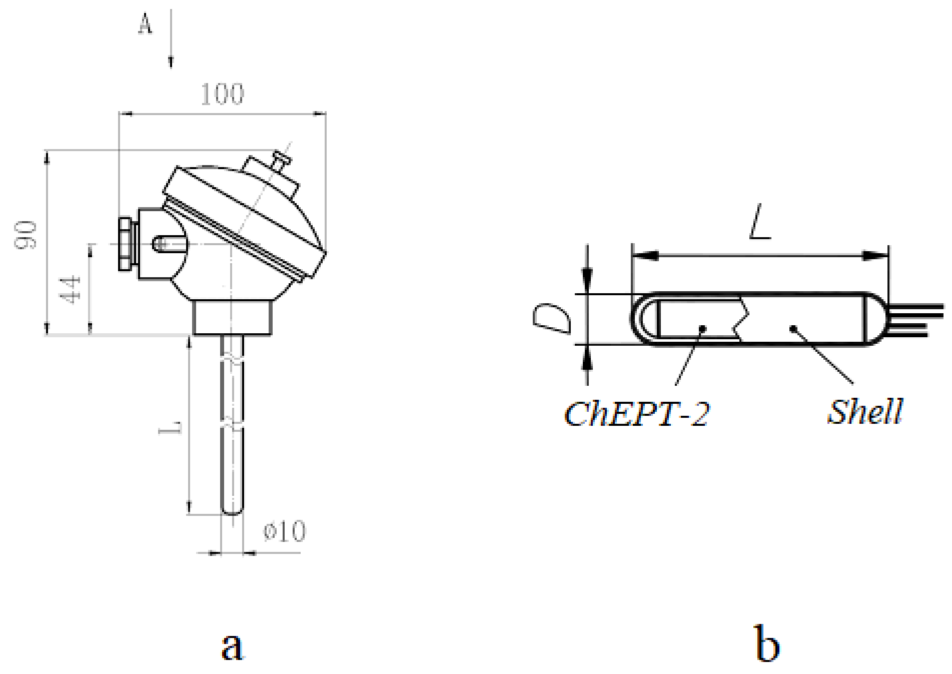

Figure 17 – Temperature meters:

a – TSPU-2222; b – ChEPT-2

Resistance thermometers TSPU-2222 are installed on the flow and suction pipelines (Figure 17.a). Change in temperature is converted into a current signal from 4 to 20 mA, which goes to the universal millivoltmeter ИРТ-1730У/М, where it is displayed in ˚C.

Thermocouples CHEPT-2 are installed inside of tank (Figure 17.b). Three thermocouples at a depth of 3 m next to the distribution vessel, and three thermocouples in the decay vessel. They record temperature before and after core. Thermocouples work in pairs: one at the inlet and the other at the outlet. Next, the signal goes to the temperature signal conversion unit, then the signal is output to the display workstation, which displays the digital temperature value in ˚C.

In Figure 18 we can see location of thermocouples in tank.

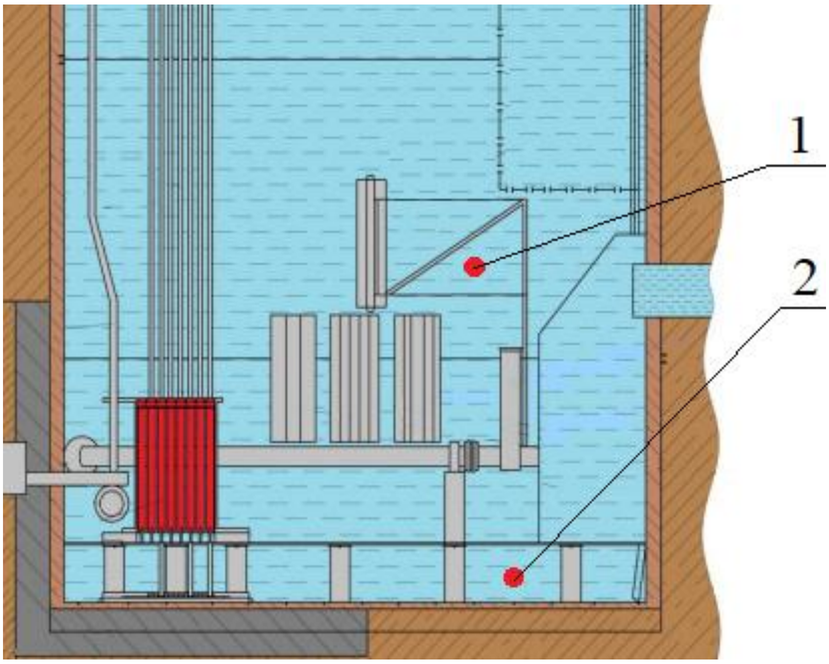

Figure 18 – Location of ChEPT-2:

1 – inlet; 2 – outlet

Temperature is measured in the range from 0 to 100 ˚C. Thermal resistance error ±0,25%, thermocouples error ±0,15% [20, 21]. Errors of measuring coolant temperature is ±0,32% and ± (0,15% from the thermocouple reading +0,5 ˚C from the conversion unit [22]) respectively.

2.2 Simulation algorithm

2.2.1 Starting point of algorithm

As mentioned earlier, the control and measuring instrumentation necessary for thermal method of power control wasn't originally designed for this, the possibility of using its readings for this purpose is in question.

And this means that the readings obtained in Figure 12 may simply be erroneous, not related to the energy actually released in the reactor. However, the need for an additional method of power control, the restrictions imposed by the location of the neutrons detector assemblies on the operation of ionization chambers, and the presence of indirect evidence of the deviation of the real power from the registered power sets us the goal of checking existing instrumentation in order to find out the relevance of their readings, which will serve as a conclusion about the possibility of using or improving the current set of sensors for thermal method of power control.

The first requirement for the calculation model is to recreate the geometry that can show the most probable coolant flow in the tank. The coolant flow affects the temperature distribution in the reactor tank, some areas may be overheated or too cold. The water is heated by core, because of means of natural convection, transfers heat throughout the volume. The tank of the IRT-T reactor, in contrast to the vessels of power reactors, serves for the most part to create a volume of water capable of serving as biological shield layer, its thermal hydraulic abilities aren't high. In the volume between flow pipeline and core, there is a continuous flow of energy due to convection, the transfer of temperature through the top sheet of the decay vessel. The temperature in the area where thermocouples work can be non-uniform.

The second requirement is that the volume in which energy is released shouldn't go beyond the core, water near the sensors shouldn't be overheated. Creating the geometry of the core is a consuming task. It is extremely complex, the gap between the fuel assembly plates is 2 mm and the height is 650 mm. It is a challenge for powerful computers to work with such large models. However, in the furtherance of this calculation there is no need for this, water passes from core to the sensors distance around 3,5 m, the temperature there should become uniform. In calculations it was assumed that the energy release is uniform over the entire volume of the core, influence of the energy release profile is neglected.

For this purpose, calculation model was created in the Ansys Fluent program. The geometry of the primary circuit within the reactor tank has been made. Table 2 shows the input parameters.

Table 2 – Input parameters [23]

Parameter	**Value**	**Unit**
Thermal power	6000	kW
Coolant flow rate	720	m^3/h
Inlet temperature	25	˚C
Inlet pressure	170	kPa

To verify the data obtained, a comparison was made with the parameters given in Table 3.

Table 3 – Operational data of IRT-T [23]

Parameter	Value	Unit
Core pressure drop	32÷34	kPa
Outlet pressure	133	kPa
Temperature at the core inlet	45÷50	˚C
Temperature at the core outlet	55÷60	˚C
Temperature difference (thermocouples)	7÷8	˚C

The flow regime is turbulent $\mathrm{Re} \approx 10^6$, model of two equations *k-ω* SST (8, 9) with a wall function is used. There is no friction of the structural elements and there are no losses through flow path.

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_T)\frac{\partial k}{\partial x_j}\right] \tag{8}$$

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_T)\frac{\partial \omega}{\partial x_j}\right] + 2(1-F_1)\sigma_\omega \frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \tag{9}$$

where: k – turbulence kinetic energy, J/kg;

ω – specific dissipation rate, 1/s.

The reactor power release isn't uniform (Table 4), different particles contribute to this release, they lose energy inside hole tank path in tank difficult to predict. A preliminary neutronic calculation wasn't fed into thesis, so for simplicity of calculation it is assumed that the energy release is limited by core volume.

Table 4 – Components of the fission energy of uranium 235

Component	, MeV	, %
Fission fragments kinetic energy	166.2	81.5
Prompt gamma-rays energy	7.8	3.8
Neutron's energy	4.9	2.4
Delay beta-particles energy	8	3.9
Delay gamma-rays energy	7.2	3.5

Antineutrino energy	10	4.9
Total fission energy	203.9	100

Two approaches are being tested by sensors and two by the power calculation method. By sensors: thermocouples in the reactor tank and thermal resistance. By methods of calculation: temperature difference and enthalpy.

Thermocouples near the core are part of the CPS, so their consideration is a priority, in addition, there is less energy loss near the zone of their location.

2.2.2 Geometry and mesh

Figure 19 shows the created geometry.

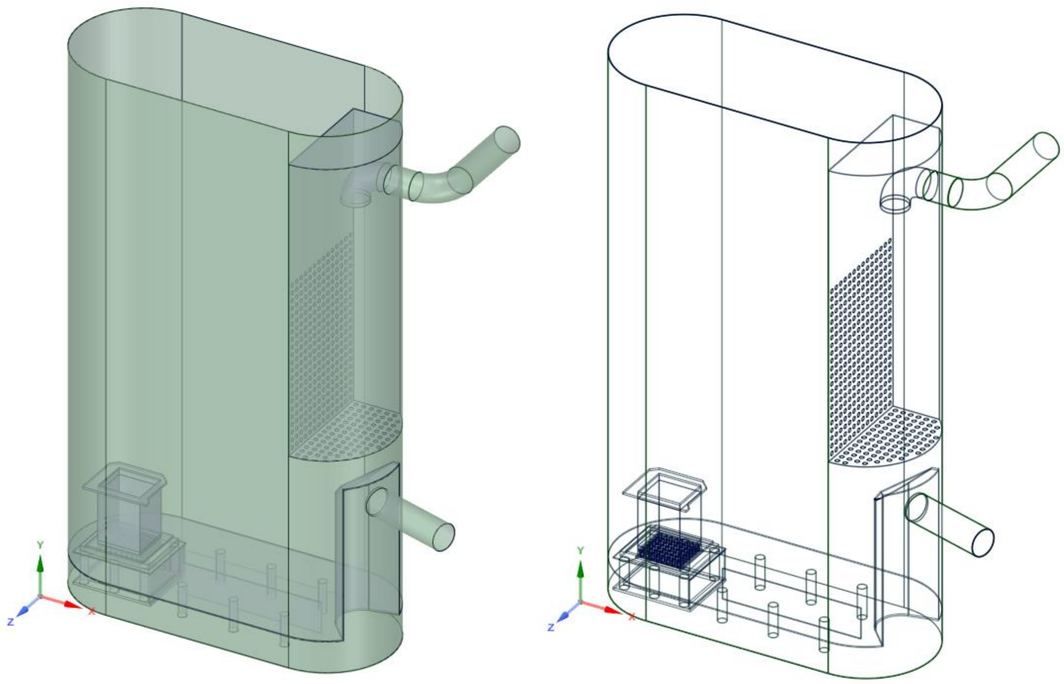

Figure 19 – First circuit geometry

The geometry is created taking into account the given conditions. Recreated all the necessary elements. To simplify the calculation the details of the fuel assemblies and beryllium blocks weren’t modeled to simplify mesh in the core.

Turbulent flow models perform poorly in the region close to the wall and well in the region of fully developed flow. There are two approaches for solving this problem: extending the mesh to the liquid-solid interface and using the wall function.

This is due to a sharp change in the curvature of the velocity profile near the fluid-solid interface, this is especially dominate for the turbulent flow regime.

This is shown in Figure 20, the thickness of the layer becomes smaller and smaller in order to correctly take into account the profile, because of this, the number of model cells increases disproportionately, such calculations are applicable only for accurate studies. In this study the wall function is used, it approximates the velocity function. The accuracy of the method is less, but it significantly reduces the number of cells and the calculation time [24].

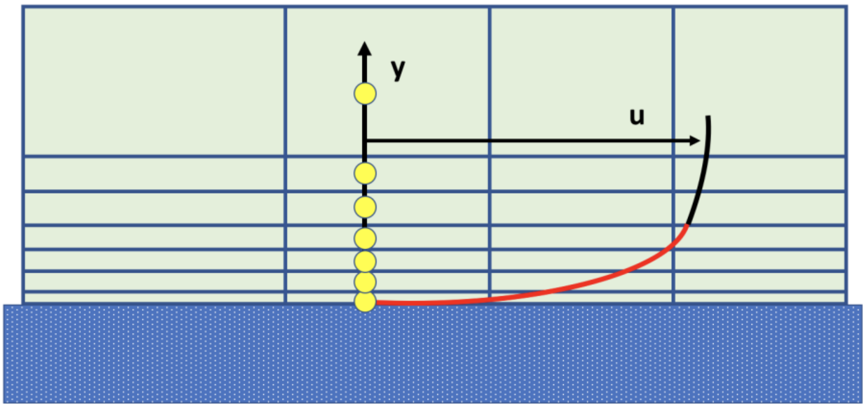

Figure 20 – Influence of mesh density

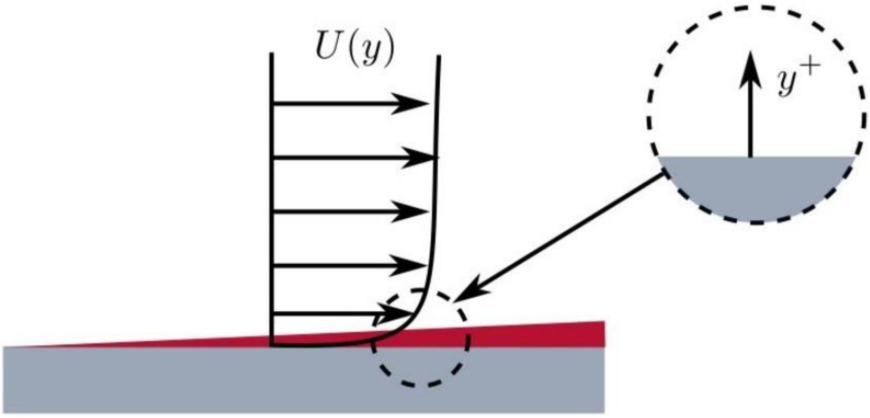

Figure 21 – Description of y^+

The dimensionless distance to the wall is used as a control parameter, it is denoted as y^+ (Figure 21). If it's value is greater than 30, but less than 150, wall function is used to approximate the velocity profile [24]. This value is used to obtain the height of the near-wall layer.

Near wall cell height is calculated according to the following algorithm [25].

Reynolds number is calculated (9):

$$\mathrm{Re} = \frac{\rho U L}{\mu}, \tag{10}$$

where: ρ – water density, kg/m^3;

U – freestream velocity, m/s;

L – characteristic length of the geometry, m;

μ – dynamic viscosity, Pa·s.

The skin friction coefficient is calculated (10):

$$c_f = (2\log_{10}(\mathrm{Re}) - 0{,}65)^{-2{,}3}. \tag{11}$$

Then wall shear stress (11):

$$\tau_w = \frac{1}{2}\rho U^2 c_f, \mathrm{Pa}. \tag{12}$$

Friction velocity (12):

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}, \mathrm{m/s}. \tag{13}$$

Finally, we can determine the thickness of the boundary layer (13):

$$h = \frac{y^+ \mu}{u_\tau \rho}, \mathrm{m}. \tag{14}$$

It is difficult to create mesh for coolant flow in such large volume of water in complex geometry. It will be enough to calculate the boundary layers for pipelines, core and holes of distribution vessel, as the most significant constrictions in the flow path. Let's take the value of y^+ equal to 30, then for the parameters indicated in Table 4 we calculate the boundary layers (Table 5). The recommended number of boundary layers for the chosen value of y^+ is 10 [24].

Table 4 – Parameters for y^+ calculation

Parameter	**Value**	**Unit**
Core		
Hydraulic diameter	550	mm
Density of water	988,1	kg/m^3

Dynamic viscosity	$5{,}5 \cdot 10^{-4}$	kg/m·s
Freestream velocity	1,3	m/s
Beryllium block channel		
Hydraulic diameter	44	mm
Density of water	988,1	kg/m^3
Dynamic viscosity	$5{,}5 \cdot 10^{-4}$	kg/m·s
Freestream velocity	3,1	m/s
Flow pipe		
Hydraulic diameter	350	mm
Density of water	997,1	kg/m^3
Dynamic viscosity	$8{,}9 \cdot 10^{-4}$	kg/m·s
Freestream velocity	2,6	m/s
Distribution vessel orifice		
Hydraulic diameter	50	mm
Density of water	997,1	kg/m^3
Dynamic viscosity	$8{,}9 \cdot 10^{-4}$	kg/m·s
Freestream velocity	0,31	m/s

Table 5 – Parameters of the inflation layers

Location	**Thickness of first layer, m**
Core	$3{,}12 \cdot 10^{-4}$
Beryllium block channel	$2{,}18 \cdot 10^{-4}$
Flow pipes	$4{,}77 \cdot 10^{-4}$
Distribution vessel orifice	$2{,}53 \cdot 10^{-3}$

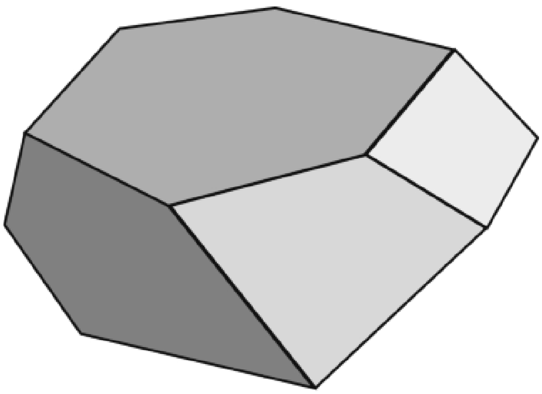

Figure 22 – Polyhedron

The mesh is built using the poly hexcore method. The main advantage of this method is that polyhedron (Figure 22), consisting of faces with a different number of sides (from 3 to 6), allow the stack to stand next to surfaces of any complexity, and then reduce it to a cubic one. The number of cells in the volume is less than for other methods, which is important for the calculation, since the calculation algorithm is the finite volume method [26].

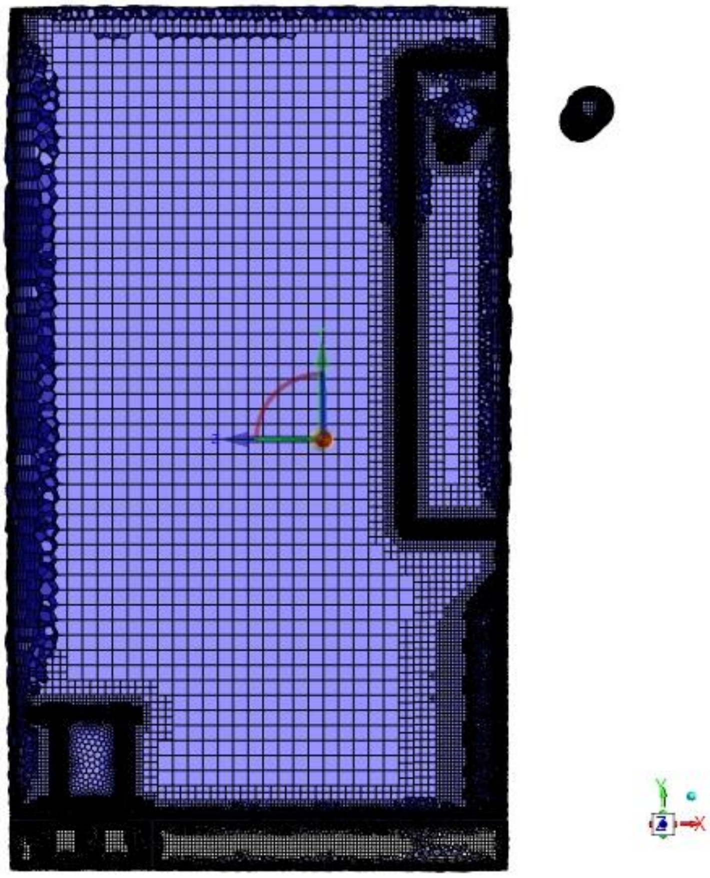

Figure 23 – Generated mesh

The result of meshing is shown in Figure 23. Appendix A provides more detailed images (Figures A.1-A.6). The grid consists of 11133321 cells. The orthogonal mesh quality is 0.3. This is a high value (Figure 24), which allows you to eliminate many errors in the calculation associated with the mesh quality.

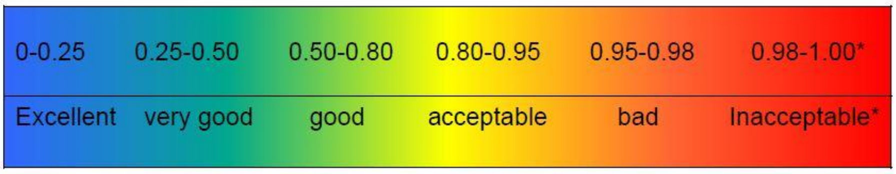

Figure 24 – Mesh orthogonal quality

3 Results of numerical simulation

The calculation reached the desired error of 0.01 in 80 iterations (Figure 25).

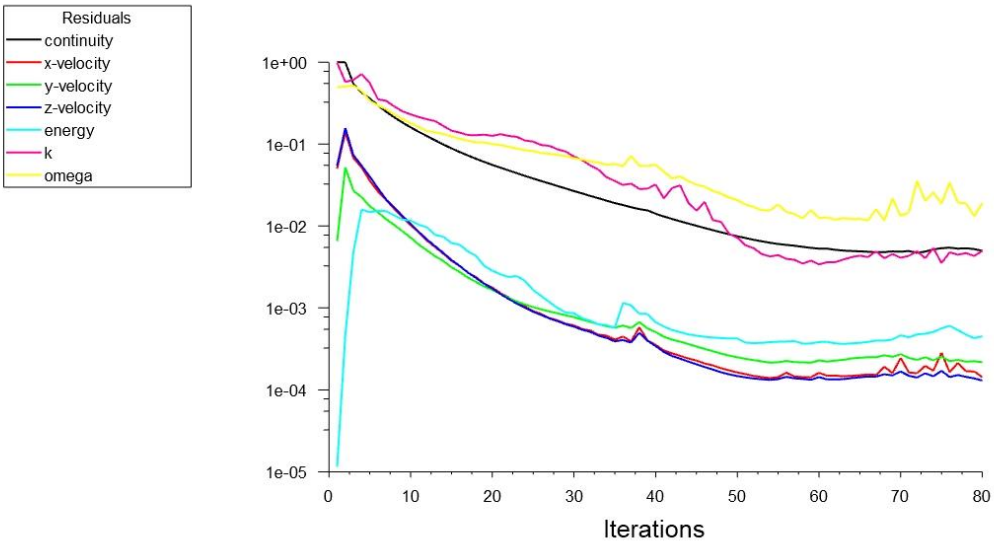

Figure 25 – Residuals plot

3.1 Temperature distribution

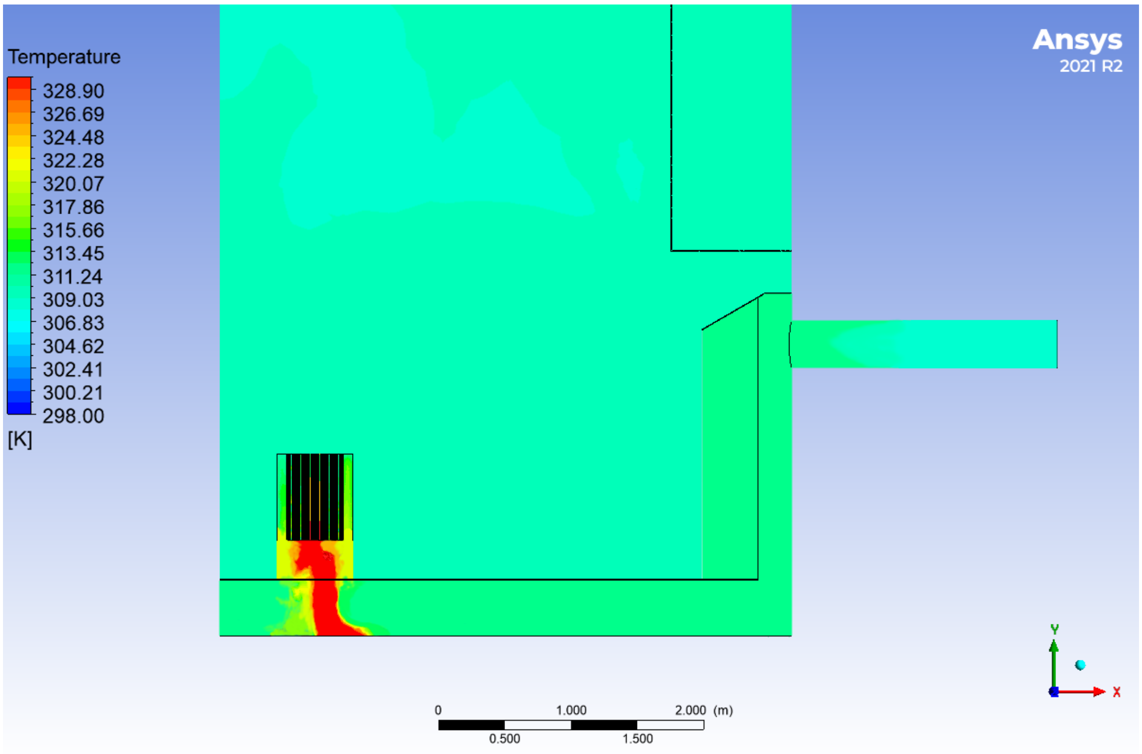

Figure 26 – Temperature contour

Figure 26 shows the temperature distribution at the bottom of the tank.

Tables 6 and 7 show temperature readings taken at points simulating RTDs and thermocouples.

Table 6 – Indications of points corresponding to thermal resistance TSPU-2222

In, ˚C	25
Out, ˚C	31,9
Difference, ˚C	6,9

Table 7 – Indications of points corresponding to thermocouples ChEPT-2

	Point 1	Point 2	Point 3
In, ˚C	35,2	35,6	35,1
Out, ˚C	42,7	42,6	42,5
Difference, ˚C	7,5	7	7,4
Reference difference, ˚C	7÷8		

As can be seen from the data given in tables 6 and 7, the difference in the readings of thermocouples and thermal resistances is approximately equal. Only thermocouples are knocked out at point 2, this is a thermocouple in the middle, from which we can conclude that there is a zone subject to heating, the reading of this thermocouple is the largest in the series.

3.2 Pressure field

Figure 27 shows the tank pressure circuit. The pressure value in Fluent does not take hydrostatic pressure into account. The impulse lines are at a distance of one meter, so the difference should be increased by 10 kPa.

The pressure value in the circuit is given in table 8.

Table 8 – Pressure

	Calculation	Reference value
Flow pipeline pressure, kPa	170	170
Suction pipeline pressure, kPa	149	133
Core pressure drop, kPa	21	34

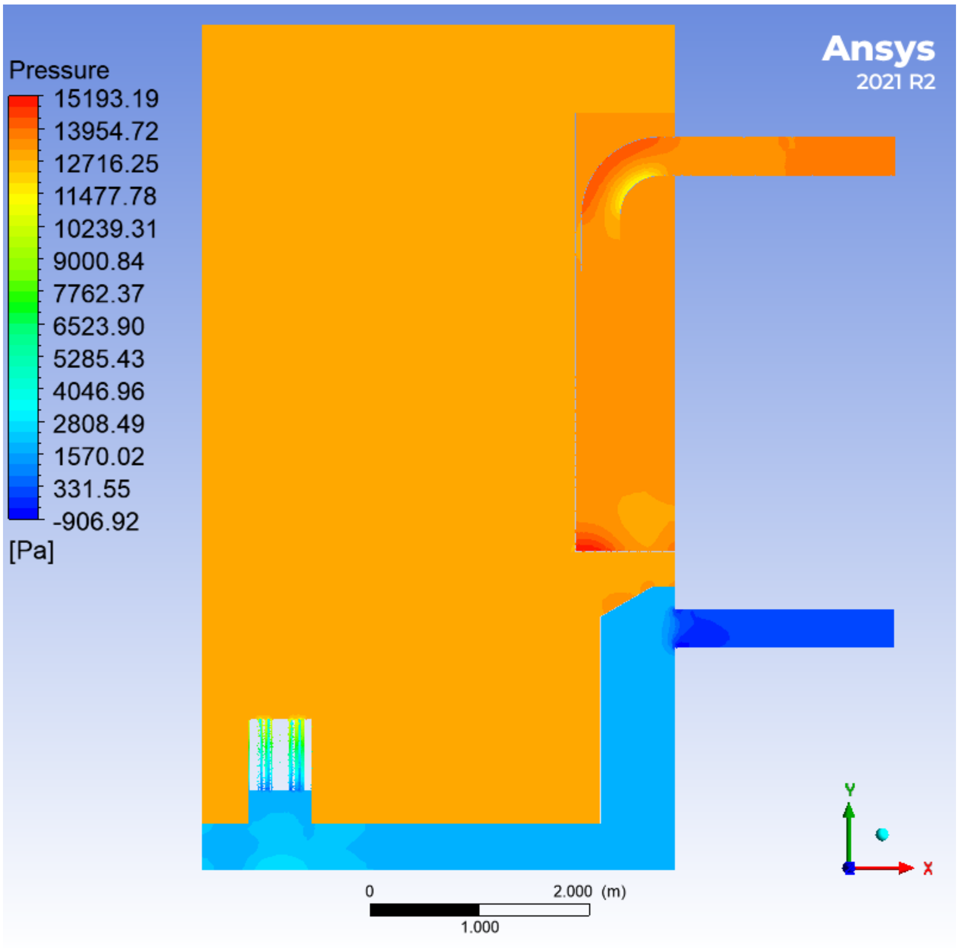

Figure 27 – Pressure contour

3.3 Total reactor power

The main goal was to determine whether the thermometer readings would be relevant for determining the reactor power, using formulas (2, 3) the reactor power was determined (Table 9).

Table 9 – Power according to thermometers

ChEPT-2		TSPU-2222	
$Q_{\Delta h}$, kW	$Q_{\Delta T}$, kW	$Q_{\Delta h}$, kW	$Q_{\Delta T}$, kW
6026,80	6032,45	5690,88	5701,91

As can be seen from the data in Table 9, the calculation by enthalpy and temperature gives almost equal results. The values for thermocouples are almost identical to the specified power of 6 MW, thermal resistances underestimate the power, this is a direct consequence of the presence of interzone elements that absorb part of the thermal energy and the presence of convection in the volume of water in the tank. Detailed outputs are made in the next chapter.

4 Analysis of results

The results of the simulation of the first circuit of IRT-T in the Ansys Fluent program are as follows.

The thermocouple readings are the most accurate result, it is identical to the rated power, despite the fact that the position of the sensors is not identical to the real one, but is selected in the area nearby. The influence of heat transfer from the water of the holding tank and the reactor vessel did not distort the readings, Figure 26 clearly demonstrates that in the vertical section, the temperature distribution near the upper sensors deviates by several tens of units. Thermal resistance slightly underestimated the power, which is obvious, heat transfer to metal structures and the upper layers of water underestimates their readings. However, the deviation is about 5 %, and with the introduction of a weighting factor, this value can be taken into account to determine the reactor power.

The power calculation methods did not show any significant difference in the power value, which means that there is no need to use the pressure value to determine the power through enthalpy, the average heat capacity of water is sufficient. The simplification of the design of the zone with the resulting decrease in the pressure drop on az did not affect the results of the work.

The energy release only inside the core body and its volume uniformity do not introduce errors into the power determination. However, for a real reactor, this can be sensitive, given that part of the energy is released by neutrons and gamma quanta in the volume of water and biological protection, but judging by the data obtained, this would have a greater impact on the readings of thermal resistances.

As a result of the foregoing, we can make an assumption about the possibility of introducing a thermal engineering method of power control at IRT-T based on the existing set of sensors. Of course, this will require much more detailed calculations and, of course, experiments.

5 Financial management, resource efficiency and resource saving

5.1 Introduction

The work was concerned with thermal-hydraulic calculation of the primary circuit of the IRT-T (Thermal research reactor – Tomsk) reactor in order to verification of the possibility of implementing thermotechnical control of its power. The object of study is the first circuit of the reactor and in-core instrumentation.

Modern world trends determine the vector of development of any technological, scientific and other industries. The question is taken up about the need of plan and organize all ongoing work in terms of resource efficiency and resource saving.

The implementation of a competent research work requires an economic assessment of all its elements: both the object of study and the methods that are used for this. Thus, there is a need to determine the costs of research and development and their duration, which, in turn, determines the economic efficiency and competitiveness of the developed solution.

The purpose of this section of the thesis was to evaluate the competitiveness and resource efficiency of the study. To achieve this goal, it is necessary to perform the following tasks:

– identify potential consumers of the developed solution;

– analyze the technical solution;

– make a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis;

– chose stakeholders of work, goals of work and present participants of working group;

– identify the structure of work, their performers and develop a schedule for the study;

– calculate the research budget;

– make comparative evaluation of project.

The section is made according to the methodology presented in the manual [27].

5.2 Potential consumers of the research results

The obtained results of the analysis of the possibility of implementing thermal method of power control by reactor's existing instrumentation make it possible to advance in the issue of efficient use of the reactor, increasing its power and, thereby, increasing competitiveness. The target consumers of the study are the research reactor itself, as well as organizations involved in the operation of reactors like IRT-T (9 IRT (Thermal research reactor)-type reactors were built) or specializing in the development and/or design of reactor installations. They are interested in reducing costs and getting the most out of their installations.

The nuclear power market can be segmented according to many criteria, one of which is the ability to perform high-level studies on the research reactors and the level of neutron flux density achieved in research reactor (RR) (Figure 28).

		RR neutrons flux density		
		~10^{14} n/cm^2·s	~10^{15} n/cm^2·s	≥10^{16} n/cm^2·s
Opportunities for experiments	High			■
	Medium		■	
	Low	■		

Figure 28 – Market segmentation map

The parameters of the IRT-T reactor belong to the category of low possibilities for experiments. The implemented solution will improve power control at the reactor, which will contribute to the project to bring the reactor to a new power level, which means moving to another group and increasing its competitiveness.

5.3 Competitiveness analysis of technical solution

The work investigated the method and devices for thermal method of power control for the IRT-T reactor. This method is more accurate and less restrictive than neutronic, which allows it to be used for power control at a research reactor so that it can remain competitive.

Competitors of the chosen method are neutronic methods (ionization chambers and direct discharge sensors). Analysis of competitive technical solutions is made by the formula (14):

$$C = \sum P_i \cdot W_i, \qquad (15)$$

where: C – the competitiveness of research or a competitor;

P_i – criterion weight;

W_i – point of i-th criteria.

The weights of the criterions, determined by an expert, should total 1. Table 10 presents a map of the competitiveness of various characteristics of the mentioned methods, where P_{th} is the thermal method, P_{n1} is the ionization chambers, P_{n2} is the direct charge sensors.

Table 10 – Evaluation card for comparison of competitive technical solutions

Evaluation criteria	**Criterion weight**	**Points**			**Competitiveness**		
		P_{th}	P_{n1}	P_{n2}	C_{th}	C_{n1}	C_{n1}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
Method accuracy	0,2	4	2	3	0,8	0,4	0,6
Effect on core	0,15	3	5	3	0,45	0,75	0,45
Autonomy	0,1	5	1	5	0,5	0,1	0,5
Ease of operation	0,1	4	4	4	0,4	0,4	0,4
Response time	0,05	4	2	2	0,2	0,1	0,1
Economic criteria for performance evaluation							
Cost of service	0,1	3	4	3	0,3	0,4	0,3
Cost of unit	0,1	5	3	3	0,5	0,3	0,3
Service life	0,15	3	5	2	0,45	0,75	0,3
Market penetration rate	0,05	5	5	5	0,25	0,25	0,25
Total:	**1**	**36**	**31**	**30**	**3,85**	**3,45**	**3,2**

The data provided above make it possible to perform analyze of power control equipment. Based on the data obtained in the Table 10, it can be concluded that the thermal method is superior to all other methods and the study will improve the efficiency and competitiveness of the reactor.

5.4 SWOT analysis

SWOT – Strengths, Weaknesses, Opportunities and Threats – is a comprehensive analysis of any research project. SWOT analysis is used to study the external and internal environment of the project. Analysis is a universal tool for strategic analysis and planning, used to evaluate the phenomena and factors influencing on project or development. The conclusions drawn from it are descriptive without recommendations or prioritization.

Strengths can be factors that reflect the most competitive side of the solution in question.

Strengths:

– the need to use an additional method of power control;

– ease of implementation of the obtained results and methods in the actual process of reactor operation;

– low time and money costs for research.

Weaknesses are those features of the object in question that may prevent its most beneficial and unhindered use.

Weaknesses of the study:

– the study isn’t based on a real reactor run and uses only the nominal characteristics of the plant;

– the model is maximally simplified due to its complexity, as a result of which the results reflect only the general picture and the fundamental possibility of thermal method of power control (recommendations) without detailed steps for implementing the method.

Opportunities include any preferred present or future situation arising from the project environment.

The possibilities include:

– the implementation of a power control channel for calibrating the current;

– improving plant safety and efficiency;

– improvement of the control system to further increase the power of the reactor.

Threats are any undesirable situations, trend or change in an entity's environmental conditions that may be disruptive or threatening to its present or future competitiveness.

Threats include:

– probable inaccuracies in the calculation won't allow the implementation of the methodology and will require new work in this area;

– disinterest of target users in the results of work.

Table 11 presents the SWOT analysis in tabular form.

Table 11 – SWOT matrix

	Strengths of the research project: S1. The need to use an additional method of power control. S2. Ease of implementation of the obtained results and methods in the actual process of reactor operation. S3. Low time and money costs for research	**Weaknesses of the research project:** W1. Study isn't based on a real reactor run and uses only the nominal characteristics of the plant. W2. Model is maximally simplified due to its complexity, as a result of which the results reflect only the general picture and the fundamental possibility of thermal method of power control (recommendations) without detailed steps for implementing the method.
Opportunities: O1. Implementation of a power control channel for calibrating the current. O2. Improving plant safety and efficiency. O3. Improvement of the control system to further increase the power of the reactor.	1. Calibration of the reactor power readings will increase its efficiency and safety. 2. Calibration of existing power control detectors to new readings will improve their performance.	1. The implementation of the methodology may require changes to the control and protection system, these measures are extremely time-consuming, which will lead to reactor downtime.
Threats: T1. Probable inaccuracies in the calculation won't allow the implementation of the methodology and will require new work in this area. T2. Disinterest of target users in the results of work.	1. The results of the study make it possible to use the reactor more efficiently. 2. Refinement of the basic characteristics of the reactor increases the interest in conducting such experiments and the accuracy of their results.	1. Probable inaccuracies and simplifications may alienate potential users due to lack of confidence in the results.

Performed SWOT-analysis allows to determine the further position of the object in question in the relevant market with sufficient accuracy for this work. The introduction of a thermotechnical control method will make it possible to increase the efficiency and safety of a research reactor and avoid unforeseen situations caused by only one method of power control.

5.5 Project initiation

In this section presented information about:

– project stakeholders and their expectations for project (Table 12);
– purpose and results of project (Table 13);
– information about project working group (Table 14).

Table 12 – Stakeholders of the project

Project stakeholders	Stakeholder expectation
Nuclear industry: operators of research reactors, designers of reactor installations	Accuracy of results; Possibility of implementation or ready for start-up of method.

Table 13 – Purpose and results of the project

Purpose of the project	Verify the implementation and possible improvement of the thermotechnical method for the thermal power control of the IRT-T reactor
Expected results of the project	Model should present a good quality data that can describe temperature field near the sensors to confirm or deny experimental values and determine the ability of thermal method implementation and the necessary changes in instrumentation system
Criteria for acceptance of the project results	Convergence of experimental values with calculated
	Requirement
Requirements for the project results	Project complete in time
	Calculation results compared with experimental
	Instrumentation choice is justified

Table 14 – Working group of the project

№	Participant	Role in the project	Functions	Labor time, hours
1	A.A. Rybachenko	Project Executor (Engineer)	Work on the project implementation	528

Table 14 continuation

2	Y.B. Chertkov	Project Manager (Supervisor)	Work on implementation of the project within the specified resource constraints, coordinates the activities of the project	64
3	L.Y. Spicyna	Project Expert	Consultant of “Financial Management, Recourse Efficiency and Resource Saving” section	8
4	Y.V. Perederin	Project Expert	Consultant of “Social Responsibility” section	8
			Total:	**608**

5.6 Planning of scientific and technical project management

Planning scientific research allows us to identify the stages of work and rationally divide time between them. Table 15 shows the stages, their duration and the participants involved in them. Appendix B contains Table B.1 which visualizes the information from the Table 15.

Table 15 – Project schedule

Job title	Duration, working days	Start date	Date of completion	Participants
Drawing up the technical assignment	2	01.02.22	03.02.22	Supervisor
Literature review	15	07.02.22	27.02.22	Engineer
Development of a work schedule	2	07.02.22	09.02.22	Supervisor
Preparation of working methods	15	01.03.22	20.03.22	Engineer
Evaluation of the chosen methods	2	21.03.22	23.03.22	Both
Computer calculation	10	01.04.22	10.04.22	Engineer
Analysis and processing of the obtained data	5	11.04.22	16.04.22	Engineer
Evaluation of the results	2	18.04.22	20.04.22	Both
Summing up the work	2	02.05.22	04.05.22	Engineer
Drawing up a final report	15	09.05.22	29.05.22	Engineer

The work was divided into 10 stages: the stages are associated with specific sections of the thesis.

Two work control points have been added. The control of the completed stages increases the efficiency of work, since the time spent on it allows you to avoid unforeseen time costs if the results of the completed stages are unsatisfactory.

In total, the engineer spent 66 full days on work, the supervisor 8 days.

5.7 Scientific and technical research budget

The cost sheet for realisation of this study contains all the costs necessary for the implementation of a set of works necessary for realization of tasks assigned to the project. The calculation of the full (estimated) cost of the study is carried out according to the following costs:

– material costs;
– basic salary;
– additional salary;
– labor tax;
– overhead costs.

5.7.1 Calculation of materials costs

This term includes the cost of materials, purchased products, semi-finished products and other material assets consumed directly in the process of performing work on the design object. This also includes specially purchased equipment, tools and other items classified as fixed assets worth up to 40000 rubles inclusive.

The price of material resources is determined by the relevant price tags or supply contracts. In addition, it includes the so-called transportation and procurement costs associated with transportation from the supplier to the consumer, storage and other processes that ensure the movement (delivery) of material resources from suppliers to the consumer.

This also includes the costs of the purchase and sale transaction (transaction). Approximately they are estimated as a percentage of the selling price of purchased materials, as a rule, it is 3 – 5%. Let's say that they are 5% of the selling price of materials. The performer of the work independently chooses their value within the limits presented in Table 13.

Cost of every position in Table 16 calculated by equation (15):

$$C_m = (1 + k_T)\sum_{i=1}^{m} P_i N_{consi}, \text{ RUB}, \quad (16)$$

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 (units, kg, m, m^2, etc.);

P_i – the acquisition price of a unit of the i-th type of material resources consumed (RUB/units, RUB/kg, RUB/m, RUB/m^2, etc.);

k_T – coefficient taking into account transportation costs.

Energy costs are calculated by the formula (16):

$$C = P_{el} \cdot P \cdot F_{eq}, \text{ RUB}, \quad (17)$$

where: P_{el} − power rates (2,73 rubles per 1 kWh);

P − power of equipment, kW;

F_{eq} − equipment usage time, hours.

Table 16 – Material costs

Name	**Unit**	**Amount**	**Price per unit, RUB**	**Material costs, RUB**
Printer paper	unit	1	450	472,50
Electricity	kWh	220,8	2,73	632,92
Internet connection	unit	4	590	2478
Copy book	unit	1	150	157,50
Pencil	unit	2	100	210
Pen	unit	2	100	210
Eraser	unit	1	60	63
Total:	**4223,92**			

Cost of all used materials (and spend electricity) equal to 4224 RUB.

5.7.2 Basic salary

This article includes the basic salary of scientific and engineering workers, workers of model workshops and experimental production facilities directly involved in the performance of work on this topic. The amount of salary expenses is determined based on the labor intensity of the work performed and the current system of remuneration. The basic salary includes a bonus paid monthly from the salary fund. The calculation of the basic salary is summarized in Table 17.

Monthly salary is calculated by formula (17):

$$S_{mounth} = S_{base} \cdot (1 + k_{premium} + k_{bonus}) \cdot k_{reg}\text{, RUB,} \tag{18}$$

where: S_{base} – base salary, RUB;

$k_{premium}$ – premium rate;

k_{bonus} – bonus rate;

k_{reg} – regional rate (for Tomsk region is equal 1,3).

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 average daily salary is calculated by the formula (18):

$$W_d = \frac{S_{month} \cdot M}{F_v}\text{, RUB/day,} \tag{19}$$

where: M – the number of months of work without leave during the year: at holiday in 48 days, M = 11.2 months, 6 day per week;

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

The basic salary (W_{base}) is calculated according to the following formula (19):

$$W_{base} = W_d \cdot T_p\text{, RUB,} \tag{20}$$

where: T_p – the duration of the work performed by the scientific and technical worker, working days;

W_d – the average daily salary of participant, RUB.

Table 17 – Basic salary

Performers	S_{base}, RUB	$k_{premium}$	k_{bonus}	k_{reg}	S_{month}, RUB	W_d, RUB/day	T_p, work days	W_{base}, RUB
Supervisor	37700	0,3	0,25	1,3	75965,50	3389,70	8	27117,56
Engineer	13 890				27988,35	1248,88	66	82426,25
							Total:	**109543,81**

Total basic salary for participants – 109544 RUB (supervisor – 27118 RUB, engineer – 82426 RUB).

5.7.3 Additional salary

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

Additional salaries are calculated on the basis of 10 – 15% of the base salary of workers (20):

$$W_{add} = k_{extra} \cdot W_{base}, \text{ RUB,} \quad (21)$$

where: W_{add} – additional salary, RUB;

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

W_{base} – base salary, RUB.

Table 18 shows the form for calculating the basic and additional wages.

Table 18 – Additional salary

Performers	W_{add}, RUB
Supervisor	2711,76
Engineer	8242,62
Total:	**10954,38**

Total additional salary for participants – 10954 RUB.

5.7.4 Labor tax

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 (21):

$$P_{social} = k_b \cdot (W_{base} + W_{add}), \text{RUB}, \qquad (22)$$

where: k_b – coefficient of deductions for labor tax.

Amount of insurance contributions is set at 30,2%.

Results present in Table 19.

Table 19 – Labor tax

Performers	**P_{social}, RUB**
Supervisor	9008,46
Engineer	27382,00
Total:	**36390,46**

Total labor tax for participants – 36390 RUB.

5.7.5 Overhead costs

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

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

Overhead is calculated according to the formula (22):

$$C_{ov} = k_{ov} \cdot (W_{base} + W_{add}), \text{ RUB}, \qquad (23)$$

where: k_{ov} – overhead rate (30%).

Results present in Table 20.

Table 20 – Overhead costs

Performers	**C_{over}, RUB**
Supervisor	8948,80
Engineer	27200,66

Table 20 continuation

Total:	**36149,46**

Total overhead costs for participants – 32655 RUB.

5.7.6 Formation of budget costs

Finally, the total budget of work can be seen in Table 21. It is the sum of all positions showed above.

Table 21 – Budget

Budget position	Cost	
	, RUB	, %
Material costs	4223,92	2,14
Basic salary	109543,81	55,53
Additional salary	10954,38	5,55
Labor tax	36390,45	18,45
Overhead	36149,46	18,33
Total:	**197262,03**	**100**

In a result budget equal to 197262 RUB.

5.8 Evaluation of the comparative efficiency of the project

Determination of efficiency is based on the calculation of the integral indicator of the efficiency of scientific research. Its finding is associated with the determination of two weighted averages: financial efficiency and resource efficiency.

An integral indicator of the financial efficiency of scientific research is obtained in assessing the budget of costs of three (or more) variants of the implementation of scientific research (Table 22). For this, the largest integral indicator of the implementation of a technical problem is taken as the basis of the calculation (as the denominator), with which the financial values for all execution options are correlated.

Integral financial indicator is determined by formula (23):

$$I_f^p = \frac{F_{pi}}{F_{\max}}, \tag{24}$$

where: F_{pi} – price of *i*-th variant execution;

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

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

The integral indicator of the resource efficiency of the variants of the object of research can be defined as follows (24):

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a ,\ I_m^p = \sum_{i=1}^{n} a_i b_i^p , \tag{25}$$

where: a_i – weight coefficient of the *i*-th parameter;

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

Analogues from Table 10 are taken for comparison.

Table 22 – Comparative evaluation of the characteristics of the project execution options

Criteria	**Parameter weight factor**	**Project**	**Analog 1**	**Analog 2**
Working efficiency growth	0,1	5	5	5
Convenience in operation (meets the requirements of consumers)	0,15	5	3	1
Immunity	0,15	4	2	2
Energy efficiency	0,2	5	2	5
Reliability	0,25	3	5	2
Material consumption	0,15	5	1	5
Total:	1			

Project = 4,35; Analog 1 = 3,05; Analog 2 = 3,20.

5.9 Section conclusions

The section is made according to the methodology presented in the manual [27]. The results of the section are as follows:

– potential consumers of the study have been identified, these are the IRT-T reactor and reactors of a similar design. A map of market segmentation was drawn up;

– comparative analysis of the proposed solution with its competitors was done. The analysis confirmed the advantage of the chosen solution;

– SWOT analysis of the work was done. Strengths and weaknesses, opportunities and threats in the implementation of the work were identified, a matrix was compiled;

– stakeholders and their requirements for work, goals of work and working group participants are determined;

– work schedule has been drawn up, stages of work and their participants have been determined;

– budget of the work is calculated. It is 197 thousand rubles. The budget is based on: materials costs, basic salary, additional salary, labor tax and overhead costs;

– comparative efficiency of the project in comparison with analogues was determined.

6 Social responsibility

6.1 Introduction

In modern conditions, one of the main directions for the radical improvement of all preventive work to reduce occupational injuries and occupational morbidity is the widespread introduction of an integrated labor protection management system, that is, by combining disparate measures into a single system of targeted actions at all levels and stages of the production process.

Rules on labor protection and safety are introduced in order to prevent accidents, ensure safe working conditions for workers and are mandatory for workers, managers, engineers and technicians.

The work is concerned with the thermal hydraulic calculation of the primary circuit of the IRT-T reactor in order to verify the possibility of implementing thermal method of power control. The object of study is the first circuit of the reactor and instrumentation.

Section related consideration of dangerous and harmful factors, fire and explosion safety, electrical safety and actions in case of emergency at the object under study – control room of the reactor.

The section was completed according to the methodology presented in the manual [28].

6.2 Hazards. Dangerous and harmful factors

Table 23 lists the dangerous and harmful factors that may occur during operation.

Table 23 – Dangerous and harmful factors [29]

Factors (GOST 12.0.003-2015)	Stages of work			Regulations
	Develop ment	Impleme ntation	Operatio n	

Table 23 continuation

1. Deviation indoor climate	+	+	+	SanPiN 1.2.3685-21 "*Gigiyenicheskiye normativy i trebovaniya k obespecheniyu bezopasnosti i (ili) bezvrednosti dlya cheloveka faktorov sredy obitaniya*" (In Russian)
2. Lack of artificial and natural illumination	+	+	+	
3. Ionizing radiation	+	+	+	
4. Noise	+	+	+	

6.2.1 Indoor climate

The indicators characterizing the indoor climate [29]:

– air temperature;
– relative humidity;
– air speed;
– intensity of thermal radiation.

The source of the occurrence of deviations of the above parameters is: heating of the surfaces of process equipment, environmental influence on the working room, incorrect design and/or selection of materials for the working room, incorrect ventilation mode.

In general, the deviation of microclimate indicators leads to a decrease in human performance, overwork and the risk of diseases. Each of the microclimate parameters affects a person, and together they can increase the negative impact on the body.

Thus, decrease in air temperature leads to hypothermia of the body, increase in the speed of air movement only enhances this effect. Increase in air temperature leads to overheating of the body, if at the same time the humidity of the air is high, then sweat evaporates less intensively and the faster the body overheats, leading to a decrease in efficiency. Intense thermal radiation leads to excessive heating of the air in the room with all the ensuing consequences.

Each category of work is assigned certain optimal and permissible microclimate parameters. The work of personnel at the RR is categorized as light physical work (category 1b) [30]. Values for temperature, humidity and air velocity are provided in Appendix C in Table C.1.

In addition, there is a remark in clause 1.4 [31], according to which: "In cabins, on consoles and control posts for technological processes, in computer rooms and other industrial premises, when performing operator-type work associated with neuro-emotional stress, optimal the air temperature is 22-24 °C, its relative humidity is 60-40 % and the speed of movement (no more than 0,1 m/s)".

The intensity of thermal irradiation of surfaces of technological equipment, lighting devices, insolation at permanent and non-permanent workplaces shouldn't exceed 35 W/m when irradiating 50 % of the body surface or more, 70 W/m - when the size of the irradiated surface is from 25 to 50 % and 100 W/m - when irradiating no more than 25 % of the body surface.

In the presence of thermal radiation, the air temperature at permanent workplaces should not exceed the upper limits of optimal values specified in Table E.1 for the warm period of the year.

All of the above are the requirements stated in [29-31].

Personal protective equipment is special cloths and special shoes [32].

As a means of collective protection against changes in microclimate indicators in industrial space the following should be used: thermal insulation or heat shields, heating, local air conditioning systems, air showering, rest rooms, regulation of work and rest times, etc. [33].

Ventilation is done to maintain the required microclimate. The required air flow is based on the air exchange rate (26):

$$L = n \cdot S \cdot H,\ \mathrm{m^3/h}, \qquad (26)$$

where: n – air exchange rate (n = 1,5);

S – room space, m^2;

H – room height.

The control room of the reactor is a rather small room, but combined with office, so we will consider their area together. The air flow is:

$$L = 1,5 \cdot 40 \cdot 2,5 = 150\,\mathrm{m}^3/\mathrm{h}.$$

This room can be ventilated by one MM 120 fan with a flow rate equal to 150 m^3/h [34].

The calculation of ventilation of the room was made in accordance with the requirements [35].

6.2.2 Quantity of illumination

In the working rooms of the reactor, combined illumination is used - artificial and natural. Artificial is created by fluorescent lamps of the LD type. The work process refers to the work of high accuracy, it is necessary that the illumination parameters of the workplace meet the requirements [29].

Since the work involves long-term monotonous operations with a high level of visual work, that is, distinguishing objects of high accuracy, ranging in size from 0,3 to 0,5 mm, it is necessary to take at least 300 lux and not more than 500 lux as the norm for workplace illumination. For an engineer at research reactor in the rooms of the control rooms illumination of the workplace should be equal to 500 lux. The pulsation coefficient in both cases shouldn't exceed 15 % [36].

The required number of lamps is determined as follows (27):

$$n = \frac{E \cdot S \cdot Z \cdot K}{F \cdot \Phi \cdot m}, \tag{27}$$

where: E – normalized illumination, E = 500 lux;

S – room area, S = 16 m^2;

Z – coefficient of illumination variation (pulsation), Z = 1,15;

K – factor of margin, K = 1,1;

F – luminous flux of one bulb, F = 1200 lm;

Φ – use coefficient, Φ = 0,52;

m – number of bulbs in a lamp, m = 4 units.

$$n = \frac{500 \cdot 16 \cdot 1,15 \cdot 1,1}{1200 \cdot 0,52 \cdot 4} = 4,05 \text{ units.}$$

In order to avoid areas with insufficient illumination, the required number of lamps is rounded up to a whole number. Thus, the number of lamps will be 4.

The number of lamps in the room according to [16] is 4, which corresponds to the calculated value of 4 lamps.

6.2.3 Ionizing radiation

Sources of ionizing radiation [37]:

- technogenic sources due to the normal operation of technogenic radiation sources;
- technogenic sources as a result of a radiation accident;
- natural sources;
- medical sources.

The source of IR is the IRT-T core, which is categorized as a technogenic source in normal operation.

Radiation exposure can be internal or external. Internal exposure to ionizing radiation occurs when radionuclides are inhaled, ingested, or otherwise introduced into the body. External radioactive contamination can occur when radioactive material in the air (dust, liquid, aerosols) is deposited on the skin or clothing.

A classic example of radiation damage to the human body is acute radiation sickness that occurs after a single external uniform exposure. Exposure above certain thresholds may impair tissue and/or organ function and may cause acute reactions such as reddening of the skin, hair loss, increased chance of future cancer, radiation burns, or acute radiation syndrome.

To determine the exposure limit, the following categories of exposed persons are established [37]:

- personnel (groups A and B);
- the entire population, including persons from personnel outside the scope and conditions of their production activities.

The main dose limits (DL) given in Appendix C in Table C.2.

All of the above are the requirements stated in [29, 37].

Personal protective equipment includes special clothes, respiratory and eye protection [38].

The means of collective protection against IR include protective devices, warning devices, reducing the duration of work in the radiation zone, shielding the source, devices for trapping and purifying air and liquids, decontamination devices, automatic control devices, remote control devices, means of protection during transportation and temporary storage of radioactive substances, safety signs, containers for radioactive waste [39].

6.2.4 Noise

Noise at 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 leads to hearing loss of the worker up to his complete deafness [40].

Sudden high-intensity noises, even short-term ones (explosions, impacts, etc.), can cause both acute neurosensory effects (dizziness, tinnitus, hearing loss) and physical damage (rupture of the eardrum with bleeding, damage to the middle ear and snails).

The noise level in the working room with the presence of personal computers shouldn't exceed 65 dB [41].

Means and methods of protection against noise in relation to the protected object are divided into [42]:

– means and methods of collective protection (acoustic, architectural and planning, organizational and technical):

– personal protective equipment (anti-noise headphones that cover the auricle from the outside, anti-noise inserts that block the external auditory canal or adjacent to it, anti-noise helmets and helmets, anti-noise suits).

All of the above are the requirements stated in [29, 40-42].

6.3 Fire and explosion safety

Buildings (structures, fire compartments and parts of buildings, structures - rooms or groups of rooms that are functionally interconnected) according to the class of functional fire hazard depending on their purpose, as well as on the age, physical condition and number of people in the building, structure, the possibilities of their stay in a state of sleep are divided into: F1, F2, F3, F4, F5. The room, according to the degree of fire and explosion hazard, belongs to category F5.1, i.e. industrial buildings, structures, industrial areas and laboratory, workshops [41].

Possible causes of fire:

– malfunction of current-carrying parts of installations;

– work with open electrical equipment;

– short circuits in the power supply;

– carelessness of fire safety rules;

– the presence of combustible components: documents, doors, tables, cable insulation, etc.

Measures for fire prevention are divided into: organizational, technical, operational and regime.

Organizational measures provide for the correct operation of equipment, the correct maintenance of buildings and territories, fire safety briefing for workers and employees, training of production personnel in fire safety rules, publication of instructions, posters, and an evacuation plan.

Technical measures include: compliance with fire regulations, norms in the design of buildings, in the installation of electrical wires and equipment, heating, ventilation, lighting, proper placement of equipment.

Regime measures include the establishment of rules for the organization of work, and compliance with fire prevention measures. To prevent a fire from short circuits, overloads, etc., the following fire safety rules must be observed:

– exclusion of the formation of a combustible environment (sealing of equipment, air control, working and emergency ventilation);

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

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

– proper maintenance of buildings and territories (exclusion of the formation of an ignition source - prevention of spontaneous combustion of substances, restriction of hot work);

– training of production personnel in fire safety rules;

– publication of instructions, posters, availability of an evacuation plan;

– compliance with fire regulations, standards in the design of buildings, in the installation of electrical wires and equipment, heating, ventilation, lighting;

– proper placement of equipment;

– timely preventive inspection, repair and testing of equipment.

In the event of an emergency:

– notify the manager;

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

– take action as instructed.

All of the above are the requirements stated in [41].

6.4 Electrosecurity

Consider the control room of a nuclear reactor. According to [42], this room belongs to the second category of rooms with electrical installations with a voltage of more than 1000 V.

It doesn’t to work with a computer in conditions of high humidity (relative air humidity exceeds 75 % for a long time), high temperature (more than 35 °C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with ground-connected metal elements and the metal case of electrical equipment. The computer operator works with electrical appliances: a computer (display, system unit, etc.) and peripheral devices. There is a danger of electric shock in the following cases:

– by direct contact with current-carrying parts during computer repair;

– when touching non-current-carrying parts that are energized (in case of violation of the insulation of the current-carrying parts of the computer);

– when touching the floor, walls that are energized;

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

If any part of the computer malfunctions electrical current may be present in the case, which may result in electrical injury or electric shock. To eliminate this, it is necessary to ensure the connection of the metal cases of the equipment to the ground conductor.

Organizational measures for electrical safety are periodic and unscheduled briefings. Periodic briefing is carried out for non-electrotechnical personnel performing the following work: turning on and off electrical appliances, cleaning rooms near electrical panels, sockets and switches, etc.

Non-electrotechnical personnel are certified for the first qualification group in electrical safety. Periodic training is carried out at least once a year. Unscheduled briefing is carried out by the head of the unit when new technical electrical equipment is put into operation.

All of the above are the requirements stated in [42].

6.5 Ecological safety

The solution being developed directly affects the operation of the reactor. The operation of the reactor is associated with the use and production of radioactive materials that are deadly for the environment, so the release of these materials outside the reactor in cases not provided for by the technological process is unacceptable.

Leaving the reactor, radioactive materials will be transported in the atmosphere and hydrosphere, migrate in the soil, accumulate in plants, food, gradually dispersing and lowering their concentration.

To protect against such impact, it is necessary to create:

– containment barriers, with control of the integrity of physical barriers on the path of transfer of ionizing radiation and radioactive substances into the environment;

– permanent dosimetric monitoring, radiation monitoring system, which should ensure the measurement of the values of controlled parameters characterizing the radiation state at the NPP and in the environment in a certain volume under all operating modes of the NPP, as well as during design basis and beyond design basis accidents;

– sanitary protection zones, continuous measurements in the sanitary protection zone and the observation zone of the ionizing radiation dose rate, wind speed and other meteorological parameters, as well as periodic measurements of the density of radioactive fallout to assess and predict the radiation situation in the surrounding area during normal operation of the nuclear power plant and violations of normal operation, including design basis and beyond design basis accidents;

– accounting and control of nuclear materials, radioactive substances and radioactive waste, including fresh and spent nuclear fuel, dismantled radioactive equipment, contaminated tools, clothing, industrial waste, and other sources of ionizing radiation.

In order to ensure the safety of the population around facilities and industries that are sources of impact on the environment and human health special area with a special regime of use is established. In accordance with this, for such objects it is necessary to organize work on the assessment of atmospheric air pollution, physical impact on atmospheric air, on the basis of which a decision should be made to justify the need to create a sanitary protection zone.

All of the above are the requirements stated in [43].

6.6 Safety in emergency situations

Table 24 discusses emergency situations that may arise at the IRT-T research reactor.

Table 24 – Emergencies, prevention measures and emergency response [44-47]

№	Emergency situation	Prevention measures	Emergency response
1	Fire	– check the condition of electrical devices, in case of detection of problems, do not proceed with self-elimination; – comply with fire safety rules in accordance with the requirements of regulatory documentation; – train and instruct employees, develop firefighting skills.	– turn off electrical equipment; – use powder and carbon dioxide fire extinguishers; – in case of a threat to life, evacuate; – call 101, 112.
2	Electric shock	it is forbidden: – work with wet and dirty hands; – touch the connectors of the connecting cables; – Troubleshoot equipment yourself – touch the power wires and grounding devices; – to train and instruct employees.	– eliminate the effect of current on the victim; – lay the victim on a hard surface; – check for breathing and pulse; – calling 103 or 112 is mandatory in all cases.
3	Fall from height resulting in injury	– make sure that computer wires are not in the way of movement, in case of violation, inform the manager; – do not use a chair, table, etc. instead of a ladder; – do not allow equipment and documentation to be placed on shelves and cabinets that cannot be accessed without a ladder; – when moving up stairs, always hold on to the handrail and look at your feet; – do not keep your hands in your pockets, because in case of a fall, instinctive movements will help you stay on your feet; – never carry objects by holding them in front of you, blocking the view; – clean shoes from dirt, ice and other contaminants before entering the building; – to train and instruct employees.	– inspect the body and head of the victim for open wounds and abrasions; – ask to make movements with your fingertips, which will eliminate damage to the spine; – movement of arms and legs will eliminate the presence of fractures; – interrogate the victim about violations of general well-being: dizziness, drowsiness, nausea - these signs indicate a concussion; – in the absence of serious injuries, a cold compress is placed on the site of the bruise and the victim is escorted home; – the forced adoption of the “frog” pose indicates the presence of serious injuries, in this case it is forbidden to try to lift the victim or take off his clothes. In this case, you need to call 103 or 112 and report the incident.

6.7 Section conclusions

The results of this section are as follows:

– harmful and dangerous factors were identified: deviation of microclimate indicators, insufficient illumination, ionizing radiation and noise;

– considered fire and explosion and electrical safety;

– an assessment of the environmental impact of the facility on the environment was given;

probable emergencies at the facility are considered.

The property is assigned:

– according to the category of severity of work to category 1b [30];

– for fire and explosion safety to category F5.1 [42];

– on electrical safety to the second category [43].

Conclusion

In a result of writing a master's thesis, a thermal hydraulic calculation of the primary circuit of the IRT-T reactor was done using the Ansys Fluent program. The purpose of the work was to analyze the possibility of implementing a thermotechnical method of power control at the reactor using standard means and sensors.

The following results are obtained:

– temperature difference by thermal resistances was 6.9 ˚C;

– temperature difference for thermocouples is: 7.5 ˚C, 7 ˚C, 7.4 ˚C, respectively. The data are within the range described in the literature and obtained experimentally;

– pressure drop across the core is 21 kPa. The pressure drop is due to the simplification of the geometry and had no effect on performance;

– reactor power according to the readings of thermal resistances - 5702 kW, thermocouples (their average value) give a value of - 6032 kW. Thermocouples turned out to be more accurate, in addition, they are part of the control system and work according to the majority logic, this is a huge advantage that the sensor from the control system turned out to be the most accurate. However, thermal resistances give a small error;

– measurement of power by the method of enthalpy difference has not found practical use.

As a result, the study achieved its goal and the analysis confirmed the possibility of thermotechnical control of power by the available sensors on the IRT-T and, based on the results of improving the system, it is not required. All this, of course, only within the framework of the calculation model.

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Appendix A

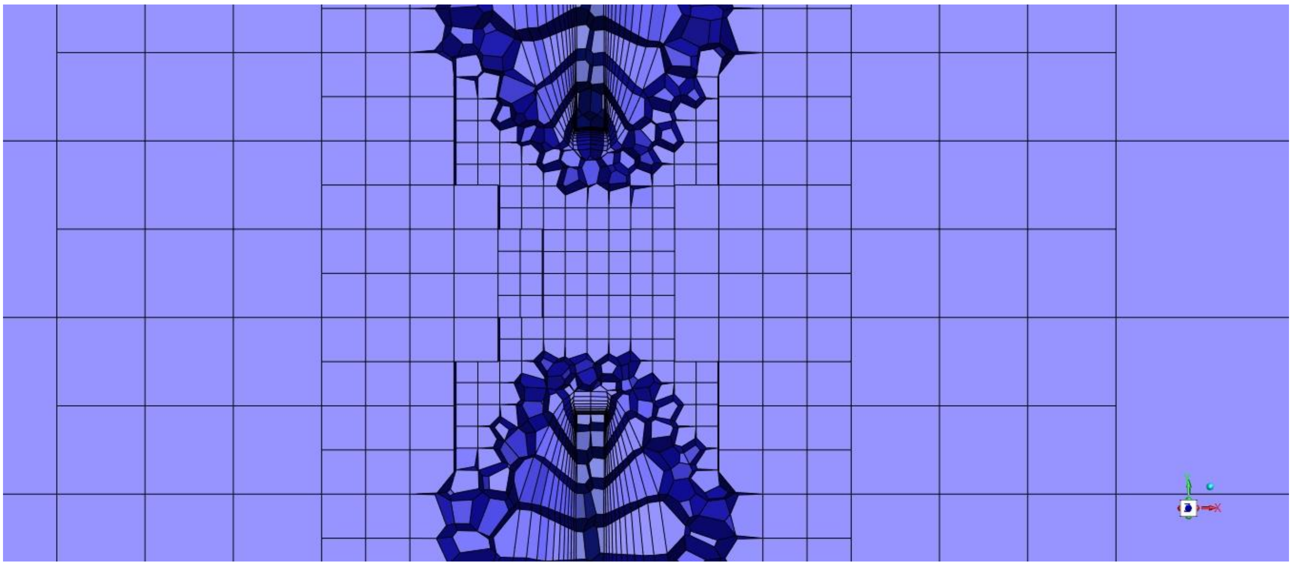

Figure A.1 – Mesh near distribution vessel holes

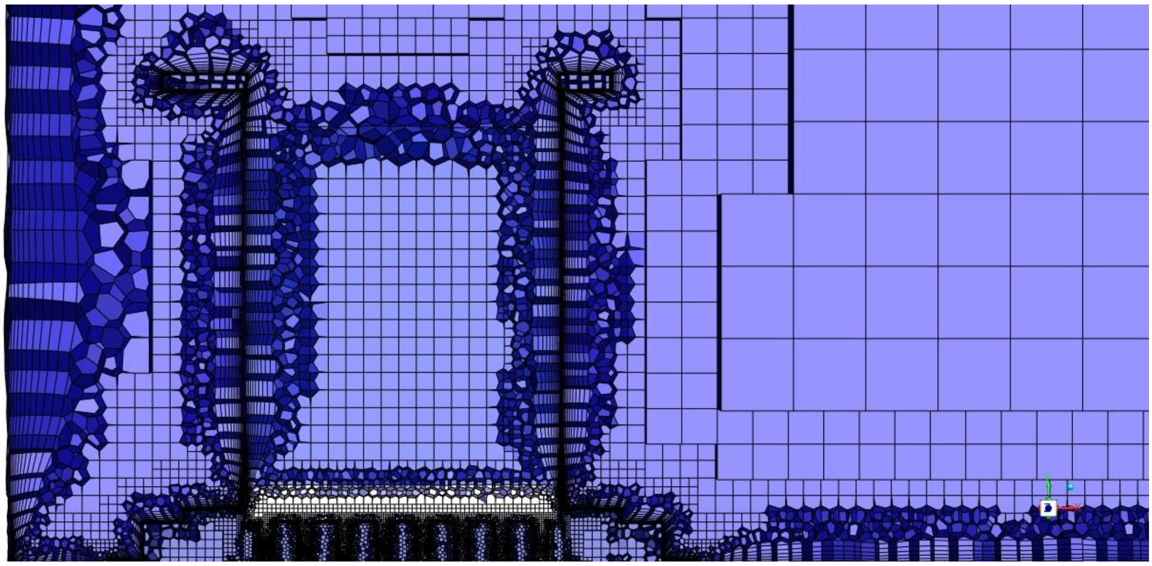

Figure A.2 Mesh near core

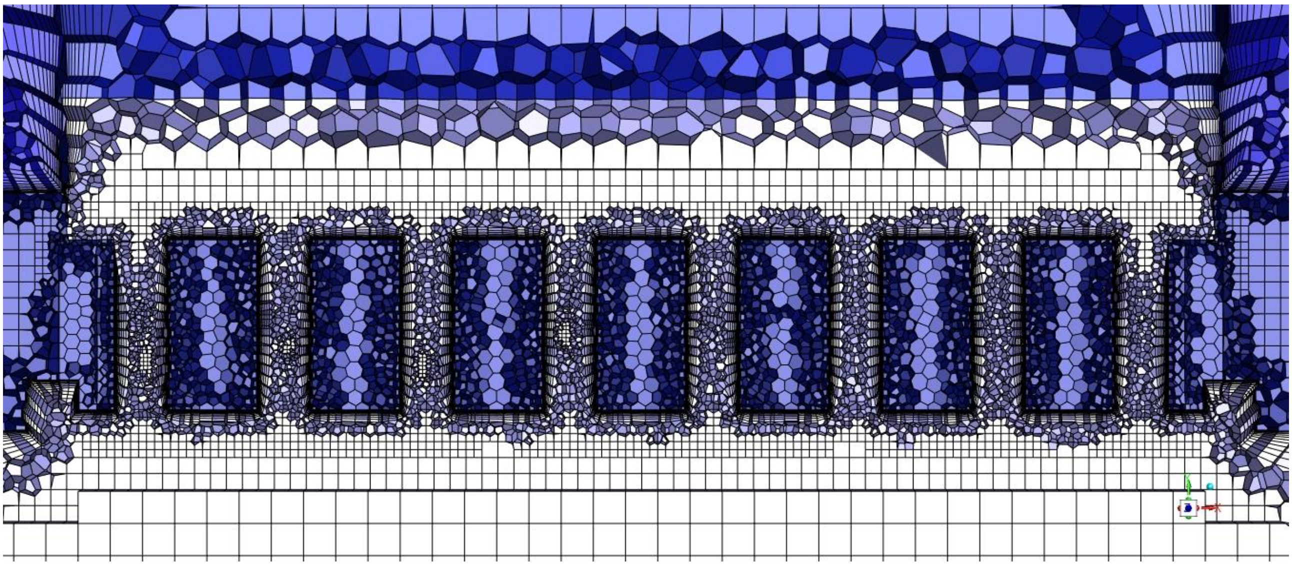

Figure A.3 – Mesh near spacer grid

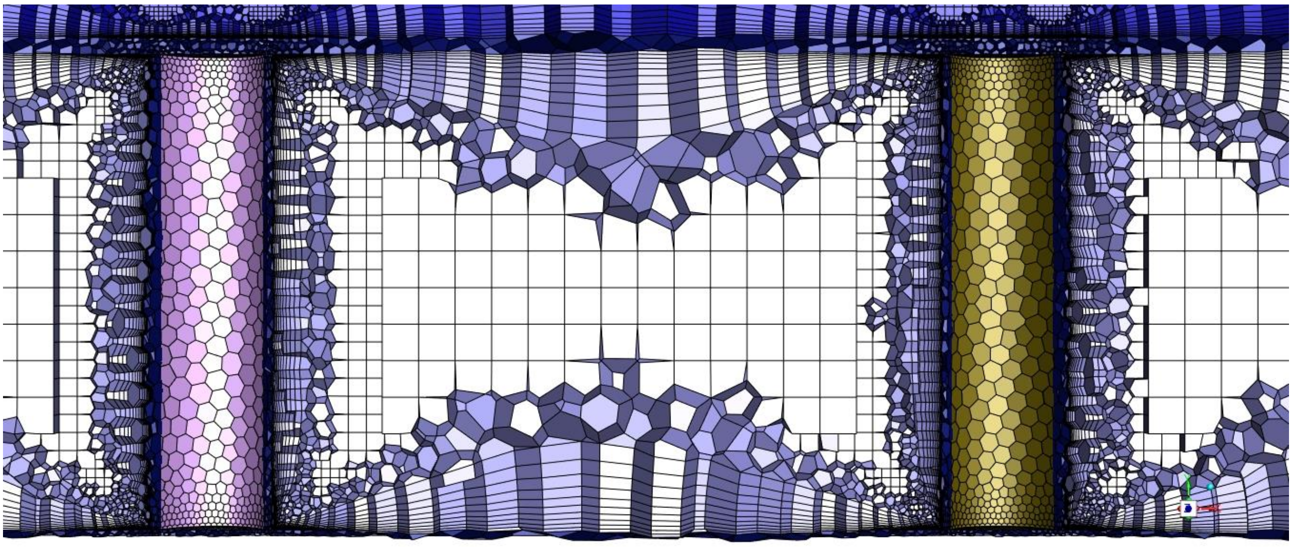

Figure A.4 Mesh in decay vessel

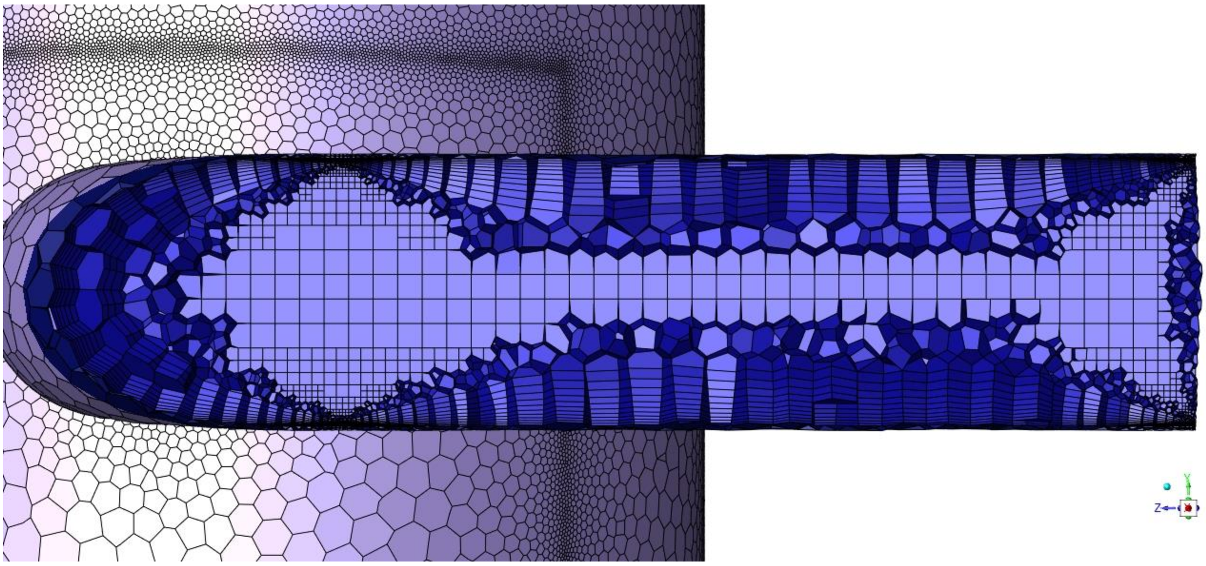

Figure A.5 – Inlet mesh

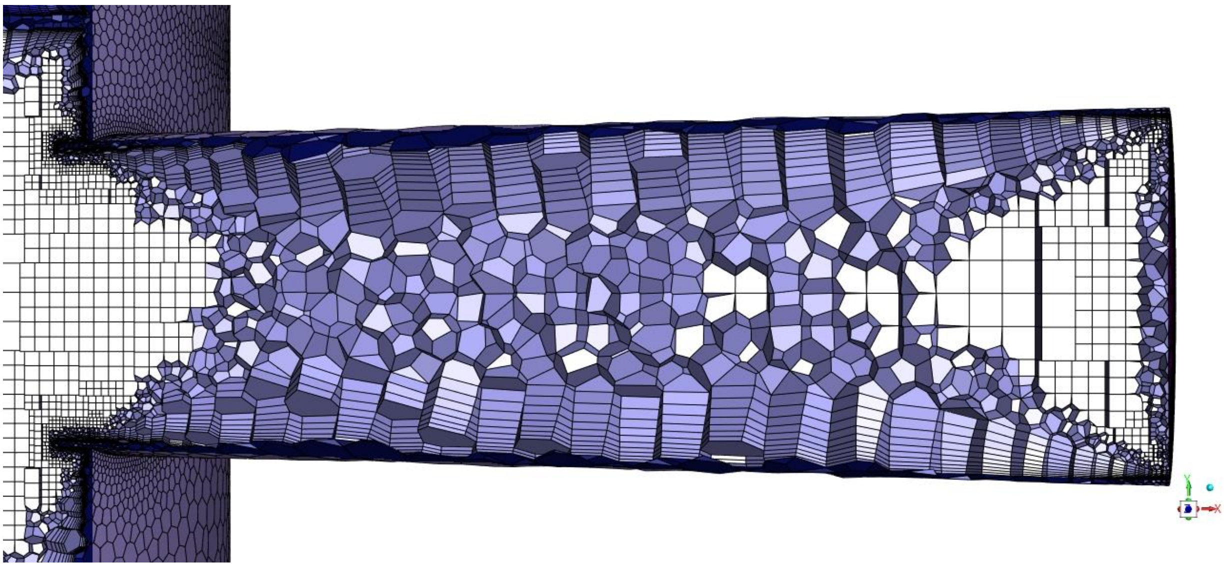

Figure A.6 – Outlet mesh

Appendix B

Table B.1 – Schedule of the thesis design

№	Activities	Participants	T_c, days	Duration of the activity															
				February				March				April				May			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Drawing up the technical assignment	Supervisor	2																
2	Literature review	Engineer	15																
3	Development of a work schedule	Supervisor	2																
4	Preparation of working methods	Engineer	15																
5	Evaluation of the chosen methods	Both	2																
6	Computer calculation	Engineer	10																
7	Analysis and processing of the obtained data	Engineer	5																
8	Evaluation of the results	Both	2																
9	Summing up the work	Engineer	2																
10	Drawing up a final report	Engineer	15																

	Supervisor
	Engineer
	Both

Appendix C

Table C.1 – Optimal and permissible norms of microclimatic parameters in the working area [29]

<table>
<tr><th rowspan="3">Period of the year</th><th rowspan="3">Category of works</th><th colspan="3">Temperature, °C</th><th colspan="2" rowspan="2">Relative humidity, %</th><th colspan="2" rowspan="2">Velocity, m\s</th></tr>
<tr><th rowspan="2">optimal</th><th colspan="2">permissible</th></tr>
<tr><th>upper bound</th><th>lower bound</th><th>optimal</th><th>permissible</th><th>optimal</th><th>permissible</th></tr>
<tr><td>Cold</td><td rowspan="2">Easy - 1b</td><td>21-23</td><td>24</td><td>20</td><td>40-60</td><td>75</td><td>0,1</td><td>no more 0,2</td></tr>
<tr><td>Warm</td><td>22-24</td><td>28</td><td>21</td><td>40-60</td><td>60
(at 27°C)</td><td>0,2</td><td>0,1- 0,3</td></tr>
</table>

Table C.2 – Dose limits [36]

<table>
<tr><th rowspan="2">Normalized values</th><th colspan="3">Dose limits</th></tr>
<tr><th>Staff
(Group A)</th><th>Staff
(Group B)</th><th>Population</th></tr>
<tr><td>Effective dose, mSv/year</td><td>20, but not more than 50 for 5 last years</td><td>5, but not more than 12.5 for 5 last years</td><td>1 mSv, but not more than 5 for 5 last. years</td></tr>
<tr><td>Equivalent dose, mSv/year
– lens of the eye
– skin
– hands and feet</td><td>
150 mSv
500 mSv
500 mSv</td><td>
37,5 mSv
125 mSv
125 mSv</td><td>
15 mSv
50 mSv
50 mSv</td></tr>
</table>