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)

Школа: Инженерная школа ядерных технологий
Направление подготовки: 14.04.02 Ядерные физика и технологии
Отделение школы (НОЦ) Отделение ядерно-топливного цикла

# МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

| Тема работы |
|---|
| **Оптимизация загрузки газоохлаждаемого реактора с унифицированным ториевым топливом** |

УДК 621.039.534.3:621.039.543

Студент

| Группа | ФИО | Подпись | Дата |
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| 0АМ7И | Селевич Сергей Викторович | | |

Руководитель ВКР

| Должность | ФИО | Ученая степень, звание | Подпись | Дата |
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| Доцент | Чертков Ю.Б. | к.ф-м.н | | |

## КОНСУЛЬТАНТЫ ПО РАЗДЕЛАМ:

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| Старший преподаватель | Веригин Д.А. | к.ф-м.н. | | |

## ДОПУСТИТЬ К ЗАЩИТЕ:

| Руководитель ООП | ФИО | Ученая степень, звание | Подпись | Дата |
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Томск – 2019 г.

TOMSK POLYTECHNIC UNIVERSITY — ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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«Национальный исследовательский Томский политехнический университет» (ТПУ)

School: School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Physics and Technology
Division: Nuclear-Fuel Cycle

## MASTER'S GRADUATION THESIS

| **Topic of research work** |
|---|
| **Optimization of gas-cooled reactor loading with unified thorium fuel** |

UDC 621.039.534.3:621.039.543

Student

| **Group** | **Full name** | **Signature** | **Date** |
|---|---|---|---|
| 0АМ7И | Selevich S.V. | | |

Scientific supervisor

| **Position** | **Full name** | **Academic degree, academic rank** | **Signature** | **Date** |
|---|---|---|---|---|
| Associate Professor | Chertkov Y.B. | PhD | | |

## ADVISERS:

Section "Financial Management, Resource Efficiency and Resource Saving"

| **Position** | **Full name** | **Academic degree, academic rank** | **Signature** | **Date** |
|---|---|---|---|---|
| Associate Professor | Menshikova E.V. | PhD | | |

Section "Social Responsibility"

| **Position** | **Full name** | **Academic degree, academic rank** | **Signature** | **Date** |
|---|---|---|---|---|
| Senior lecturer | Verigin D.A. | PhD | | |

## ADMITTED TO DEFENSE:

| **Director of the programme** | **Full name** | **Academic degree, academic rank** | **Signature** | **Date** |
|---|---|---|---|---|
| Nuclear Power Installation Operation | Verkhoturova V.V. | PhD | | |

Tomsk – 2019

*Expected learning outcomes*

| Learning outcome (LO) code | Learning outcome<br>(a graduate should be ready) | Requirements of the FSES HE, criteria and / or interested parties |
|---|---|---|
| *Professional competencies* | | |
| LO1 | To apply deep mathematical, scientific, socio-economic and professional knowledge for conducting theoretical and experimental research in the field of the use of nuclear science and technology/ | FSES HE Requirements (PC-1,2, 3, 6, UC-1,3), Criterion 5 RAEE (p 1.1) |
| LO2 | To demonstrate ability to define, formulate, and solve interdisciplinary engineering tasks in the nuclear field using professional knowledge and modern research methods. | FSES HE Requirements (PC-2,6,9,10,14, UC-2,3,4, BPC1,2), Criterion 5 RAEE (p 1.2) |
| LO3 | To plan and conduct analytical, simulation and experimental studies in complex and uncertain conditions using modern technologies, and to evaluate critically research results. | FSES HE Requirements (PC-4,5,6,9,22, UC-1,2,5,6), Criterion 5 RAEE (p 1.3) |
| LO4 | To use basic and special approaches, skills and methods for identification, analysis, and solution of technical problems in the field of nuclear science and technology. | FSES HE Requirements (PC-7,10,11,12,13, UC-1-3,BPC1,3), Criterion 5 RAEE (p 1.4) |
| LO5 | To operate modern physical equipment and instruments, to master technological processes in the course of preparation for the production of new materials, instruments, installations, and systems. | FSES HE Requirements (PC-8,11,14,15, BPC-1), Criterion 5 RAEE (p 1.3) |
| LO6 | To demonstrate ability to develop multi-option schemes for achieving production goals with the effective use of available technical means and resources. | FSES HE Requirements (PC-12,13,14,16, BPC-2), Criterion 5 RAEE (p 1.3) |
| *Cultural competencies* | | |
| LO7 | To demonstrate ability to use a creative approach to develop new ideas and methods for designing nuclear facilities, as well as to modernize and improve the applied technologies of nuclear production. | FSES HE Requirements (PC-2,6,9,10,14, UC-1,2,3), Criterion 5 RAEE (p 1.2,2.4,2.5) |
| *Basic professional competencies* | | |
| LO8 | To demonstrate skills of independent learning and readiness for continuous self-development within the whole period of professional activity. | FSES HE Requirements (PC-16,17,21, UC-5,6, BPC-1), Criterion 5 RAEE (p 2.6) coordinated with the requirements of the international standard EURACE & FEANI |
| LO9 | To use a foreign language at a level that enables a graduate to function successfully in the international environment, to develop documentation, and to introduce the results of their professional activity. | FSES HE Requirements (BPC-3, UC-2,4), Criterion 5 RAEE (p 2.2) |

| | | |
|---|---|---|
| LO10 | To demonstrate independent thinking, to function efficiently in command-oriented tasks and to have a high level of productivity in the professional (sectoral), ethical and social environments, to lead professional teams, to set tasks, to assign responsibilities and bear liability for the results of work. | FSES HE Requirements (PC-18,20,21,22,23, UC-1,4, BPC-2), Criterion 5 RAEE (p 1.6,2.3) coordinated with the requirements of the international standard EUR-ACE & FEANI |

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«Национальный исследовательский Томский политехнический университет» (ТПУ)

School: School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Physics and Technology
Division: Nuclear-Fuel Cycle

APPROVED BY:
Director of the programme
_____________ Verkhoturova V.V.
«____» ____________ 2019

**ASSIGNMENT**
**for the Graduation Thesis completion**

In the form:

| |
|---|
| Master's thesis |

For a student:

| Group | Full name |
|---|---|
| 0АМ7И | Selevich Sergei Viktorovich |

Topic of research work:

| | |
|---|---|
| Optimization of gas-cooled reactor loading with unified thorium fuel | |
| Approved by the order of the Director of School of Nuclear Science & Engineering (date, number): | №1711/c at 5.03.2019 |

| | |
|---|---|
| Deadline for completion of Master's Graduation Thesis: | 3.06.2019 |

**TERMS OF REFERENCE:**

| | |
|---|---|
| **Initial data 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.)* | Literary and design sources containing information about high-temperature gas-cooled nuclear reactor with unified thorium fuel and program WIMS-5B. |

| **List of the issues to be investigated, designed and developed**<br>*(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).* | - Review of the design and layout of the reactor;<br>- Review of the program WIMS-5B;<br>- Create a design model of a fuel assembly for gas-cooled reactor with unified thorium fuel;<br>- Research the effect of increasing the fuel load in the reactor in order to increase the duration of the campaign and the burnup depth. |
|---|---|
| **List of graphic material**<br>*(with an exact indication of mandatory drawings)* | N/A |

**Advisors to the sections of the Master's Graduation Thesis**
*(with indication of sections)*

| Section | Advisor |
|---|---|
| Literature review, methodology and results | Chertkov Y.B. |
| Financial Management, Resource Efficiency and Resource Saving | Menshikova E.V. |
| Social Responsibility | Verigin D.A. |

| **Date of issuance of the assignment for Master's Graduation Thesis completion according to the schedule** | |
|---|---|

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

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

**Assignment accepted for execution by a student:**

| Group | Full name | Signature | Date |
|---|---|---|---|
| 0АМ7И | Selevich Sergei Viktorovich | | |

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

To the student:

| Group | Full name |
|---|---|
| 0AM7И | Selevich Sergei Viktorovich |

| | | | |
|---|---|---|---|
| **School** | Nuclear Science & Engineering | **Division** | Nuclear-Fuel Cycle |
| **Degree** | Master | **Educational Program** | 14.04.02 Nuclear Physics and Technology |

| **Input data to the section «Financial management, resource efficiency and resource saving»:** | |
|---|---|
| 1. *Resource cost of scientific and technical research (STR): material and technical, energetic, financial and human* | – Salary costs – 154916.11 rub;<br>– STR budget – 193641.77 rub. |
| 2. *Expenditure rates and expenditure standards for resources* | – Electricity costs – 5.8 rub per 1 kW |
| 3. *Current tax system, tax rates, charges rates, discounting rates and interest rates* | – Labor tax – 27.1 %;<br>– Overhead costs – 30%. |
| **The list of subjects to study, design and develop:** | |
| 1. *Assessment of commercial and innovative potential of STR* | – Comparative analysis with other researches in this field. |
| 2. *Development of charter for scientific-research project* | – SWOT-analysis. |
| 3. *Scheduling of STR management process: structure and timeline, budget, risk management* | – Calculation of working hours for project;<br>– Creation of the time schedule of the project;<br>– Calculation of scientific and technical research budget. |
| 4. *Resource efficiency* | – Integral indicator of resource efficiency for the developed project. |
| **A list of graphic material** *(with list of mandatory blueprints):* | |
| 1. *Competitiveness analysis*<br>2. *SWOT- analysis*<br>3. *Gantt chart and budget of scientific research*<br>4. *Assessment of resource, financial and economic efficiency of STR*<br>5. *Potential risks* | |

| **Date of issue of the task for the section according to the schedule** | 05.03.2019 |
|---|---|

**Task issued by adviser:**

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

**The task was accepted by the student:**

| Group | Full name | Signature | Date |
|---|---|---|---|
| 0AM7И | Selevich Sergei Viktorovich | | |

## TASK FOR SECTION
## "SOCIAL RESPONSIBILITY"

To the student:

| Group | Full name |
|---|---|
| 0AM7И | Selevich Sergei Viktorovich |

| | | | |
|---|---|---|---|
| **School** | Nuclear Science & Engineering | **Department** | Nuclear-Fuel Cycle |
| **Degree** | Master | **Specialization** | 14.04.02 Nuclear Physics and Technology |

| **Input data to the "social responsibility":** | |
|---|---|
| *1. Describe workplace (work area) for occurrence of:* | – Harmful factors of the environment: microclimate, illumination, noise, vibration, electromagnetic fields, ionizing radiation;<br>– dangerous factors of environment: electrical, fire and explosive nature. |
| *2. Acquaintance and selection of legislative and normative documents on the topic* | – electrical safety;<br>– fire and explosion safety;<br>– labor protection requirements when working on a PC. |
| **The list of subjects to study, design and develop:** | |
| *1. Analysis of the identified harmful factors of the environment in the following sequence:* | – The effect of the factor on the human body;<br>– Reduction of permissible standards with the required dimensionality (with reference to the relevant normative and technical document);<br>– Proposed remedies (collective and individual). |
| *2. Analysis of identified hazards of the environment:* | – Electrical safety (including static electricity, protective equipment);<br>– fire and explosion safety (causes, preventive measures, primary fire extinguishing agents). |

| **Date of issue of the task for the section according to the schedule** | |
|---|---|

**Task issued by consultant:**

| Position | Full name | Scientific degree, rank | Signature | date |
|---|---|---|---|---|
| Senior lecturer | Verigin D.A. | PhD | | |

**The task was accepted by the student:**

| Group | Full name | Signature | date |
|---|---|---|---|
| 0AM7И | Selevich Sergei Viktorovich | | |

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«Национальный исследовательский Томский политехнический университет» (ТПУ)

School: School of Nuclear Science & Engineering
Field of training (specialty) 14.04.02 Nuclear Physics and Technology
Level of education: Master's Degree
Division: Nuclear-Fuel Cycle
Period of completion: spring semester 2019

Form of presenting the work:

| |
|---|
| Optimization of gas-cooled reactor loading with unified thorium fuel |

**SCHEDULED ASSESSMENT CALENDAR**
**for the Master's Graduation Thesis completion**

| | |
|---|---|
| Deadline for completion of Master's Graduation Thesis: | 3.06.2019 |

| **Assessment date** | **Title of section (module) / type of work (research)** | **Maximum score for the section (module)** |
|---|---|---|
| 11.02.19 | Literature review of the reactor and the program WIMS-5B | |
| 11.03.19 | Create a design models of a fuel assemblies for gas-cooled reactor with unified thorium fuel | |
| 29.03.19 | Execution of calculations and evaluation of results | |
| 10.05.19 | Financial Management and Social Responsibility | |
| 21.05.19 | Writing the Master's thesis | |

**COMPILED BY:**
**Scientific supervisor:**

| **Position** | **Full name** | **Academic degree, academic status** | **Signature** | **Date** |
|---|---|---|---|---|
| Associate Professor | Chertkov Y.B. | PhD | | |

**AGREED BY:**

| **Director of the programme** | **Full name** | **Academic degree, academic status** | **Signature** | **Date** |
|---|---|---|---|---|
| Nuclear Power Installation Operation | Verkhoturova V.V. | PhD | | |

**Abstract**

Final qualifying work contains 94 pages, 23 figures, 34 tables, 30 sources.

Keywords: high-temperature reactor, thorium-plutonium nuclear fuel, duration of the campaign, burnup depth.

The object of the research is a high-temperature gas-cooled reactor with unified thorium fuel.

The purpose of this research is to study the possibility of increasing the duration of the campaign and the burnup depth with an increase in the load of fuel in the gas-cooled thorium reactor.

It was in studies revealing that, a design model of a fuel assembly of a gas-cooled thorium reactor was created in the WIMS-5B program. In numerical experiments, calculations were made of the duration of the campaign, the burnup depth of the fuel and changes in its isotopic composition when fuel channels are added to the basic design of fuel assemblies and an increased fuel load.

As a result of research, an increase in the duration of the campaign, changes in the isotopic composition and the burnout of the fuel in a gas-cooled thorium reactor was calculated.

The main design and technological characteristics: the thermal power of the reactor installation is 60 MW, the reactor core is made up of six-sided graphite blocks of a unified design. Fuel is a BISO type microfuel dispersed in a graphite matrix with a core (Th,Pu)N, the percentage of Pu is 50%.

Applications: regional nuclear power, electricity and heat in remote areas, hydrogen production, design engineering department.

Contents

## Introduction

Currently, a large number of developments in the field of low-power nuclear power plants around the world are underway, since low-power installations may become the basis for regional power engineering of countries in the near endless future. This is especially promising for sparsely populated remote regions, for which extremely important properties of the installation are its transportability, short installation time and the ability to operate for a long time without overloading.

Modern scientific research on the implementation of the latest technological platform conducted in Russia is based on the physical principles of fast-neutron reactors and the goal of expanded reproduction of fuel in a closed fuel cycle. The most promising direction in this field of promotion of nuclear energy is high-temperature gas-cooled nuclear reactors with low-power thorium-plutonium fuel.

Such conclusions were made thanks to the numerical experiments of the Forschungszentrum Julich Scientific Center (Germany, Julich) of the Institute for Safety and Reactor Technologies (ISR-2). It was recorded that the ratio of moderator volume to fuel volume for thorium-plutonium fuel composition, at which the resonance absorption of neutrons is minimal, significantly exceeds this ratio for uranium fuel composition with equal concentrations of fissile nuclides, which made it possible to establish the core geometry and the composition of thorium-plutonium fuel for the possibility of organizing a long campaign.

It is noteworthy that the installation is capable of operating at low capacities, quite a bit of fuel will be required for the core of the thorium reactor, and the percentage of its burning out will be higher than in existing reactors today. After reprocessing, the remaining weapons-grade plutonium will no longer present a nuclear hazard. At the output a mixture of graphite, plutonium and decomposition products is formed, which will be very difficult to use for any other purposes. These remnants can only be buried.

Also one of the main advantages of such reactors is their multifunctionality. Thus, nuclear facilities can be used not only for generating energy, but also for desalination of water or the production of hydrogen from helium on an industrial scale, since most HTGR projects use helium as a coolant. In the reactor core, helium will be heated to a temperature of 1250 °C, and then fed to a hydrogen production unit. In the future, the scale of hydrogen production at such a nuclear power plant will be much higher than at the existing chemical plants.

In this master’s thesis, a high-temperature gas-cooled thorium reactor with a capacity of 60 MW is considered. Such small modular reactors have the greatest chances to form the basis of Russia's regional energy industry.

The purpose of this master’s thesis is to study the possibility of increasing the duration of the campaign and the burnup depth with an increase fuel loading in the gas-cooled thorium reactor.

To achieve this purpose, it’s necessary to perform the following tasks:

- review of the design and layout of the reactor;
- review of the program WIMS-5B;
- create a design model of a fuel assembly for gas-cooled reactor with unified thorium fuel;
- research the effect of increasing the fuel loading in the reactor in order to increase the duration of the campaign and the burnup depth.

# 1 Literature review

## 1.1 The HTGR industrial history

The industrial history of high-temperature gas-cooled reactors dates back to 1944 in America. Responsible for the HTGR project was General Atomic, a joint venture created by Gulf Oil and Royal Dutch Shell. Its first prototype was the Peach Bottom 40 MW reactor, built in 1967.

From 1979 to 1988, the nuclear power plant Fort St. Vrain, built in Colorado, 56 km north of Denver, is the first high-capacity full-scale power reactor to operate. At NPP Fort St. Vrain has one reactor with a thermal capacity of 822 MW and an electrical capacity of 330 MW. The reactor reached criticality in February 1974 and began operating at a nominal power level in 1979. The main features of this system include the thorium-uranium fuel cycle with particulate fuel with coatings, the use of graphite as fuel cladding shells and moderator, helium coolant with a temperature at the outlet of the core of 770 °C, one-way modular steam generators with an integral arrangement of steam superheaters and a pre-stressed concrete casing.

The reactor core has a cylindrical shape with a height of 4.75 meters and a diameter of 6 meters. It is surrounded by a graphite reflector with a thickness of 1 meter at the upper end and 1.2 meters at the lower end and on the side surfaces. The reactor core is composed of 247 vertical fuel assemblies, each of which contains six elements mounted one above the other along the vertical axis. These elements with a length of 0.79 meters have a prismatic shape with a hexagonal cross-section of 0.36 meters wide faces. To organize the fuel overload, the core is divided into separate zones, each of which, except for several zones on the border, contains seven fuel assemblies. These seven assemblies of each zone are mounted on a single hexagonal block. The blocks themselves rest on the supporting concrete floor of the core protected by a steel shell cooled by water. The entire graphite structure is surrounded by a steel cylinder, which serves as a lateral support for the fuel rods and the reflector[10].

Fuel elements are installed in 210 vertical channels passing through each hexagonal graphite block. This unit also contains 108 vertical channels for the passage of coolant.

Fuel and raw materials in the form of coated particles are distributed in a graphite matrix. The core of a fuel particle contains a mixture of uranium and thorium dicarbides, and the core of a raw material particle contains only thorium dicarbide.

Each type of particle has a four-layer coating. The inner layer of the coating is made of porous pyrocarbon, which absorbs fission fragments, and gaseous fission products accumulate in its pores. The next coating layer is high-density pyrolytic carbon, and the third layer is silicon carbide, which is impermeable to volatile solid fission products, such as strontium and cesium. The fourth layer of pyrolytic carbon is designed to increase the strength of the composite coating and protect silicon carbide from the chemical effect of the coolant. The diameter of the particles of the raw material is 2 times the diameter of the fuel particles. Burnable absorbers in the form of boron carbide are also introduced into the cavities in the fuel or into special channels. These absorbers compensate for changes in reactivity due to fuel burnout and accumulation of fission products.

The fuel is reloaded when the reactor is stopped. At the same time, 1/6 of the fuel loading is replaced. Fort St. Vrain reactor began operating in open fuel cycle mode without uranium-233 processing. Spent fuel is stored for future use. Tests conducted at the Peach Bottom reactor and at other reactors provide confidence in the stability of dispersed fuel of coated particles at a burnout depth of this order.

Due to the water-induced corrosion problems and electrical problems, plant shutdowns were common. As a result, Public Service Company of Colorado began to question the economics of continued commercial operation. An increase in performance was observed from 1987 – 1989, suggesting some of the problems had been worked out of the system, but Public Service was not persuaded. In 1989 Public Service indicated that the plant was under consideration for closure. Later that same year a critical part of the reactor was found to have long-term corrosion and required replacement. The replacement cost was deemed excessive and the plant was shut down. The decommissioning and removal of the fuel was completed by 1992.

The ultimate goal of the Americans was to create a nuclear power plant with a 1200 MW high-temperature reactor. The possibility of generating high-grade thermal energy and low radioactive emissions have initiated activities to develop high-power HTGR projects. These are the projects “Fulton” and “Summit” with a capacity of 860 MW and 1160 MW, respectively, intended for the joint production of electricity and potential thermal energy. These reactors were planned to be used in refineries and other industries. Energy companies ordered 8 NPPs of this type for construction in the US domestic market, however, due to the 1974 oil crisis, a number of reasons arose (rising construction costs of NPPs, energy-saving policies of some of the leading countries of the world, etc.) that led to a reduction in orders for NPP including mastered types. This also led to termination of contracts in the United States for the construction of nuclear power plants with HTGR.

The THTR-300 Thorium High Temperature Thorium Reactor (“Thorium Hochtemperaturreaktor”) project was designed and built by Brown Boveri / Krupp in Germany with the support of the central German government and North Rhine-Westphalia. The construction of the demonstration unit began in 1971 after the 15-megawatt AVR (Jülich) research reactor was tested on the principle of operation of a high-temperature granular fuel reactor.

The AVR fuel is a mixture of uranium-235 and coated thorium particles distributed in a spherical graphite matrix of 6 cm in diameter. These spherical fuel rods slowly circulate through the reactor core. The advantages of such a system include the absence of the requirements of tight tolerances inherent in conventional construction, and the absence of problems of thermal expansion and changes in the dimensions of the structural elements of the core under radiation effect.

A typical ball fuel rod is a homogeneous mixture of fuel with a moderator, which provides moderate temperature gradients and low thermal stresses in the fuel cell. Continuous circulation of the fuel rods ensures uniform burnout of the fuel and allows working with a relatively low excess reactivity. One of the drawbacks of a spherical fuel rod reactor is the difficulty of ensuring reliable movement of the control rods through the ball filling of the fuel rods in the core. Solving this problem requires the use of complex and expensive drive mechanisms.

Synchronization of the THTR-300 with the power system occurred only in November 1985. In the core of this reactor, 675000 spherical fuel elements with a diameter of 6 cm are poured. The 33000 fuel particles 400 meters in diameter are dispersed inside each spherical graphite fuel rod covered with a shell of 0.5 cm thickness. The core has a cylindrical shape with a diameter of 5.6 meters and a height of 6 meters. Ball pellets slowly circulate through the core from top to bottom under the influence of gravity, leaving through the outlet channel in the bottom of the core. Then they pass through the sorting system, in which damaged fuel rods are displayed and fuel burnup is measured. Only fuel rods selected for recirculation are returned to the core, which are loaded from the top in the reactor vessel via pneumatic actuators[13].

Four years later, a decision was made on the final shutdown of the reactor. The reasons for the refusal of Germany from the THTR-300 are complex (in many respects, for political reasons). By the year 2000, in Germany, all work related to thorium nuclear fuel was curtailed.

After the USA and Germany, development began in South Africa. In 1998, a project was launched which was named PBMR (Pebble-Bed Modular Reactor). South Africans have redeemed the licenses for the main technologies used in the German HTGR from German colleagues.

Designers from South Africa did not contribute anything fundamentally new to the technologies received from Germany. Unlike the German projects, the PBMR reactor has a single circuit, and helium from the core goes directly to the turbine. The helium temperature at the entrance to the PBMR core is 500 °C, and its inlet pressure is 9 MPa. The gas passes the zone from the top down and leaves it, heated to 900 °C. Then helium goes to the turbine, leaves it at a temperature of 500 °C and a pressure of 2.6 MPa, is cooled, compressed, re-heated and fed to the input of the core. The high temperature and pressure of the coolant provide in PBMR increased efficiency, reaching 41%.

The reactor vessel is a vertical steel vessel with a height of 27 meters and a diameter of 6 meters. PBMR fuel cells are $UO_2$ balls coated with silicon carbide and pyrographite. Micro fuel with a diameter of 0.92 mm each are immersed in a graphite matrix (fuel sphere with a diameter of 60 mm). A total of 450000 fuel spheres are in the core during operation. The fuel is reloaded right during the reactor operation. Fresh fuel spheres are poured on top of the core, and burned fuel is removed from the bottom of the core.

Further, Asia decided to develop high-temperature technology. In Japan, after long hesitations, an HTTR research reactor with an electrical power of 30 MW of a prismatic type was built. It was launched in 1998. The pressure is about 4 MPa, the inlet temperature of 395 °C, and the outlet temperature of 850–950 °C. The fuel is uranium oxide (enriched to an average of about 6%).

Following Japan, China has shown increased interest. But, unlike Japan, China followed the path of South Africa. Chinese innovation in the field of HTGR is nothing more than a slightly modified 1968 clone of German technologies. The practical experience of the high-temperature program in China began with the HTR-10 research reactor, built in Beijing and first criticized in 2000. And in 2012, construction began on the Shidao Bay-1 station with HTR-PM high-temperature reactors based on the prototypes of their predecessors. The reactor plant has a thermal capacity of 250 MW, and two reactors are connected to one steam turbine to generate 210 MW of electricity.

In the 1970–1990s, a number of HTGR various purpose and power level projects were developed in Union of Soviet Socialist Republics. Active research began with the development of projects for the experimental reactor ABTU-15 and the pilot plant ABTU-c-50 with the reactor VGR-50. With the scientific leadership of the Kurchatov Institute of Atomic Energy in the Experimental Mechanical Engineering Design Bureau developed projects of pilot industrial installations VG-400 for combined generation of process heat and electricity in the steam turbine cycle, reactor installation VG-400GT with a direct gas turbine energy conversion cycle, nuclear power plant VGM-P for energy supply of a typical refinery plant. Ampoule testing of the fuel under the scientific guidance of the Kurchatov Institute of Atomic Energy was also carried out at the Scientific Research Institute of Atomic Reactors at SM-3, RBT-6, as well as at the IVV-2 and VVR-C reactors from the L.Ya. Karpov Physico-Chemical Institute.

One of the new-generation reactors that meet the requirements of a developing large-scale nuclear power industry is a high-temperature gas turbine modular helium reactor (GT-MHR), the design of which is currently being developed in the framework of international cooperation by cooperation of Russian developers together with General Atomics (USA), Framatome (France) and Fuji Electric (Japan)[15].

### 1.2 Physical and technical fundamentals of HTGR core composition

High-temperature gas-cooled reactors of two types have received the main development: with ball and prismatic fuel rods, which are based on the use of micro-fuel.

The whole set of properties should be taken into account when choosing a coolant: thermophysical (density, heat capacity, viscosity, thermal conductivity, etc.), nuclear physical (influence on reactor criticality, radiation resistance, activation, etc.), chemical (compatibility with construction materials), technological (methods of production, toxicity, heat resistance, fluidity, explosion and fire hazard, etc.). Since the purpose of the HTGR is to obtain high-temperature thermal energy and the temperature of the coolant can reach 1000 °C, the choice among possible coolants is limited to helium, since helium is practically the only one that satisfies most of the requirements. The use of other gases as a coolant of this type of reactor was rejected for several reasons.

The use of hydrogen is very problematic, despite its good thermo physical properties. This can be explained by its explosiveness when mixed with air and high chemical activity with respect to structural materials of the reactor cores at temperatures from 800 °C and above.

The use of nitrogen is difficult because of its low thermophysical properties, high chemical activity in the high temperature region and the effect on reactivity.

The use of carbon dioxide in magnox gas-cooled reactor (MGCR) and advanced gas-cooled reactor (AGR) showed its fairly good thermophysical properties, but, nevertheless, carbon dioxide cannot be considered as HTGR coolant, because at high temperature $CO_2$ dissociates, and dissociation products intensively interact with the main structural material of the HTGR core – graphite, which leads to the mass transfer of carbon from the core to the cold places of the contour[4].

Helium, in addition to its chemical inertness, due to which nuclear fuel and structural materials of the core can operate at high temperatures, also has good nuclear physical properties: it practically does not absorb and does not scatter neutrons, is not activated under irradiation. Although it is inferior to some coolants in specific heat capacity and power consumption for pumping, however, having good thermal conductivity, even at moderate pressure (40-50 kgf/cm$^2$) provides excellent conditions for the removal and transfer of thermal energy in the primary circuit. This allows obtaining a higher energy density of the core and requires a much smaller surface of the heat exchange equipment.

Special experimental methods have shown that helium does not diffuse through steel at a temperature of 800 °C and pressure up to 6.0 MPa (1X18H10T, 12X1MF, EI437B, etc.). Its penetration through pipes in separate experiments is a consequence of submicroscopic metal defects. With high quality welding, appropriate control over the manufacture of equipment, and its installation, the problem of keeping helium in the circuit at high pressures and temperatures is successfully solved.

A characteristic feature of HTGR along with the use of helium is the use of graphite as a moderator, a reflector and the main structural material of the reactor core. The absence of metal structures in the reactor core, as well as the use of micro-fuel included in ball graphite or prismatic graphite fuel assemblies make it possible to achieve significantly higher temperatures than at nuclear power plants with other types of reactors.

Thus, the use of helium coolant and graphite gives the most favorable combination of materials and provides the main fundamental advantages of HTGR reactors – good neutron-physical characteristics and the possibility of obtaining a high coolant temperature. The use of uranium-graphite fuel elements and a helium coolant in the core leads to good neutron saving. Also in the HTGR various fuel cycles can be applied: uranium or thorium-plutonium cycles. At the same time, since uranium-233 has the highest neutron yield, the thorium cycle is especially beneficial, in which the breeding factor can reach unity.

### 1.3 The main design solutions of HTGR core composition

The design of the HTGR core is determined by the type of fuel elements used.

The reactor core, recruited from prismatic graphite fuel assemblies, is a homogeneous structure with uniformly alternating fuel elements and channels for helium. Prismatic hexagonal blocks are located in several rows along the height of the reactor core. Reactor radial and end reflectors are made of similar prismatic core blocks, but without fissile material[29].

A graphite prismatic block, the dimensions of which have different values, has many through holes drilled along the longitudinal axis of the block. Some of the holes are occupied by fuel cores (compacts), and helium is blown through the remaining channels. Basically, large holes serve to pass the gaseous coolant, and fuel pellets are installed in small holes.

The three-dimensional model of a prismatic graphite fuel assembly is presented in figure 1.

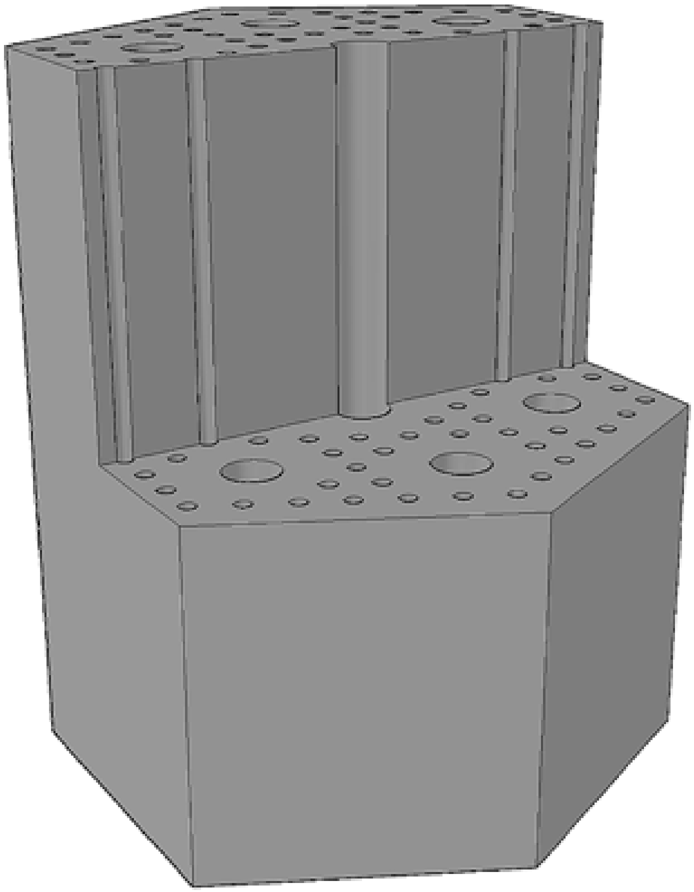

Figure 1 – Prismatic graphite fuel assembly

Fuel cylindrical pellets are sintered from a mixture of graphite powder and micro-fuel, similarly to the cores of spherical fuel elements. Micro-fuel is a spherical fuel core coated with successive layers of pyrolytic carbon (PyC) and silicon carbide (SiC) dispersed in a graphite matrix of cylindrical fuel pellets placed in the reactor core[3].

A cylindrical fuel pellet of high-temperature gas-cooled reactor is shown in figure 2.

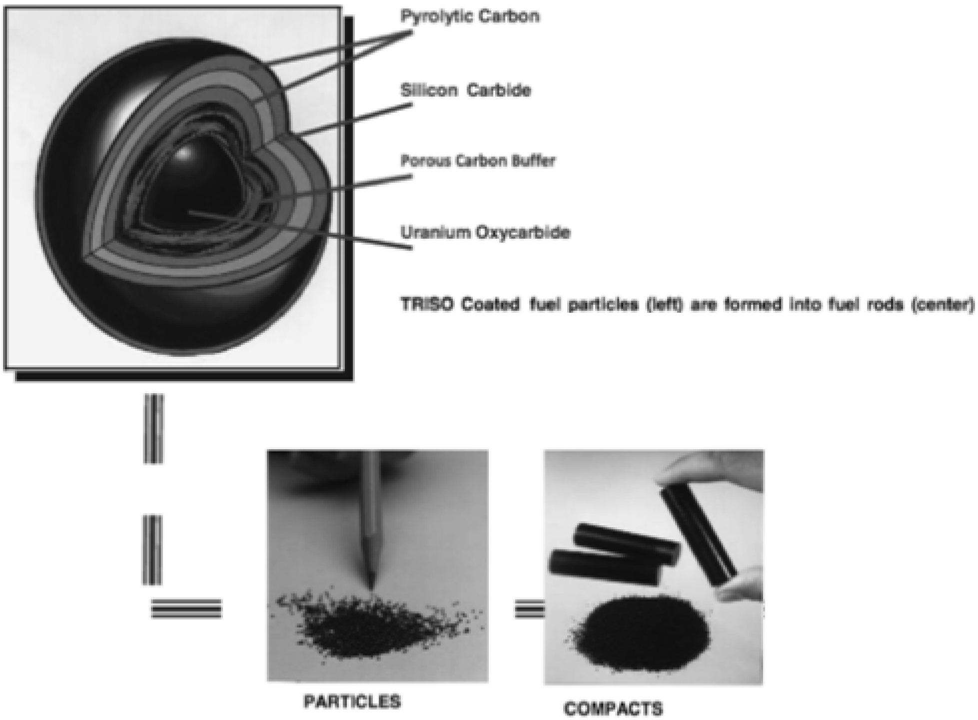


Figure 2 – A cylindrical fuel pellet of high-temperature gas-cooled reactor

As the fissile material burns out, the formed fission products in the fuel core diffuse at high temperatures, but as a result of using the matrix coating system, they remain within the limits of the microfuel and the fuel core. Moreover, the PyC layer localizes gaseous fission products and is the first diffusion barrier protecting the second SiC layer from the corrosive effects of solid fission products on it. In this case, the SiC layer, due to its excellent physicomechanical and thermal characteristics, is the main force coating and diffusion barrier, first of all, to solid fission products. An additional safety barrier is formed by a graphite matrix and an airtight shell on the surface of the fuel core in the form of a SiC coating[8].

The disadvantage of microfuel with a silicon carbide coating includes low corrosion resistance of SiC layer when it contacts with metals (impurities in nuclear core, structural elements of fuel assemblies), the interaction with which proceeds at a noticeable rate at high temperatures, which leads to the formation of low-melting eutectic and destructive coating[12].

Another concept of HTGR, which also became widespread, is the use of spherical fuel elements (an example of such a reactor is AVR). In this case, the reactor core is a free pebble of fuel elements into a hollow cylinder made of graphite blocks that serve as a reflector. A high-level of pebble is free. Helium is fed into the space between this level and the upper (graphite) reflector. In high-power reactors, passing through the core from top to bottom, through collectors in the lower graphite reflector, helium heated to ~ 1000 °C is sent to high-temperature heat exchangers and steam generators, and then cooled to 300–350 °C with blowers returned to the reactor core. The helium flows are organized in such a way that all the surfaces of the reinforced concrete hull and other elements under pressure are washed by helium, which has an entrance temperature to the core.

A distinctive feature of the reactor cores of this type is that the transfer of spherical fuel elements can be carried out continuously during the operation of the reactor. For this purpose, a system of mechanisms and sluice chambers are provided at the reactor, which provide loading and unloading of fuel elements without depressurizing the primary circuit and without reducing power.

The fuel part of the spherical fuel element is made in the form of a ball prepared from a mixture of graphite powder and micro-fuel elements. The ball is encased in graphite. There are two options for ball fuel. In one of them (composite fuel element), the spherical shell of the fuel element is machined from a graphite billet, and the fuel is placed in the internal cavity, which is then sealed with graphite cork and pyrocarbon. In the second variant (monolithic fuel element), a spherical fuel element shell is formed together with a core of graphite powder with a bundle, followed by roasting to remove the bundle and improve thermal conductivity and strength properties of graphite. This option is more technological and therefore more common. The external diameter of the spherical fuel element in existing and developed projects is assumed to be 60 mm[4].

The design of spherical fuel elements in two versions is shown in figure 3.

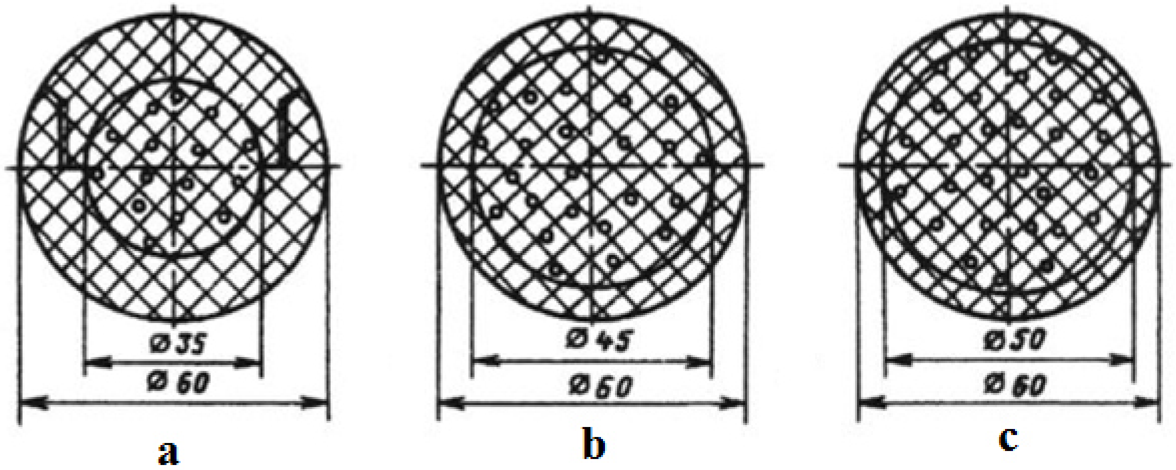


Figure 3 – Spherical fuel element design:
a – composite fuel element of VGR-50; b – monolithic fuel element of VGR-50;
c – monolithic fuel element of VG-400

### 1.4 Dispersed nuclear fuel

The type of fuel in which the microparticles of fissile material are distributed over the volume of non-fissile material (matrix) is called dispersed nuclear fuel. Fissile material is introduced in the form of small particles of metal alloys, intermetallic compounds or compounds of uranium and plutonium. Metals, alloys, intermetallics, as well as non-metals, such as graphite, can be used as matrix elements. The advantage of dispersive fuel is high radiation damage stability due to the ability to hold fission products in the fuel, small areas of neutron induced damage that do not overlap each other. Zones of neutron induced damage to the matrix should not overlap with each other, so that the fission products are fragmented. This prevents the formation of gaseous nuclear fission products and gaseous fission product yield from the fuel.

The fissile material is part of a non-fissioning matrix in the form of some particles, usually spherical, with sizes ranging from 10 to 1000 microns. On a microscopic scale, a spherical particle is an independent fuel element. The fissile phase is the place where the fission reaction occurs. The strongest radiation (and temperature) is recorded there, therefore this phase is selected in such a way that the melting point is as high as possible and the strength to thermal and mechanical loads as high as possible. At the same time, low porosity and high concentration of fissile material are required (therefore, enriched fuel is used).

Dispersed nuclear fuel element has the strength of ceramic fuel, thermal conductivity and plasticity of the matrix material, unique nuclear-physical and anti-corrosion properties. The division and the attendant damage in the fissile material are concentrated almost entirely in the fuel particle surrounded by the matrix. However, part of the matrix in contact with nuclear fuel is subject to fission products.

Dispersed nuclear fuel elements with good thermal conductivity of the matrix, which ensures reliable thermal contact between the nuclear fuel and the shell, significantly reduce the temperature in the center of the fuel pellet. Reducing the temperature gradient allows you to successfully operate fuel elements in maneuverable modes, to make them safer in emergency situations, and in case of a depressurization of a fuel element to reduce the degree of contamination of the coolant, since it will contact with nuclear fuel only at the defect site.

Disadvantages of a dispersed nuclear fuel include the high manufacturing cost due to the need to use highly enriched uranium (up to 96% $^{235}U$) due to the presence of non-fissioning nuclei in the fuel that uselessly absorb neutrons, as well as more sophisticated manufacturing and regeneration technology. The dimensional stability of a dispersed nuclear fuel, significant for achieving great burnup depth, is determined by many factors, in particular, the structure, nature, properties, compatibility, and radiation resistance of fuel particles and materials used as a matrix, the design of fuel elements and their operating conditions.

### 1.5 Nuclear physical features of thorium fuel

In the case of using thorium-232 as a raw nuclide, its much lower resonance absorption provides two important advantages. The first is a strong internal block effect in the distribution of the flux density of epithermal neutrons over the volume of the fuel core, leading to the absorption of slowing neutrons in relatively thin peripheral layers, in the thorium system is much lower. As a result, the integral number of divisions in a nuclear fuel cell with its unchanged size increases. This provides a significant increase in fuel efficiency, including by increasing the duration of the campaign. The second is a much larger amount of moderator in the thorium system. This provides a significant increase in thermal inertia, with all the resulting advantages in terms of safety and reliability.

The value of the average neutron yield per absorption $\nu_{ef}$ for uranium-233 exceeds the value for uranium-235 in the whole range of neutron energies of interest; for plutonium-239, at energies up to 30 keV, and for plutonium-241, at energies below 1 eV.

The indicated habit of $\nu_{ef}(E_n)$ determines the ratio of the values of nuclear fuel breeding factors for nuclear installations of various types in the thorium and uranium fuel cycles. It is known that the maximum possible value of the breeding factor, excluding neutron multiplication in a raw material ($^{232}$Th or $^{238}$U), excluding unproductive neutron losses and leakage, is determined by $BF_{max} = \bar{\nu}_{ef} - 1$.

The value $\bar{\nu}_{ef}$ in a nuclear reactor depends on the specific type of neutron energy spectrum. In a thermal reactor, the average value $\bar{\nu}_{ef}$ is primarily determined by its value in the energy range from 0.01 to 1.00 eV. In order to illustrate the changes in the values for different fissile elements in the spectrum of a thermal power reactor, Table 1 shows the values for the spectrum of a high-temperature gas-cooled reactor: the moderator temperature is 600 °C, the ratio of carbon and fissile element concentrations is about 5000, the ratio of carbon and thorium nuclei approximately 200[1].

Table 1 – Averaged over the spectrum of a HTGR type reactor values $\bar{\nu}_{ef}$

| Fissionable nuclide | $^{233}$U | $^{235}$U | $^{239}$Pu |
|---|---|---|---|
| $\bar{\nu}_{ef}$ | 2.24 | 1.95 | 1.78 |

As can be seen from table 1, uranium-233 shows its properties most well in HTGR reactors.

Special scientific interest in the use of thorium appeared after the approval of the program for the disposal of weapons-grade uranium and plutonium. In the case of the use of thorium, it is possible to organize the deep burning of weapon materials without subsequent chemical processing and without plutonium co-production. The scheme of the thorium cycle without chemical processing is important from the point of view of the problem of non-proliferation of fissile materials, especially in the development of nuclear energy in non-nuclear countries.

The main ways to achieve this goal can be used:

- optimization of loading pattern and off-line refueling;
- an increase in the concentration of fissile nuclides in the fuel;
- optimization of the concentration ratio of fissile nuclides in the fuel assemblies of different types;
- the use of thorium-containing fuel compositions, providing a greater value of the negative temperature coefficient of reactivity (Doppler effect).

Now the main areas of involvement of thorium in nuclear energy are considered:

- thorium light water reactor with heterogeneous core composition with fuel ($^{235}U$ - $^{232}Th$);
- fast neutron reactors with thorium screens;
- high-temperature gas-cooled reactor (HTGR);
- molten salt reactor (MSR) operating on uranium-233 and thorium melts.

Currently, the uranium-plutonium fuel cycle has been implemented and is successfully functioning in Russia. Now there are no valid reasons for replacing it with a thorium fuel cycle. The thorium fuel cycle should not be viewed as an alternative to the uranium-plutonium one, but as its natural supplement, expanding the raw material base of nuclear energy. For the practical implementation of the thorium cycle will require a significant investment[13].

### 1.6 Description of the WIMSD-5B program

The theory of reactors focuses on the presentation of simple calculation methods that allow a qualitative analysis of the processes occurring in the reactor.

The first design programs, which appeared in the 60s, were written in machine codes and allowed in diffusion, one-dimensional (the reactor seemed to be an infinite cylinder, and finiteness of the height was taken into account by introducing corrections to macroscopic cross-sections) and the small group approximation to calculate distributions of neutron fluxes in the radial direction and get an estimate of the effective neutron multiplication factor.

In the late 60s, algorithmic programming languages appeared, more powerful computing equipment appeared, and multigroup two- and three-dimensional computational programs began to be intensively developed. At the same time, databases (libraries of microconstants) were developed, which contained microscopic cross-sections for the interaction of neutrons with matter, and the necessary methods for calculating a nuclear reactor.

The rapid development of calculation methods, multigroup neutron data libraries and calculation programs began in the 90s with the advent of computers and the Internet. The amount of memory and performance of computers led to the emergence and development of new and improved old software systems.

There are a large number of different codes that solve the preparation of few-group constants using different calculation methods (First Collision Probability method, Monte Carlo method, Discrete ordinates method, etc.), various constant software, mathematical models, etc.

WIMS (Winfrith Improved Multigroup Scheme) is a program for calculating a lattice cell of a reactor. This is a well-known English program designed for the detailed, neutron-physical calculation of reactor lattice cells of various types, including taking into account the burnout. The program is used to calculate both thermal and fast reactors. It is successfully used for designing reactors and for calculating and analyzing various effects in existing reactors[5].

This program was transferred to Russia at the end of 1977, and in September 1990 it was adapted for personal computers.

At present, the program is equipped with a universal 69-group system of nuclear microscopic cross-sections prepared on the basis of estimated neutron data files (ENDF, JEF, JENDL) at the State Science Center of the Russian Federation, Institute for Physics and Power Engineering.

The transport code WIMSD-5B uses the First Collision Probability method for solving discrete in energy and space neutron transport equations, and $S_N$ – the Discrete Ordinate method.

The input information is entered in a fairly simple form and contains a description of the considered variant, i.e. information about the materials and geometry of the cell.

The program provides for the calculation of the following geometries:

- lattice rods (including bundles of plates);
- clusters in cylindrical geometry;
- cylinders in (r,z) geometry.

Most of the most important procedures for the WIMSD-5B code cannot be directly used for hexagonal or square fuel assemblies of reactors. In geometric models of the WIMSD-5B code, hexahedral fuel assemblies are converted into equivalent cylindrical assemblies.

The program has a very detailed output. The output is made in parts (segments, blocks), and the user is given the opportunity to choose which blocks and with what detail you want to print.

The calculation of the problem of the spatial-energy distribution of the neutron flux density is carried out in 2 stages.

At the first stage ("Spectrox" - method) the real one, the initial cell is transformed into a three- or four-zone simplified one, equivalent to the area of the real one. In a cylindrical geometry, this cell contains zones with conditional names: "fuel" (1), "shell" (2), "coolant" (3) and "moderator" (4), the latter two zones can be combined into one. The division of the source cell into zones, i.e. the inclusion of cell elements in a particular zone is made by the user. An example of such a four-zone cell is presented in figure 4.

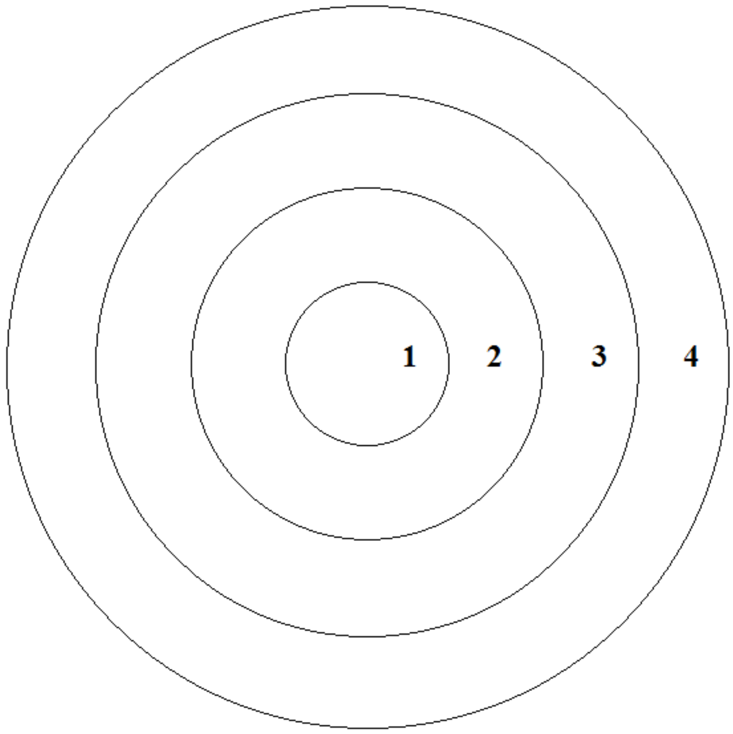


Figure 4 – Four-zone simplified cell:
1 – fuel; 2 – fuel cladding; 3 – coolant; 4 – moderator

At subsequent stages, the user is given the choice of the calculation method:

- discrete ordinate method (DSN) – the transfer equation is solved in differential form for infinite cylinders or plates;
- the first collision probability method – the transfer equation is solved for problems with cylindrical and flat geometries, clusters, finite rods and plates, there are opportunities to solve problems in two-dimensional geometries ($r,\vartheta$ or $r,z$) and in polycell.

When choosing the method of collision probabilities, in contrast to the first stage, the problem is solved with splitting into any number of geometrical zones. The equations used are similar to those used in the "Spectrox" stage. Here it is also possible to choose one of three variants of the calculation method depending on the type of the problem being solved (single fuel element, cluster, r-Z geometry).

When choosing the method of discrete ordinates, one of the varieties of the method is used, namely Sn - method (in the program it is called DSN). The higher the order of the chosen approximation (N = 2-64), the higher the accuracy of the calculation. Only infinite cylinders and plates can be calculated using this method.

The method can also be applied if there are empty zones. The system of equations of the DSN method is solved iteratively, the criterion for the end of the iterations is the reduction of the eigenvalue difference in two subsequent iterations to <0.0001, but you can set another error value.

In addition to the spatial and energy distribution of the neutron flux density in the cell, the program calculates the magnitudes of the infinite multiplication factor and the effective multiplication factor.

The complete calculation of the spatial and energy distribution of neutrons in the reactor cell is as follows:

- a detailed spectrum is calculated in 69 groups in each of the zones typical for the cell: in fuel, shell, coolant and moderator;
- the convolution of the cross sections to a given small-group approximation is carried out, in which the detailed spatial distributions of neutrons per cell are calculated;
- modification of the solution obtained is carried out taking into account leakage;
- the few-group flows unfold into a 69-group representation and the reaction rates for the given isotopes are calculated.

## 2 Neutron-physical calculations

### 2.1 Description of the basic design of gas-cooled thorium reactor

In early researches, the optimization of the geometric characteristics of fuel elements and the composition of nuclear fuel, including the size of particles and coatings of microencapsulated fuel dispersed in graphite fuel blocks, made it possible to develop a basic design of a 60 MW high-temperature gas-cooled thorium reactor[23].

Micro-fuel is a core of fissile material with a coating dispersed in a graphite matrix of cylindrical fuel pellets that are placed in the reactor core. Micro-fuel has two coating layers: pyrolytic carbon (PyC) with a density of 1.9 $g/cm^3$, and silicon carbide (SiC) with a density of 3.2 $g/cm^3$.

The fuel pellet is an oxide fuel composition $(Me)O_2$. The design characteristics of the fuel pellets are as follows: diameter is 12 mm (with a coating of SiC), height is 20.6 mm (with a coating of SiC), volume is 2330 $mm^3$.

By heavy metal, plutonium and thorium were used as fissile material and taken at a ratio of 50/50%, since early calculations showed that with equal proportions the distribution of neutron flux and energy release becomes more uniform throughout the reactor [24]. Thorium consisted of only one isotope contained in the natural material – $^{232}Th$.

The model of a fuel pellet with microencapsulated fuel is shown in figure 5.

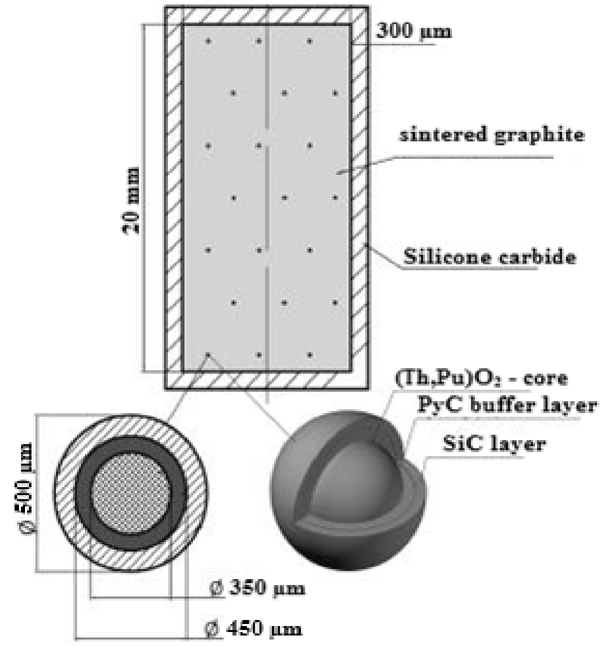


Figure 5 – The cylindrical fuel pellet of high-temperature gas-cooled reactor

The fuel assembly is a hexagonal graphite block with a turnkey size of 200 mm; 78 holes with a diameter of 12 mm for fuel pellets and 7 holes with a diameter of 24 mm for the passage of gaseous coolant (helium).

The cross-section of the fuel assembly of the basic design of the reactor installation has the form shown in figure 6.

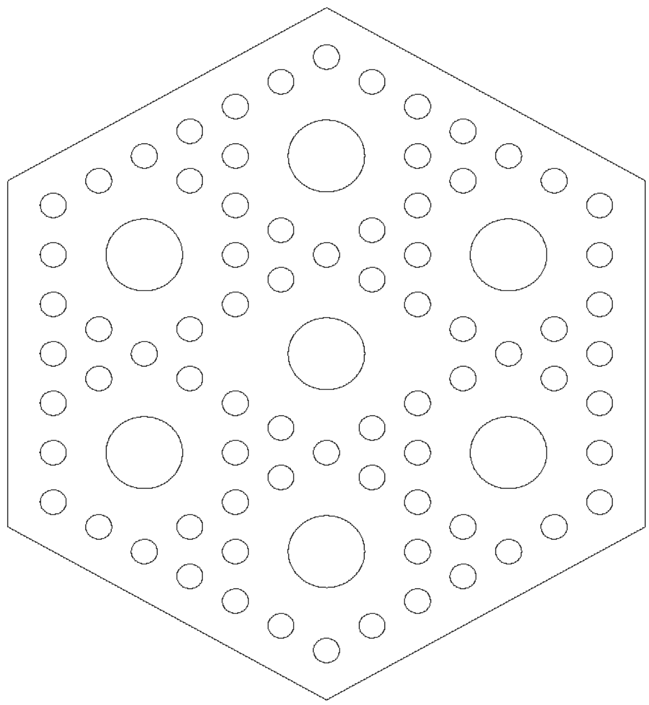

Figure 6 – The basic structure of fuel assembly

This configuration of kern, coatings, fuel pellets and fuel blocks of high-temperature gas-cooled thorium reactor eliminates contact with metals, which allows to increase the service life of microencapsulated fuel by 30%. The service life of microfuel and fuel pellets is limited to a temperature of 1250 K and a fluence of fast neutrons ~ $10^{25}$ $m^{-2}$[25].

The reactor core consists of 217 fuel assemblies. Of these, 127 fuel assemblies are fuel-containing, with a height of 2000 mm, surrounded by two rows of graphite blocks without holes. From above and below, the reactor core is surrounded by graphite 300 mm thick.

The cross section of the reactor core model with a reflector is shown in figure 7.

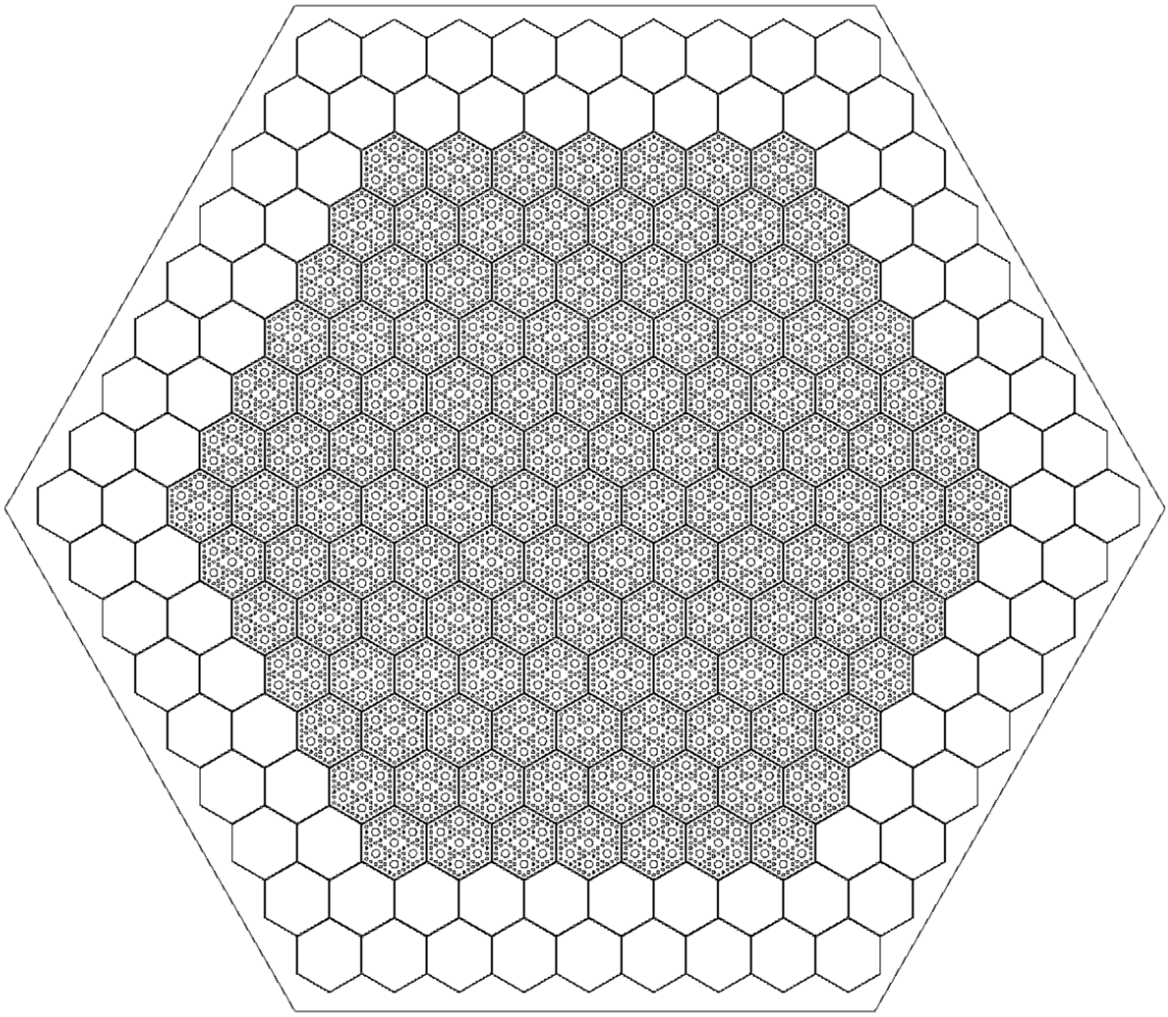

Figure 7 – The model of a gas-cooled thorium reactor core with a reflector

Technical characteristics of the basic core composition of a gas-cooled thorium reactor are listed in Table 2.

Table 2 – Technical characteristics of the basic core composition of a gas-cooled thorium reactor

| Specifications | Value |
|---|---|
| Thermal power, MW | 60 |
| Turnkey size of fuel assembly, m | 0.2 |
| Number of fuel assemblies | 217 |
| The number of fuel-containing fuel assemblies | 127 |
| The height of the fuel-containing part, m | 2 |
| The number of holes in the fuel assembly for the coolant | 7 |
| The diameter of the holes in the fuel assembly for the coolant, m | 0.024 |
| The number of holes in the fuel assembly for fuel pellets | 78 |
| Fuel composition | $(Th,Pu)O_2$ |
| Fuel pellet height, m | 0.020 |
| Fuel pellet diameter, m | 0.012 |
| SiC coating thickness, μm | 300 |
| The mass of heavy metal in the fuel pellet, kg | 0.000411 |

### 2.2 Design model of a fuel assembly for a gas-cooled thorium reactor

In this research, an improved reactor core composition was taken as the basic design of the fuel assembly, differing from the previous one by making some changes in the design.

First, a thorium-plutonium fuel composition (Th,Pu)N was used as a fissile material. The effective density of this type of fuel is 12.5 g/cm$^3$ and exceeds the density of the oxide composition $(Th,Pu)O_2$, which made it possible to place a larger amount of fuel in the reactor core. Fissile materials as well as for the base core composition were taken in equal proportions.

Secondly, the design of fuel assemblies was changed. Now, in hexagonal graphite blocks of dense high-graphite material, processed at a temperature of 3000 K, 90 holes with a diameter of 12 mm for fuel pellets and 7 holes with a diameter of 24 mm for the coolant were made.

The cross section of the fuel assembly of this type of reactor installation has the form shown in figure 8.

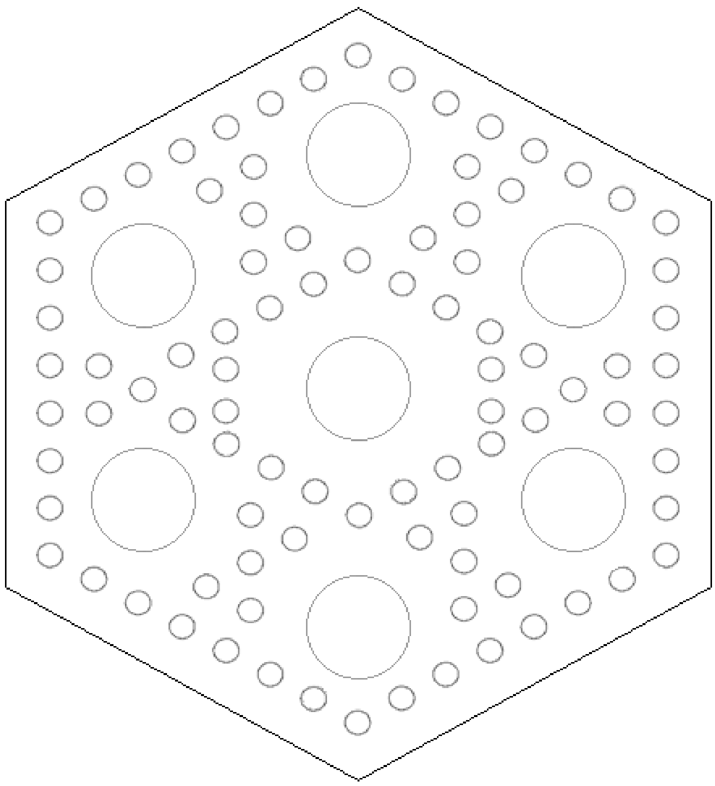

Figure 8 – The structure of fuel assembly

The remaining technical parameters of the reactor installation, including the core geometry, remained unchanged.

Technical characteristics of the core composition of a gas-cooled thorium reactor are presented in table 3.

Table 3 – Technical characteristics of the core composition of a gas-cooled thorium reactor

| Specifications | Value |
|---|---|
| Thermal power, MW | 60 |
| Turnkey size of fuel assembly, m | 0.2 |
| Number of fuel assemblies | 217 |
| The number of fuel-containing fuel assemblies | 127 |
| The height of the fuel-containing part, m | 2 |
| The number of holes in the fuel assembly for the coolant | 7 |
| The diameter of the holes in the fuel assembly for the coolant, m | 0.024 |
| The number of holes in the fuel assembly for fuel pellets | 90 |
| Fuel composition | (Th,Pu)N |
| Fuel pellet height, m | 0.020 |
| Fuel pellet diameter, m | 0.012 |
| SiC coating thickness, μm | 300 |
| The mass of heavy metal in the fuel pellet, kg | 0.000411 |

The design model of a gas-cooled thorium reactor fuel assembly was created using WIMSD-5B program written in FORTRAN programming language and intended for the neutron-physical calculation of various types of reactors.

The WIMS programs allow one-dimensional calculation of the nuclide composition of the fuel cell of the reactor under investigation when the nuclide composition of the fuel changes during operation, estimate the value of the stationary poisoning of the reactor, take into account the effect of temperature, prepare sets of macroconstants depending on temperature, poisoning and changes in the nuclide composition of the fuel.

A cluster type cell consisting of a graphite block, fuel cells and cells with a cooling gas was chosen as the design model of the fuel assembly of the reactor under investigation for the WIMS-5B program code.

The resulting design model of the fuel assembly is shown in figure 9.

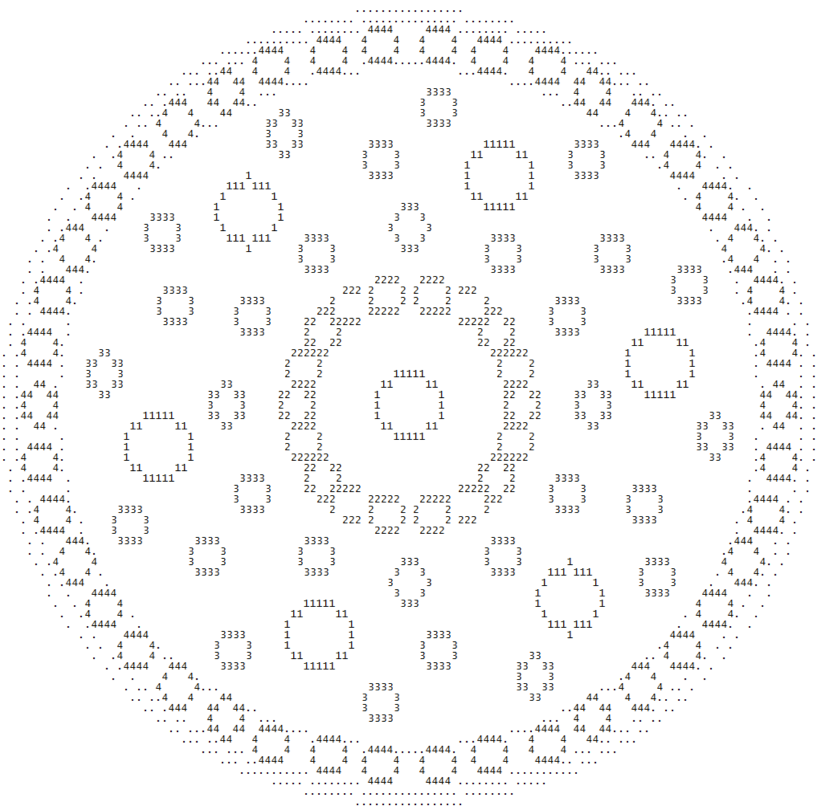

Figure 9 – Design model of a gas-cooled thorium reactor fuel assembly as defined in the WIMSD-5B program

## 2.3 The increase of fuel loading by changing the fuel assembly design

One of the ways to increase the duration of a campaign of a nuclear installation is to try to increase the fuel loading by making changes in the design of fuel assemblies by gradually adding channels to accommodate fuel pellets.

For this purpose, first of all, it was necessary to determine the operating time of the gas-cooled thorium reactor for task geometry of the basic design of fuel assemblies.

The calculation of nuclear concentrations of all elements present in the reactor core was carried out according to the following formula:

$$N_i = \frac{N_A \cdot \rho_i \cdot C_i}{A_i}, \qquad (1)$$

where $N_i$ – nuclear concentration, $cm^{-3}$;

$N_A$ – Avogadro's number, $N_A = 6.022 \cdot 10^{23}$ $mole^{-1}$;

$\rho$ – element density, $g/cm^3$;

$A_i$ – mass number of element;

$C_i$ – element content, unit fraction.

The isotopic composition of plutonium is shown in table 4.

Table 4 – The percentage of plutonium isotopes in the fuel

| Isotope | $^{238}Pu$ | $^{239}Pu$ | $^{240}Pu$ | $^{241}Pu$ | $^{242}Pu$ |
|---|---|---|---|---|---|
| % | 0 | 94 | 5 | 1 | 0 |

The obtained values of the concentrations of isotopes of thorium-plutonium nitride fuel, included in the program code for further calculations, are presented in table 5.

Table 5 – The results of calculations of the concentrations of isotopes of thorium-plutonium nitride fuel

| Isotope | Concentration, $cm^{-3}$ |
|---|---|
| $^{232}Th$ | $2.92 \cdot 10^{20}$ |
| $^{238}Pu$ | $1.00 \cdot 10^{12}$ |
| $^{239}Pu$ | $2.75 \cdot 10^{20}$ |
| $^{240}Pu$ | $1.46 \cdot 10^{19}$ |
| $^{241}Pu$ | $2.92 \cdot 10^{18}$ |
| $^{242}Pu$ | $1.00 \cdot 10^{12}$ |
| $^{14}N$ | $5.84 \cdot 10^{20}$ |
| $^{12}C$ | $8.38 \cdot 10^{22}$ |
| $^{29}Si$ | $4.79 \cdot 10^{21}$ |

In early researches, only the values of the infinite multiplication factor ($k_{inf}$) and reactivity margin ($\rho_{inf}$) were calculated[25].

In order for the program to be able to calculate the effective multiplication factor ($k_{eff}$), it is necessary to set the value of the geometric buckling in the code. The geometric buckling for the considered cylindrical reactor is determined by the formula:

$$B^2 = \left(\frac{\pi}{H}\right)^2 + \left(\frac{2,405}{R}\right)^2, \quad (2)$$

where $B^2$ – geometric buckling, $cm^{-2}$;

$H$ – height of fuel containing part, cm;

$R$ – reactor core radius, cm.

The change in the effective multiplication factor, reactivity margin, plutonium-239, thorium-232 and uranium-233 isotope concentrations for the basic fuel assembly design is presented in table 6.

Table 6 – Results of calculations for the basic design of fuel assemblies

| Reactor power operation time, days | $k_{eff}$ | $\rho$, % | *N (Pu-239)*, $cm^{-3}$ | *N (Th-232)*, $cm^{-3}$ | *N (U-233)*, $cm^{-3}$ |
|---|---|---|---|---|---|
| 0 | 1.116944 | 10.47 | 2.75E+20 | 2.92E+20 | 0 |
| 2 | 1.116382 | 10.42493 | 2.75E+20 | 2.92E+20 | 2.92E+05 |
| 10 | 1.114376 | 10.26368 | 2.74E+20 | 2.92E+20 | 7.11E+14 |
| 50 | 1.111511 | 10.03238 | 2.73E+20 | 2.92E+20 | 1.67E+16 |
| 100 | 1.100181 | 9.105865 | 2.68E+20 | 2.91E+20 | 3.07E+17 |
| 200 | 1.088231 | 8.107746 | 2.62E+20 | 2.91E+20 | 8.95E+17 |
| 300 | 1.068767 | 6.434237 | 2.49E+20 | 2.89E+20 | 2.22E+18 |
| 500 | 1.052562 | 4.99372 | 2.36E+20 | 2.88E+20 | 3.52E+18 |
| 700 | 1.028012 | 2.724871 | 2.13E+20 | 2.85E+20 | 5.98E+18 |
| 900 | 1.008477 | 0.840574 | 1.91E+20 | 2.82E+20 | 8.22E+18 |
| 1100 | 0.992082 | -0.79814 | 1.70E+20 | 2.78E+20 | 1.02E+19 |

Thus, as can be seen from the table 6, for the basic design of fuel assembly, the reactivity margin at the beginning of the campaign is 10.47%. The burnup of plutonium-239 and thorium-232 isotopes is 38.15% and 4.69%, respectively. The uranium-233 production reaches its concentration of $1.02 \cdot 10^{19}$ $cm^{-3}$ and the campaign is 986 effective days.

The design model of the fuel assembly after adding 6 fuel channels to the base geometry is shown in figure 10.

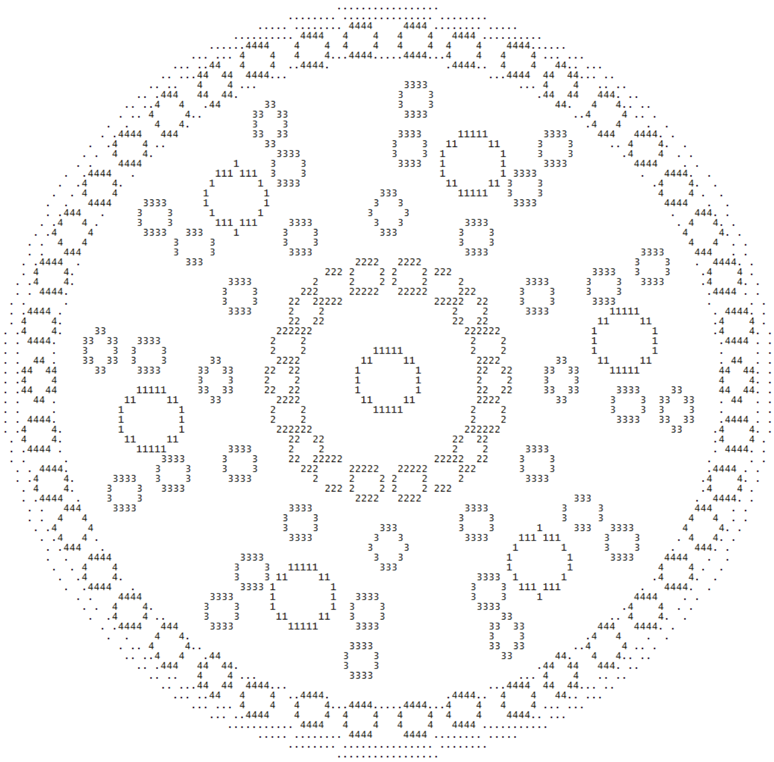

Figure 10 – Design model of a fuel assembly of a gas-cooled thorium reactor with the addition of 6 fuel channels

The change of the effective multiplication factor, reactivity margin, plutonium-239, thorium-232 and uranium-233 isotope concentrations in the design model of the fuel assembly after adding of 6 fuel channels is presented in table 7.

Table 7 – Calculation results for the model of a fuel assembly with the addition of 6 fuel channels

| Reactor power operation time, days | $k_{eff}$ | $\rho$, % | *N (Pu-239)*, cm$^{-3}$ | *N (Th-232)*, cm$^{-3}$ | *N (U-233)*, cm$^{-3}$ |
|---|---|---|---|---|---|
| 0 | 1.112454 | 10.10864 | 2.75E+20 | 2.92E+20 | 0 |
| 2 | 1.111991 | 10.07121 | 2.75E+20 | 2.92E+20 | 2.92E+05 |
| 10 | 1.110206 | 9.926626 | 2.74E+20 | 2.92E+20 | 6.98E+14 |
| 50 | 1.107501 | 9.706628 | 2.73E+20 | 2.92E+20 | 1.64E+16 |
| 100 | 1.096884 | 8.832657 | 2.69E+20 | 2.91E+20 | 3.02E+17 |
| 200 | 1.085673 | 7.891234 | 2.62E+20 | 2.91E+20 | 8.79E+17 |
| 300 | 1.067238 | 6.300188 | 2.51E+20 | 2.89E+20 | 2.18E+18 |
| 500 | 1.051708 | 4.916574 | 2.39E+20 | 2.88E+20 | 3.46E+18 |
| 700 | 1.027733 | 2.698464 | 2.17E+20 | 2.85E+20 | 5.89E+18 |
| 900 | 1.008343 | 0.827397 | 1.96E+20 | 2.82E+20 | 8.11E+18 |
| 1100 | 0.991874 | -0.81923 | 1.77E+20 | 2.79E+20 | 1.01E+19 |

As can be seen from table 7, the addition of a fuel assembly 6 fuel channels to the basic design resulted in a decrease in the initial reactivity margin of 0.36%. Burnout of plutonium-239 and thorium-232 isotopes decreased and amounted to 35.66% and 4.59%, respectively. The production of uranium-233 isotopes has also decreased by approximately 0.7%. At the same time, the duration of the campaign has increased and it amounts to 987 effective days.

The design model of the fuel assembly after adding 12 fuel channels to the base structure is shown in figure 11.

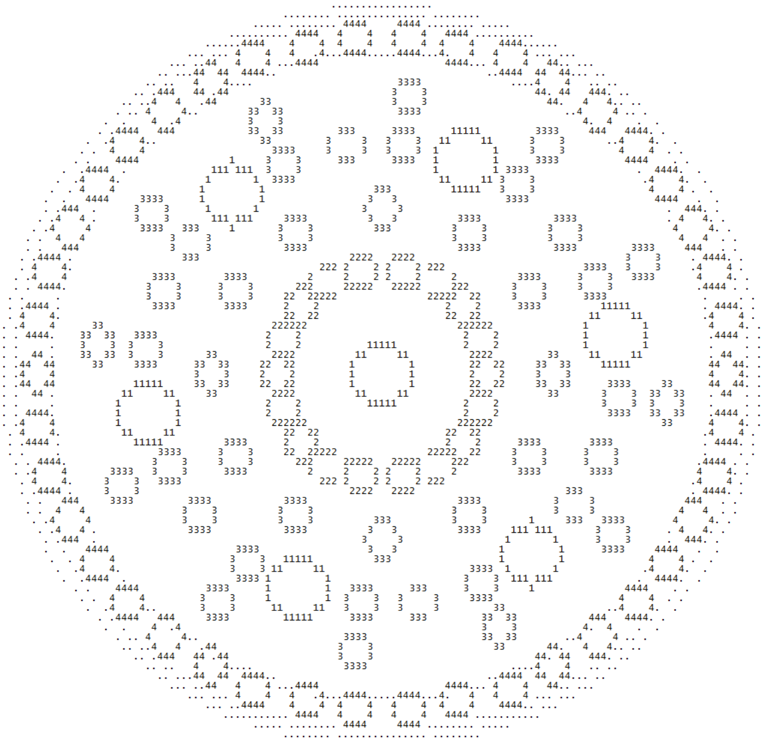

Figure 11 – Design model of a fuel assembly of a gas-cooled thorium reactor with the addition of 12 fuel channels

The change of the effective multiplication factor, reactivity margin, plutonium-239, thorium-232 and uranium-233 isotope concentrations in the design model of the fuel assembly after adding of 12 fuel channels is presented in table 8.

Table 8 – Calculation results for the model of a fuel assembly with the addition of 12 fuel channels

| Reactor power operation time, days | $k_{eff}$ | *ρ, %* | *N (Pu-239)*, $cm^{-3}$ | *N (Th-232)*, $cm^{-3}$ | *N (U-233)*, $cm^{-3}$ |
|---|---|---|---|---|---|
| 0 | 1.109514 | 9.870448 | 2.75E+20 | 2.92E+20 | 0 |
| 2 | 1.10913 | 9.839243 | 2.75E+20 | 2.92E+20 | 2.92E+05 |
| 10 | 1.107519 | 9.708095 | 2.74E+20 | 2.92E+20 | 6.84E+14 |
| 50 | 1.104952 | 9.498331 | 2.74E+20 | 2.92E+20 | 1.60E+16 |
| 100 | 1.094943 | 8.671045 | 2.69E+20 | 2.92E+20 | 2.96E+17 |
| 200 | 1.084382 | 7.781575 | 2.63E+20 | 2.91E+20 | 8.63E+17 |
| 300 | 1.066869 | 6.26778 | 2.52E+20 | 2.89E+20 | 2.14E+18 |
| 500 | 1.05193 | 4.93664 | 2.41E+20 | 2.88E+20 | 3.40E+18 |

Continuation of table 8

| | | | | | |
|---|---|---|---|---|---|
| 700 | 1.02841 | 2.762517 | 2.21E+20 | 2.85E+20 | 5.79E+18 |
| 900 | 1.009074 | 0.89924 | 2.01E+20 | 2.82E+20 | 7.99E+18 |
| 1100 | 0.992437 | -0.76203 | 1.83E+20 | 2.79E+20 | 1.00E+19 |

The addition of 12 fuel channels to the basic design of the fuel assembly also led to a decrease in the initial reactivity margin by 0.60%. Burnout of plutonium-239 and thorium-232 isotopes decreased and amounted to 35.66%, 4.59%, respectively. Uranium-233 isotope production has decreased by approximately 1.9%. The duration of the campaign has increased and it is equal to 995 effective days.

The design model of the fuel assembly after adding 18 fuel channels to the base structure is shown in figure 12.

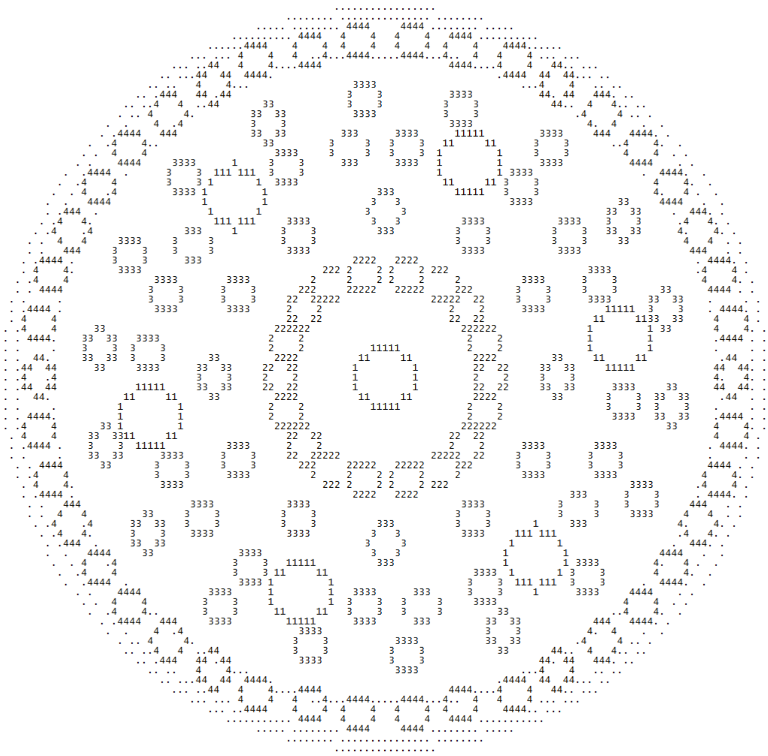

Figure 12 – Design model of a fuel assembly of a gas-cooled thorium reactor with the addition of 18 fuel channels

The change of the effective multiplication factor, reactivity margin, plutonium-239, thorium-232 and uranium-233 isotope concentrations in the design model of the fuel assembly after adding of 18 fuel channels is presented in table 9.

Table 9 – Calculation results for the model of a fuel assembly with the addition of 18 fuel channels

| Reactor power operation time, days | $k_{eff}$ | $\rho$, % | *N (Pu-239)*, $cm^{-3}$ | *N (Th-232)*, $cm^{-3}$ | *N (U-233)*, $cm^{-3}$ |
|---|---|---|---|---|---|
| 0 | 1.107566 | 9.711927 | 2.75E+20 | 2.92E+20 | 0 |
| 2 | 1.107242 | 9.685507 | 2.75E+20 | 2.92E+20 | 2.92E+05 |
| 10 | 1.105787 | 9.566671 | 2.74E+20 | 2.92E+20 | 6.66E+14 |
| 50 | 1.103379 | 9.36931 | 2.74E+20 | 2.92E+20 | 1.56E+16 |
| 100 | 1.094066 | 8.597836 | 2.69E+20 | 2.92E+20 | 2.88E+17 |
| 200 | 1.084134 | 7.76048 | 2.64E+20 | 2.91E+20 | 8.40E+17 |
| 300 | 1.067515 | 6.324501 | 2.54E+20 | 2.89E+20 | 2.09E+18 |
| 500 | 1.053194 | 5.050731 | 2.44E+20 | 2.88E+20 | 3.32E+18 |
| 700 | 1.030218 | 2.933166 | 2.24E+20 | 2.85E+20 | 5.66E+18 |
| 900 | 1.011073 | 1.095173 | 2.06E+20 | 2.82E+20 | 7.82E+18 |
| 1100 | 0.994436 | -0.55951 | 1.88E+20 | 2.79E+20 | 9.81E+18 |

The addition of 18 fuel channels to the base structure of the fuel assembly resulted in a decrease in the initial reactivity margin by 0.76%. Burnout of plutonium-239 and thorium-232 isotopes decreased and amounted to 31.41% and 4.37%, respectively. Uranium-233 isotope production has decreased by approximately 3.8%. Campaign duration has increased and is equal to 1024 effective days.

Figure 13 shows the results of comparisons of the neutron-multiplying properties (reactivity margin) of a gas-cooled thorium reactor equipped with the models of fuel assemblies described above and operating at 60 MW.

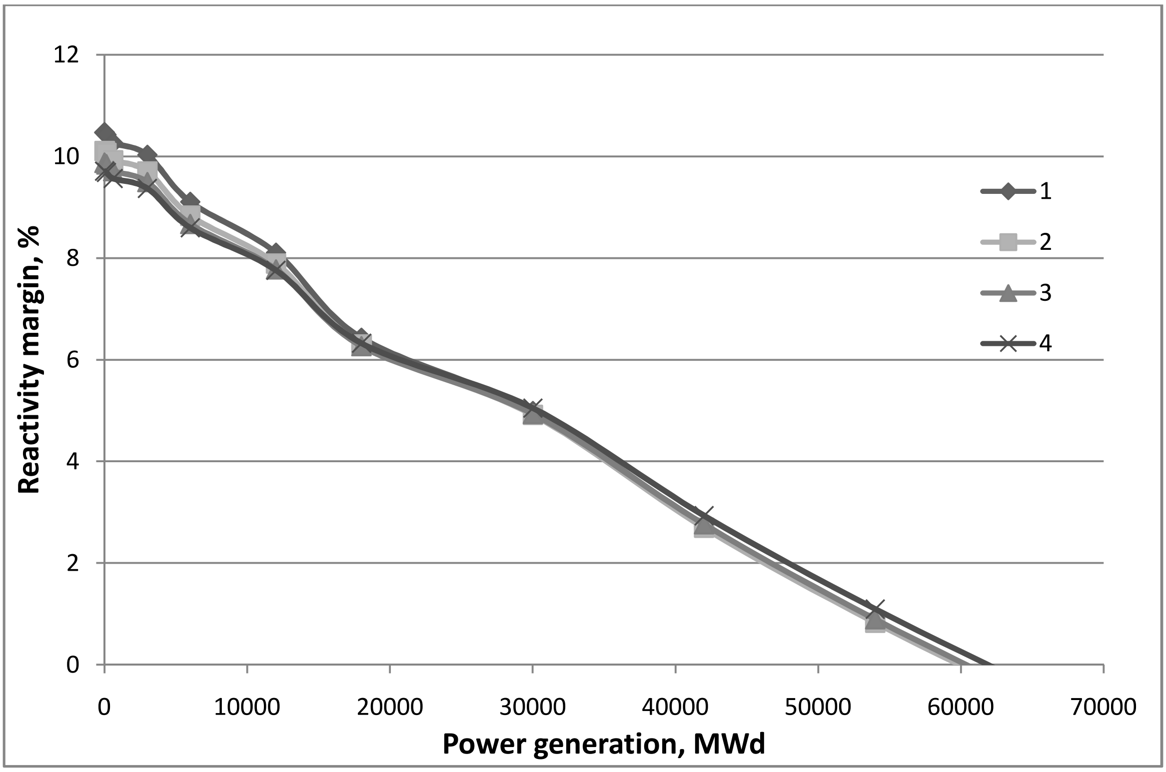


Figure 13 – Change in reactivity margin during reactor operation:
1 – basic design; 2 – adding 6 fuel channels; 3 – adding 12 fuel channels;
4 – adding 18 fuel channels

As can be seen from figure 13 and the results obtained, with an increase in the number of fuel channels (loading of a gas-cooled fuel reactor), the initial reactivity margin decreases, but there is an increase in the reactor campaign duration due to a lower reactivity loss rate when the reactor is operating at power.

For a better understanding of the processes occurring in a nuclear installation during its operation, it became necessary to determine the concentrations of nuclear fuel isotopes throughout the campaign.

Figures 14-16 show the changes in the average values of nuclear concentrations for plutonium-239, uranium-233 and thorium-232, respectively, for each of the considered design models of fuel assemblies of a gas-cooled thorium reactor.

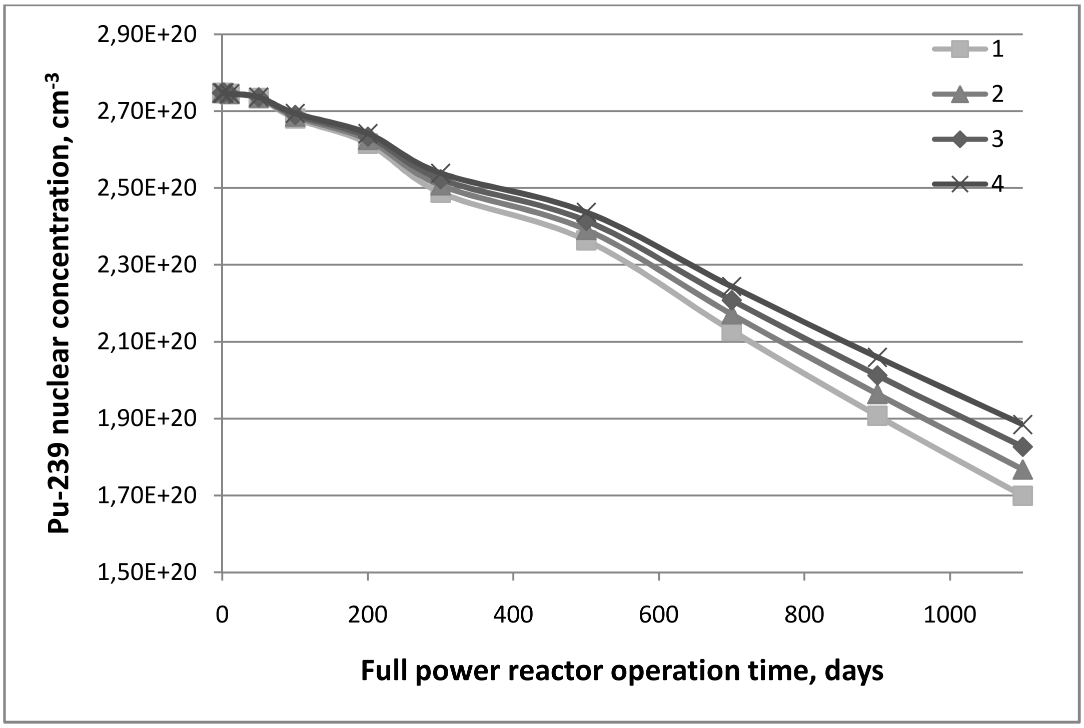


Figure 14 – Changes in Pu-239 concentration during reactor operation:
1 – basic design; 2 – adding 6 fuel channels; 3 – adding 12 fuel channels;
4 – adding 18 fuel channels

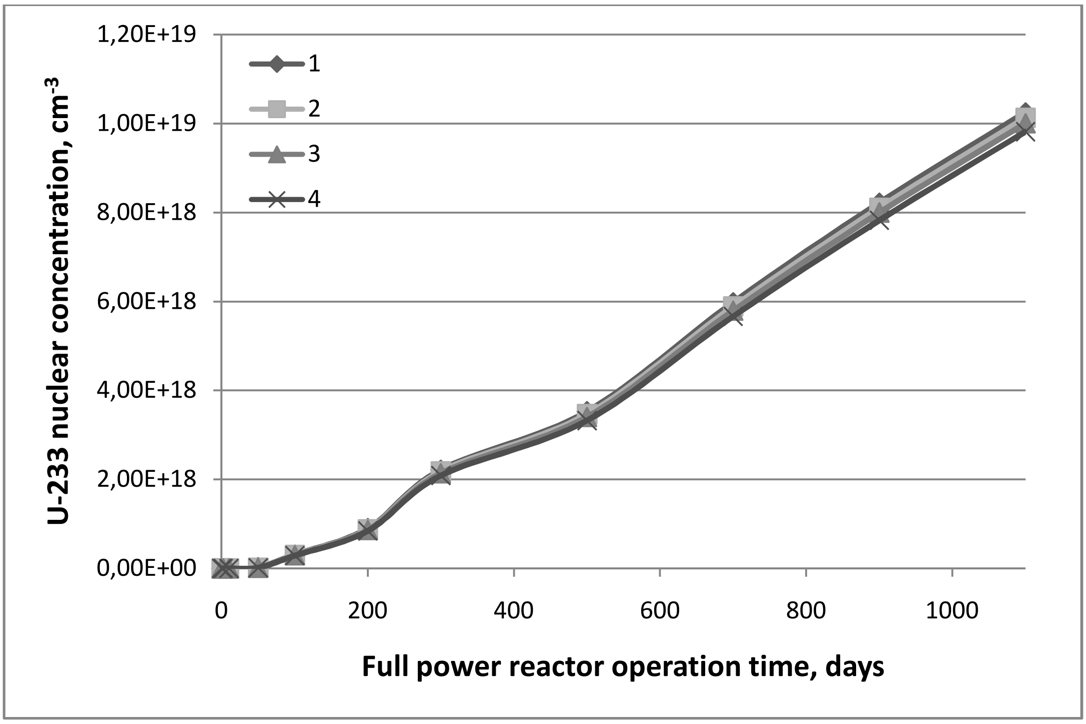


Figure 15 – Changes in U-233 concentration during reactor operation:
1 – basic design; 2 – adding 6 fuel channels; 3 – adding 12 fuel channels;
4 – adding 18 fuel channels

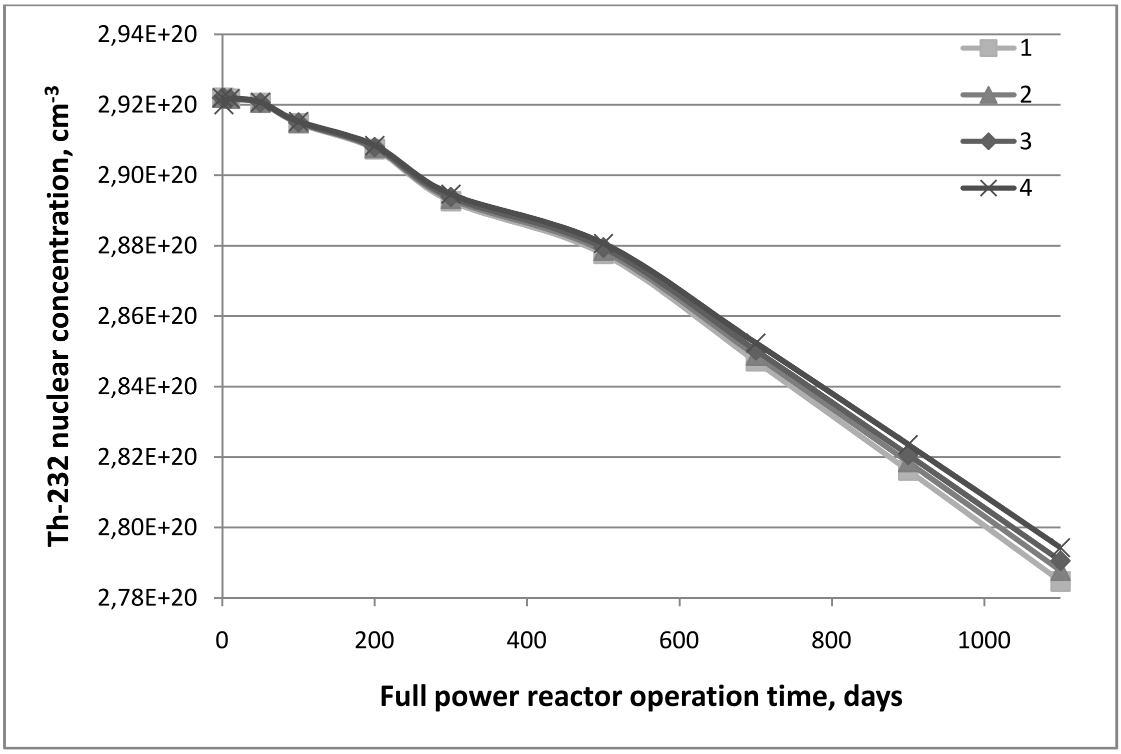


Figure 16 – Changes in Th-232 concentration during reactor operation:
1 – basic design; 2 – adding 6 fuel channels; 3 – adding 12 fuel channels;
4 – adding 18 fuel channels

Due to the isotope protactinium-233, obtained as a result of neutrons irradiation of thorium-232, an additional amount of uranium-233 isotopes participating in the fission process accumulates.

The calculated dependences of protactinium-233 concentrations on the reactor operating time at full power are shown in figure 17.

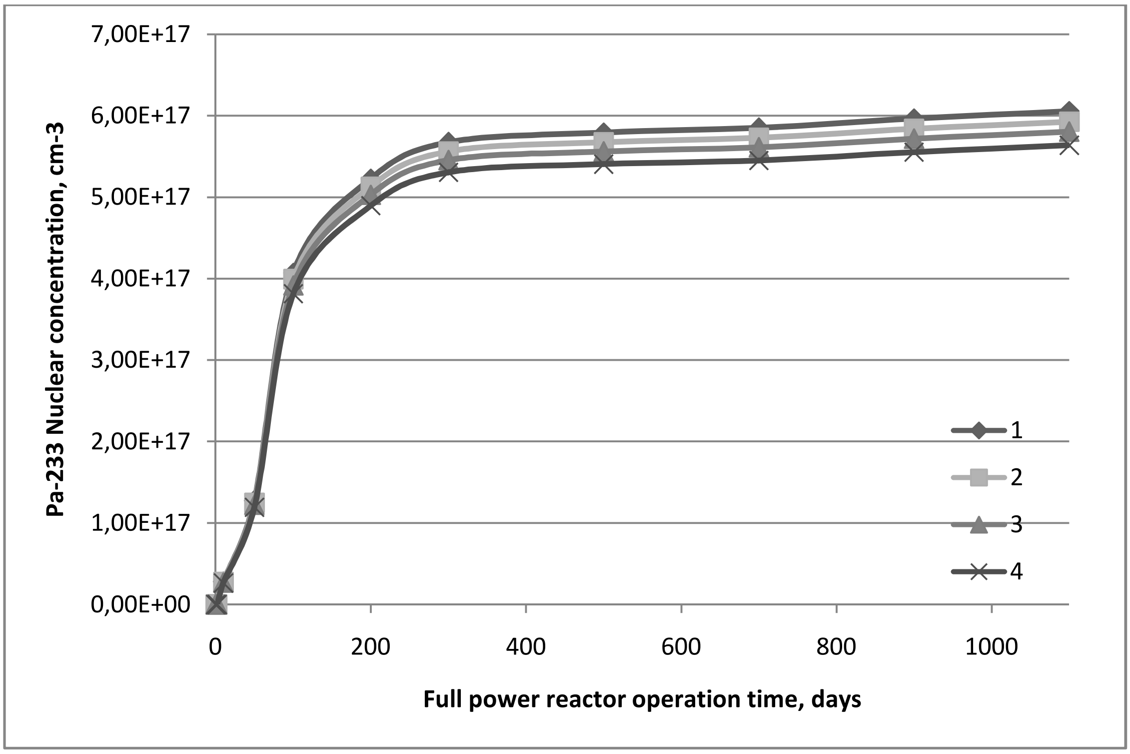


Figure 17 – Changes in Pa-233 concentration during reactor operation:
1 – basic design; 2 – adding 6 fuel channels; 3 – adding 12 fuel channels;
4 – adding 18 fuel channels

It is important to emphasize that the presence of 5% plutonium-240 isotope in weapons-grade plutonium leads to a noticeable production of plutonium-241, the nuclear concentration of which is more than twice the concentration of uranium-233 throughout the campaign, as we can see in figure 18.

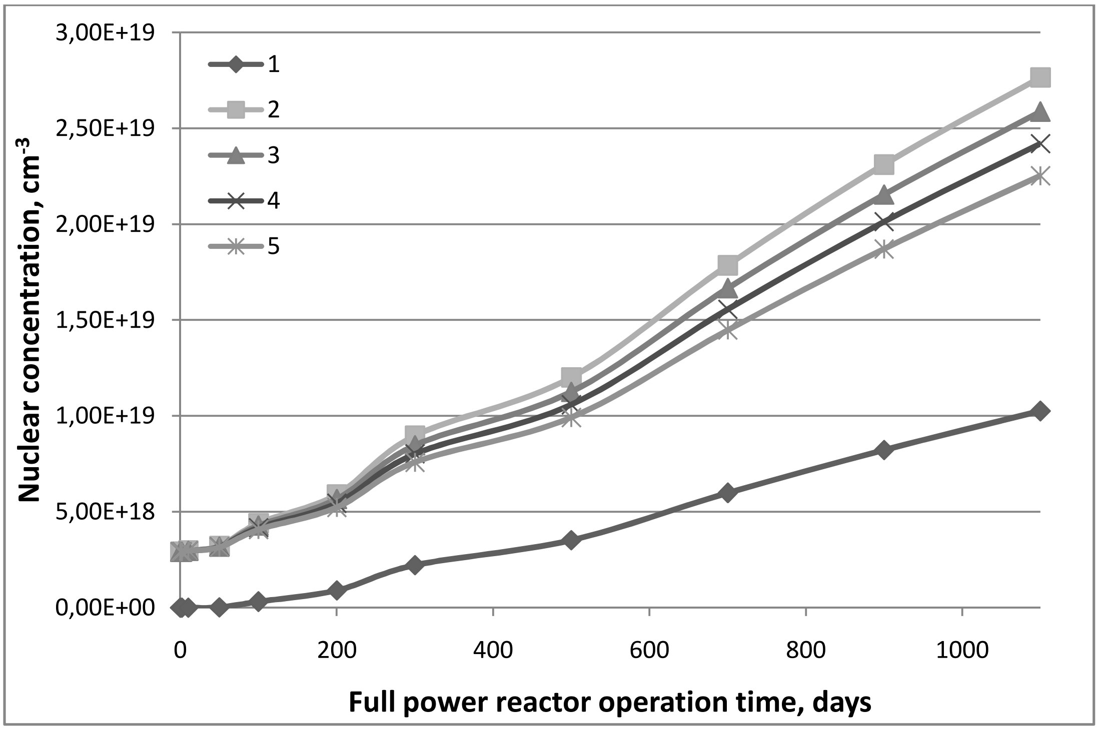


Figure 18 – Production of Pu-241 and U-233 isotopes during reactor operation: 1 – production of U-233 (basic design); 2 – production of Pu-241 (basic design); 3 – production of U-233 (adding 6 fuel channels); 4 – production of U-233 (adding 12 fuel channels); 5 – production of U-233 (adding 18 fuel channels)

Burnout of the main heavy nuclides of the gas-cooled thorium reactor for the considered fuel assembly models, as well as the resulting campaign duration and the burnup depth are presented in table 10.

Table 10 – Burnout of the main heavy nuclide, burnup depth and reactor campaign for the considered fuel assembly models

| Nuclide | Basic model | Adding 6 fuel channels | Adding 12 fuel channels | Adding 18 fuel channels |
|---|---|---|---|---|
| Burnout $^{239}$Pu, % | 38.15 | 35.66 | 33.51 | 31.41 |
| Burnout $^{232}$Th, % | 4.69 | 4.59 | 4.50 | 4.37 |
| Burnup depth, GWd/t | 126.21 | 118.32 | 112.44 | 108.54 |
| Campaign, d. | 986 | 987 | 995 | 1024 |

Based on all of the above, the main drawback of the options considered is that during the operation of the reactor, plutonium-239 and thorium-232 do not have time to burn out, and uranium-233 does not have time to accumulate in appreciable quantities. The magnitude of the burnup depth also declines with the addition of fuel channels.

Nevertheless, an increase in the total amount of fuel through additional fuel channels led to a lower rate of reactivity loss when the reactor was operating at power, which, in turn, led to an increase in the duration of the campaign.

Thus, in the considered variants, when 6, 12 and 18 fuel channels are added to the fuel assembly design, the gas-cooled thorium reactor can operate for 1, 9 and 38 effective days longer.

## 2.4 The increase of fuel loading in fuel pellet

Another way to increase the campaign duration of a gas-cooled thorium reactor is to try to increase the fuel load by changing the percentage of nuclear fuel in the fuel pellet.

With an increase in fuel loading by 10%, the weight of the heavy metal in the fuel pellet was determined. It became equal to 0.0004521 kg.

The change in the effective multiplication factor, reactivity margin and isotope concentrations of plutonium-239, thorium-232 and uranium-233 with an increased fuel loading of 10% is presented in table 11.

Table 11 – Results of calculations with an increased fuel load by 10%

| Reactor power operation time, days | $k_{eff}$ | $\rho$, % | *N (Pu-239)*, $cm^{-3}$ | *N (Th-232)*, $cm^{-3}$ | *N (U-233)*, $cm^{-3}$ |
|---|---|---|---|---|---|
| 0 | 1.116944 | 10.47 | 2.75E+20 | 2.92E+20 | 0 |
| 2 | 1.116382 | 10.42493 | 2.75E+20 | 2.92E+20 | 2.92E+05 |

Continuation of table 11

| | | | | | |
|---|---|---|---|---|---|
| 10 | 1.114609 | 10.28244 | 2.74E+20 | 2.92E+20 | 6.44E+14 |
| 50 | 1.112004 | 10.07227 | 2.73E+20 | 2.92E+20 | 1.51E+16 |
| 100 | 1.101655 | 9.22748 | 2.69E+20 | 2.92E+20 | 2.79E+17 |
| 200 | 1.09064 | 8.310717 | 2.63E+20 | 2.91E+20 | 8.13E+17 |
| 300 | 1.072426 | 6.753473 | 2.51E+20 | 2.90E+20 | 2.02E+18 |
| 500 | 1.05706 | 5.397991 | 2.40E+20 | 2.88E+20 | 3.21E+18 |
| 700 | 1.033324 | 3.224932 | 2.18E+20 | 2.85E+20 | 5.48E+18 |
| 900 | 1.014269 | 1.406826 | 1.98E+20 | 2.83E+20 | 7.56E+18 |
| 1100 | 0.998238 | -0.17656 | 1.78E+20 | 2.80E+20 | 9.48E+18 |

When comparing table 5 and table 10, it can be seen that with an increase in fuel loading by 10%, the initial reactivity margin remained unchanged at 10.47%. The burnout of plutonium-239 and thorium-232 isotopes decreased to 35.05% and 4.24%, respectively. Uranium-233 isotope production has decreased by approximately 7.1%. The duration of the campaign increased and reached 1051 effective days.

With an increase in fuel loading by 20%, it was necessary to again determine the mass of heavy metal in the fuel pellet. The mass became equal to 0.0004932 kg.

The change in the effective multiplication factor, reactivity margin and isotope concentrations of plutonium-239, thorium-232 and uranium-233 with an increased fuel loading of 20% is presented in table 12.

Table 12 – Results of calculations with an increased fuel load by 20%

| Reactor power operation time, days | $k_{eff}$ | *ρ, %* | *N (Pu-239)*, $cm^{-3}$ | *N (Th-232)*, $cm^{-3}$ | *N (U-233)*, $cm^{-3}$ |
|---|---|---|---|---|---|
| 0 | 1.116944 | 10.47 | 2.75E+20 | 2.92E+20 | 0 |
| 2 | 1.116382 | 10.42493 | 2.75E+20 | 2.92E+20 | 2.92E+05 |
| 10 | 1.114804 | 10.29813 | 2.74E+20 | 2.92E+20 | 5.89E+14 |

Continuation of table 12

| | | | | | |
|---|---|---|---|---|---|
| 50 | 1.112419 | 10.10581 | 2.74E+20 | 2.92E+20 | 1.38E+16 |
| 100 | 1.102897 | 9.329702 | 2.69E+20 | 2.92E+20 | 2.55E+17 |
| 200 | 1.092686 | 8.4824 | 2.64E+20 | 2.91E+20 | 7.44E+17 |
| 300 | 1.07558 | 7.026906 | 2.53E+20 | 2.90E+20 | 1.85E+18 |
| 500 | 1.060983 | 5.747783 | 2.43E+20 | 2.89E+20 | 2.95E+18 |
| 700 | 1.038042 | 3.664784 | 2.23E+20 | 2.86E+20 | 5.05E+18 |
| 900 | 1.019457 | 1.908565 | 2.04E+20 | 2.83E+20 | 7.00E+18 |
| 1100 | 1.003759 | 0.374492 | 1.86E+20 | 2.81E+20 | 8.80E+18 |
| 1300 | 0.989999 | -1.01025 | 1.69E+20 | 2.78E+20 | 1.05E+19 |

With an increase in fuel loading by 20%, the initial reactivity margin also remained unchanged at 10.47%. Burnout of plutonium-239 and thorium-232 isotopes increased and amounted to 38.64% and 4.76%, respectively. Uranium-233 isotope production has increased by approximately 2.6%. Campaign duration increased and equals 1143 effective days.

Figure 19 shows the change in reactivity margin during the operation of a gas-cooled thorium reactor with an increased fuel load by 10% and 20% at a power of 60 MW.

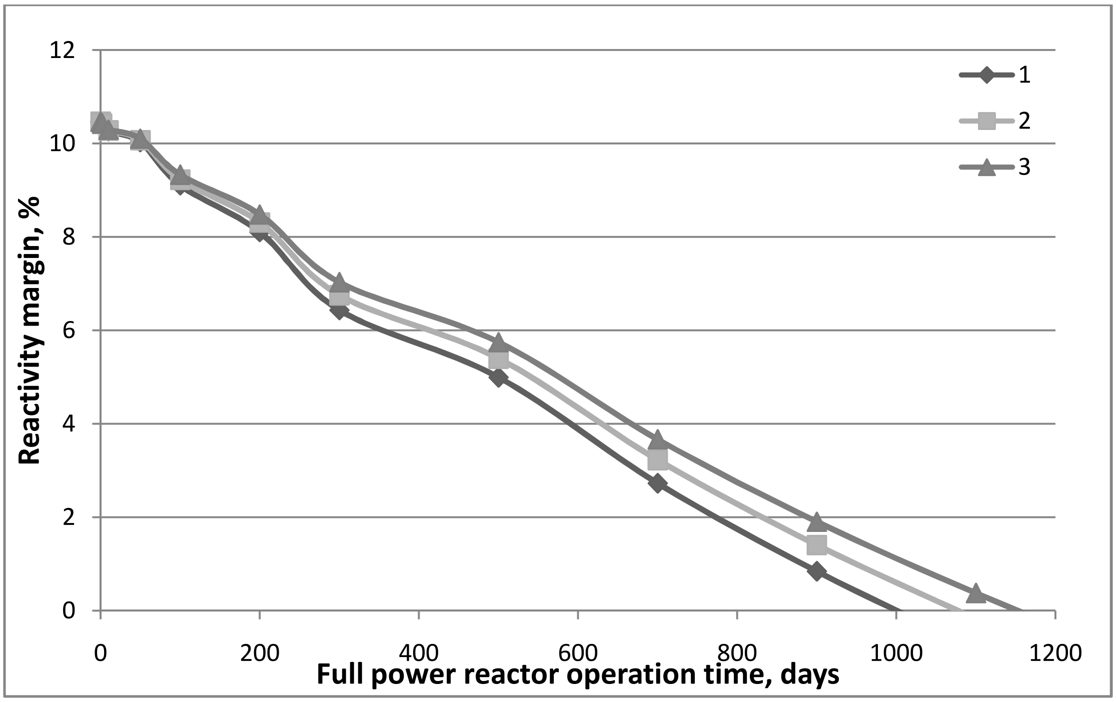


Figure 19 – Change in reactivity margin during the operation of a gas-cooled thorium reactor:

1 – basic design; 2 – increased fuel load by 10%; 3 – increased fuel load by 20%

As can be seen from Figure 19, with an increase in fuel loading by 10% and 20%, the initial reactivity margin does not change and amounts to 10.47%, and an increase in the reactor campaign duration is observed due to the lower rate of reactivity loss when the reactor is operating at power.

Figures 20-22 show changes in average values of nuclear concentrations for $^{239}Pu$, $^{233}U$ and $^{232}Th$, respectively, for each of the considered design models of fuel assemblies for a gas-cooled thorium reactor with an increased fuel load of 10% and 20%.

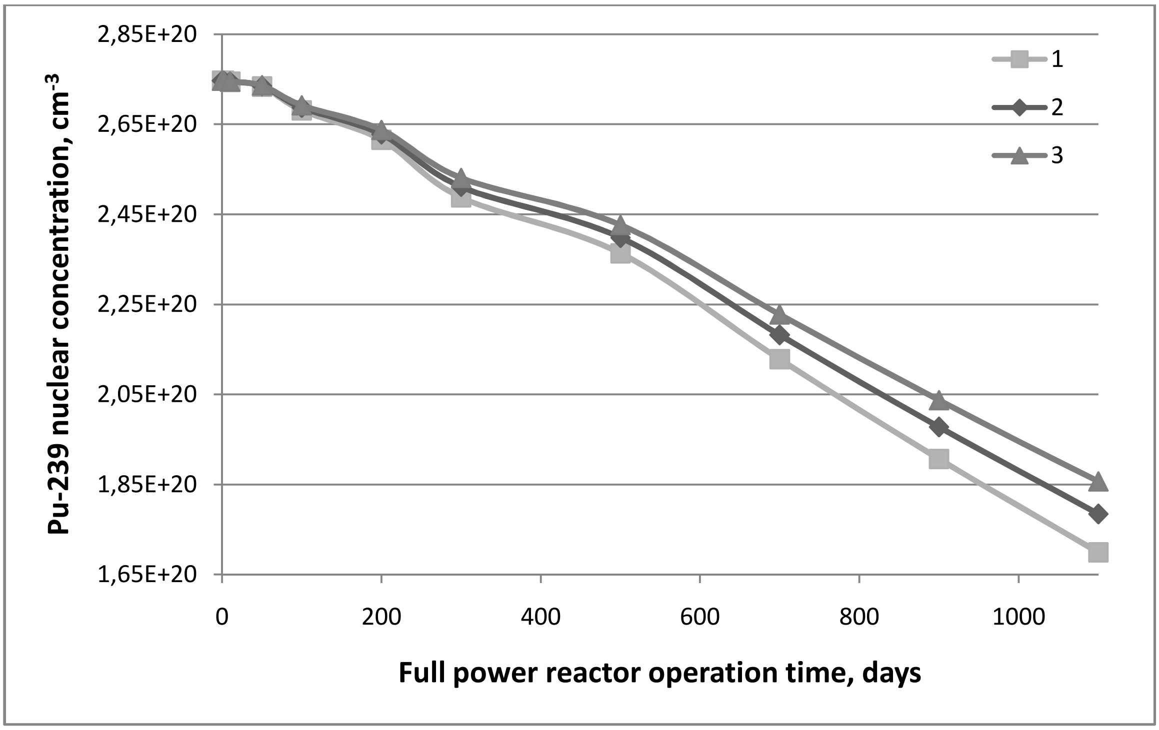


Figure 20 – Changes in Pu-239 concentration during reactor operation:
1 – basic design; 2 – increased fuel load by 10%; 3 – increased fuel load by 20%

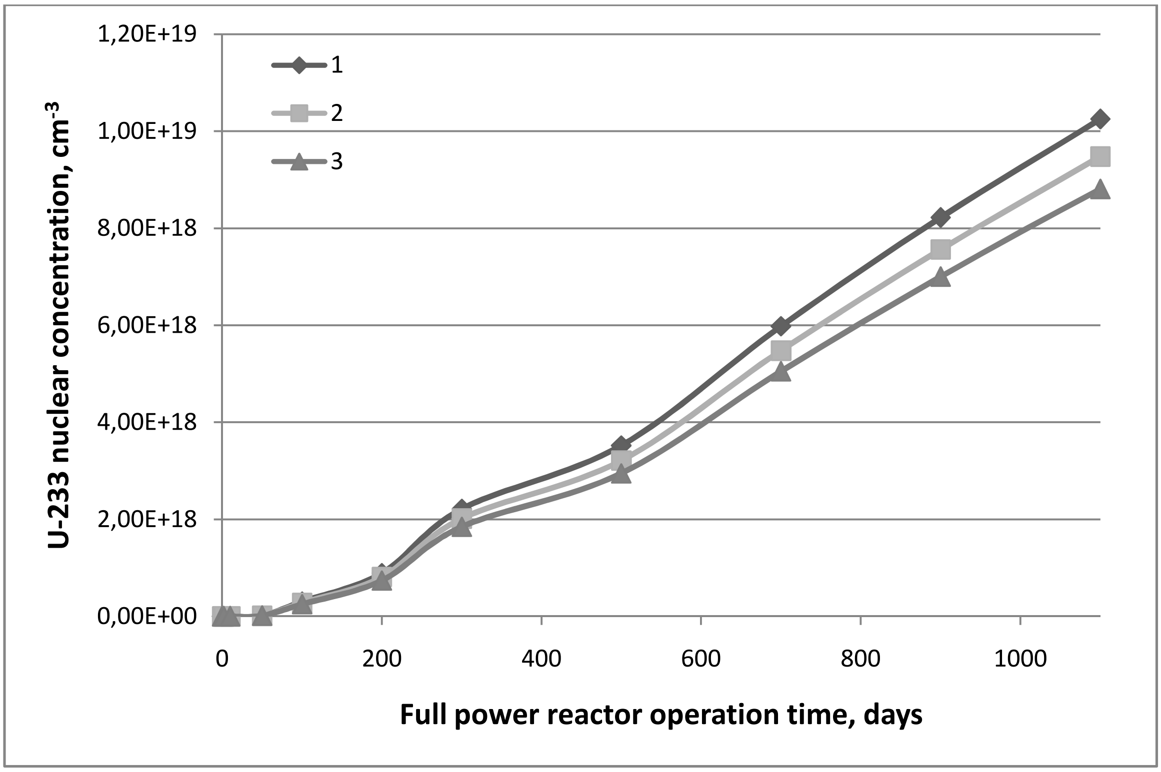


Figure 21 – Changes in U-233 concentration during reactor operation:
1 – basic design; 2 – increased fuel load by 10%; 3 – increased fuel load by 20%

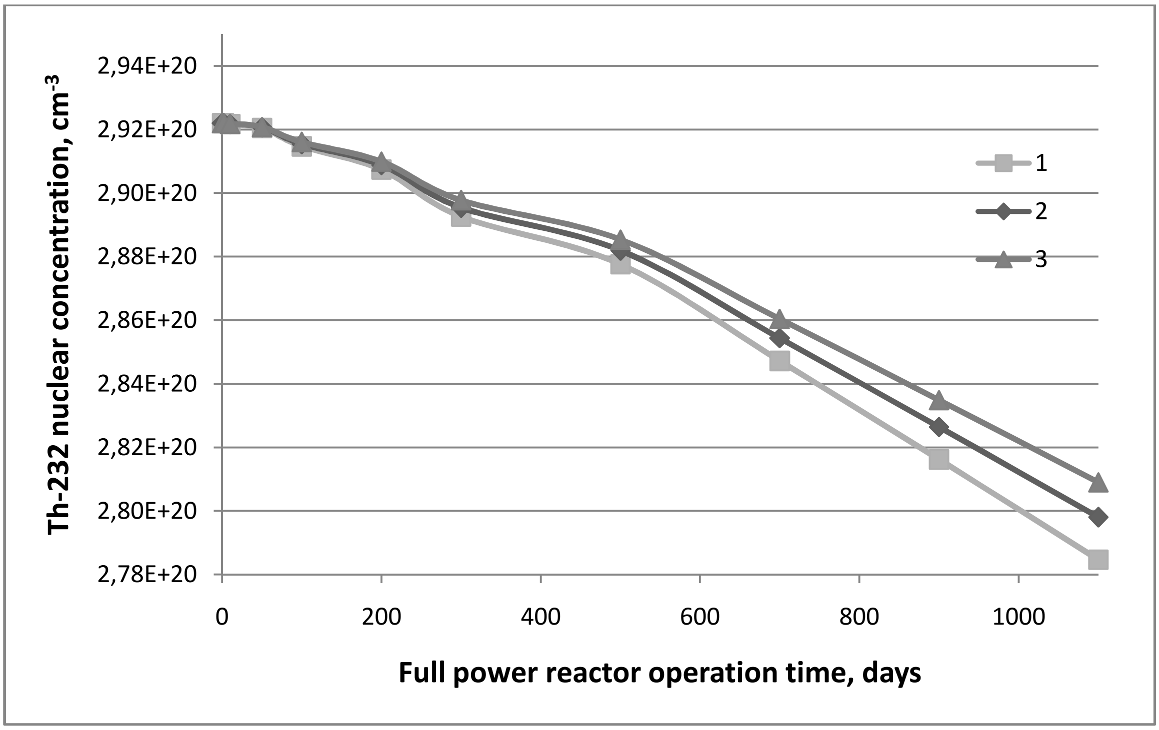


Figure 21 – Changes in Th-232 concentration during reactor operation:

1 – basic design; 2 – increased fuel load by 10%; 3 – increased fuel load by 20%

Burnout of the main heavy nuclides of the gas-cooled thorium reactor with an increase in fuel loading by 10% and 20%, and the resulting burnup depth and campaigns are presented in table 13.

Table 13 – Burnout of the main heavy nuclides, burnup depth and the campaign with an increase in fuel loading by 10% and 20%

| Nuclide | Basic model | Increased fuel load by 10% | Increased fuel load by 20% |
|---|---|---|---|
| Burnout $^{239}$Pu, % | 38.15 | 35.05 | 38.64 |
| Burnout $^{232}$Th, % | 4.69 | 4.24 | 4.76 |
| Burnup depth, GWd/t | 126.21 | 121.92 | 121.16 |
| Campaign, d. | 986 | 1051 | 1143 |

As can be seen from the obtained results, with an increased fuel load by 10% and 20%, there is a significant increase in the campaign by 65 and 157 effective days, respectively. At this time, the initial reactivity margin of the gas-cooled thorium reactor remains at 10.47%, and the rate of loss of reactivity decreases, which makes this method of increasing the load safer than previously calculated.

With an increase in fuel loading by 10%, the burnout of plutonium-239 and thorium-232 isotopes, as well as the production of uranium-233 isotopes, decreases. Burnout depth decreases too.

However, with an increase in fuel loading by 20%, the heavy nuclides Pu-239 and Th-232 burn out and the U-233 isotope production increases, and the burnup depth is less than the tenths previously obtained, which undoubtedly gives an advantage over the previous loading option.

## 3 Financial management, resource efficiency and resource saving

The purpose of this section is to design and create competitive developments and technologies that meet the requirements in the field of resource efficiency and resource saving.

Achieving the goal is provided by solving problems:

- development of a common economic project idea, formation of a project concept;
- organization of work on a research project;
- identification of possible research alternatives;
- research planning;
- assessing the commercial potential and prospects of scientific research from the standpoint of resource efficiency and resource saving;
- determination of resource (resource saving), financial, budget, social and economic efficiency of the study[17].

This master's thesis presents the optimization of a high-temperature low-power gas-cooled reactor loading with unified thorium fuel.

The developed low-temperature low-power gas-cooled nuclear reactor with unified thorium fuel is quite promising for use in remote regions of any country in the world, since it can operate for an extremely long period of time without stopping for fuel reloading. Helium was chosen as the coolant due to its good thermal, nuclear, physical, chemical and technological properties. Another feature of a nuclear installation, along with the use of helium, is the use of graphite as a moderator, reflector and the main structural material of the reactor core. The absence of metal structures in the reactor core, as well as the use of micro-fuel included in prismatic graphite fuel assemblies, allows to achieve a significantly higher temperature than at nuclear power plants with other types of reactors. Moreover, the reactor allows to solve the problem of thorium accumulated in large quantities and still not used in nuclear power, as well as with the use of weapons-grade plutonium for peaceful purposes.

Another major advantage of the reactor is its versatility. Thus, a nuclear installation can be used not only for energy, but also for desalination of water or the production of hydrogen from helium on an industrial scale. In the reactor core, helium will be heated to a high temperature, and then fed to a hydrogen production unit. In the future, the scale of hydrogen production at such a nuclear power plant will be much higher than at existing chemical plants.

## 3.1 Analysis of competitive technical solutions

In the course of this work, a high-temperature low-temperature gas-cooled reactor was considered, the competitors of which may be any nuclear power plant operating for the same purpose as the one being developed. The main ones, including those with similar technical solutions made to achieve this goal, will be an IV generation High Temperature Reactor-Pebble-bed-Module: HTR-PM ($P_{i1}$), and a Gas Turbine Modular Helium Reactor: GT-MHR ($P_{i2}$).

The evaluation analysis map is presented in table 1. The position of the development and competitors is evaluated for each indicator by an expert on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators determined by an expert in the amount should be one.

Analysis of competitive technical solutions is determined by the formula:

$$C = \sum W_i \cdot P_i, \qquad (3)$$

where $C$ – competitiveness of scientific development or competitor;

$W_i$ – weight of the indicator (in unit fraction);

$P_i$ – score of the “i” indicator.

The following parameters were chosen as technical criteria: energy efficiency, reliability, safety and functional power.

Energy efficiency is determined by the efficiency of the installation and is an important parameter.

The reliability of installations is also one of the important criteria due to the fact that a nuclear reactor is a source of electrical and thermal energy, and in the event of a breakdown, large areas can be left without heat and power supply.

Safety is the most important criterion for nuclear power plants, since a nuclear reactor is a potentially dangerous device that, in the case of emergency situations, can cause a large-scale disaster.

An equally important criterion is the functional capacity of the installation, the value of which characterizes the area of the population that the installation can provide with electric and heat energy.

Table 14 – Evaluation map for comparison of competitive technical solutions (developments)

| **Criteria for evaluation** | **Weight criterion** | **Points** | | | **Competitiveness** | | |
|---|---|---|---|---|---|---|---|
| | | $P_f$ | $P_{i1}$ | $P_{i2}$ | $C_f$ | $C_{i1}$ | $C_{i2}$ |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| **Technical criteria for evaluating resource efficiency** | | | | | | | |
| 1. Energy efficiency | 0.1 | 5 | 4 | 4 | 0.5 | 0.4 | 0.4 |
| 2. Reliability | 0.25 | 5 | 5 | 5 | 1.25 | 1.25 | 1.25 |
| 3. Safety | 0.25 | 5 | 5 | 5 | 1.25 | 1.25 | 1.25 |
| 4. Functional capacity | 0.2 | 4 | 5 | 5 | 0.8 | 1.0 | 1.0 |
| **Economic criteria for performance evaluation** | | | | | | | |
| 1. Development cost | 0.05 | 5 | 4 | 3 | 0.25 | 0.2 | 0.15 |
| 2. Market penetration rate | 0.03 | 3 | 5 | 4 | 0.09 | 0.15 | 0.12 |
| 3. Expected lifecycle | 0.1 | 5 | 4 | 4 | 0.5 | 0.4 | 0.4 |
| 4. After-sales service | 0.02 | 5 | 4 | 4 | 0.1 | 0.08 | 0.08 |
| **Total** | **1** | **37** | **36** | **34** | **4.74** | **4.73** | **4.65** |

Above is an analysis of the competitiveness of a low-temperature gas-cooled installation of low power among other developments: HTR-PM ($P_{i1}$) and

GT-MHR ($P_{i2}$). From the analysis it can be seen that the indicators of the developed NPP are very similar to those of other reactors under consideration. The indicators are fairly balanced and are not inferior to those of the other two reactors under consideration. However, in contrast to them, the developed plant assumes its use in remote regions of Russia, where it will be able to operate at low power for many years without reloading the fuel.

## 3.2 SWOT analysis

SWOT (Strengths, Weaknesses, Opportunities and Threats) is a comprehensive analysis of a research project. SWOT analysis is used to study the external and internal environment of the project[16].

Strengths are factors that characterize the competitive side of a research project. In other words, strengths are the resources or capabilities that a project management has and that can be effectively used to achieve their goals.

Weakness is the lack, omission or limitation of a research project that impedes the achievement of its goals. This is something that is bad at the project or where it has insufficient capabilities or resources compared to its competitors.

Opportunities include any present or future preferred situation arising in the project’s environmental conditions, such as a trend, change, or perceived need that supports demand for project results and allows project management to improve its competitive position.

A threat is any undesirable situation, tendency or change in the environmental conditions of a project that are destructive or threatening to its competitiveness in the present or future. The threat may be a barrier, restriction or anything else that may cause problems, destruction, damage or damage to the project.

The resulting SWOT analysis is presented in table 15.

Table 15 – SWOT analysis of the reactor.

| | | |
|---|---|---|
| | **Strengths:**<br>S1. Increased plant safety compared to conventional water cooled reactors.<br>S2. High thermal efficiency.<br>S3. The possibility of using thorium and weapons-grade plutonium as a fuel.<br>S4. Realization of hydrogen production. | **Weaknesses:**<br>W1. Low power due to the low heat capacity of the coolant and low energy density of the reactor core.<br>W2. In case of reactor depressurization, helium will be replaced by heavier air.<br>W3. The inability to reprocess spent fuel.<br>W4. Requires shutdown of the reactor for refueling. |
| **Opportunities:**<br>O1. Reducing the cost of electricity.<br>O2. Providing additional jobs.<br>O3. Use of installation in distant regions with less power consumption.<br>O4. Further development of nuclear power plants to improve its performance. | 1. Reducing energy costs due to the deep burning and super-long campaign of fuel.<br>2. The possibility of developing nuclear power plants to an even higher level and achieving greater safety of the installation.<br>3. The use of nuclear materials stored in storage and not used in nuclear power. | 1. No need for high power in distant regions.<br>2. Qualified specialists can contribute to the improvement of the quality of work of a nuclear power plant and its safety. |
| **Threats:**<br>T1. Natural disasters.<br>T2. Sabotage and terrorist actions against nuclear power plants.<br>T3. Rejection of the project by the state.<br>T4. Accident at a nuclear facility. | 1. The body type reactor serves as a protective sheath to prevent the release of radioactive substances in an accident.<br>2. The possibility of burning large quantities of weapons-grade plutonium, which will no longer pose a nuclear hazard. | 1. The occurrence of an accident will reduce the interest in projects of this kind, therefore, special attention should be paid to minimizing this risk.<br>2. The use of weapons-grade plutonium entails the involvement of actions of a terrorist and sabotage nature, therefore it is necessary to strengthen the system of physical protection of nuclear materials and facilities. |

## 3.3 Project Initiation

The initiation process group consists of processes that are performed to define a new project or a new phase of an existing one. Within the framework of initiation processes, initial goals and content are determined and initial financial resources are recorded. The internal and external stakeholders of the project who will interact and influence the overall result of the research project are determined.

Stakeholders of a project are persons or organizations that are actively involved in a project or whose interests may be affected both positively and negatively during the execution or as a result of the completion of the project. These can be customers, sponsors, the public, etc. Information on project stakeholders is presented in table 16.

Table 16 – Stakeholders of the project

| Stakeholders of the project | Stakeholder expectations |
|---|---|
| State Atomic Energy Corporation 'Rosatom' | Development of technology on the basis of which it is possible to create high-temperature gas-cooled low-power thorium reactor plants with a super-long campaign. |

Table 17 provides information on the hierarchy of project goals and criteria for achieving goals.

Table 17 – Goals and results of the project

| | |
|---|---|
| **Project goals:** | Optimization of gas-cooled reactor loading with unified thorium fuel; study of the change in the duration of the campaign with increasing fuel load to obtain the highest possible energy yield. |
| **Expected results of the project:** | The methods of fuel loading considered in the study will lead to a more efficient energy generation and an increase in the campaign, so that the reactor will be able to work for a longer time without overloading. |
| **Criteria for acceptance of the project result:** | The result of optimizing the loading of a gas-cooled reactor was any increase in the fuel campaign. |
| **Requirements for the project result:** | **Requirement:** |
| | Identify possible ways to optimize fuel loading. |
| | Examine each of the ways to change the duration of the campaign. |
| | Evaluation of the results and comparison of their effectiveness. |

### 3.4 The organizational structure of the project

At this stage of work it is necessary to solve the following questions: who will be part of the working group of this project, determine the role of each participant in this project, and also prescribe the functions performed by each of the participants and their number of personnel hours in the project.

This information is presented in table 18.

Table 18 – Project Working Group

| № | Full name, primary employment, position | Role in the project | Functions | Number of personnel hours, h |
|---|---|---|---|---|
| 1 | Chertkov Yurii Borisovich, TPU, senior lecturer | Project leader | Expert consulting | 30 |
| 2 | Selevich Sergei Viktorovich, TPU, engineer | Contractor for the project | Calculation | 570 |

### 3.5 Limitations and assumptions of the project

Project limitations are all factors that can serve as a restriction on the degree of freedom of the project team members, as well as "project boundaries" – the parameters of the project or its product that will not be implemented under this project.

Project limitations are shown in table 19.

Table 19 – Project limitations

| Factor | Limitations / Assumptions |
|---|---|
| 3.1 Project budget | 193641.77 |
| 3.1.1 Source of financing | TPU |
| 3.2 Design period: | 1.02.2019 – 31.05.2019 |
| 3.2.1 Date of approval of the project management plan | 1.02.2019 |
| 3.2.2 Completion date | 31.05.2019 |

## 3.6 Planning of research project

### 3.6.1 Project plan

As part of planning a science project, you need to build a project timeline and a Gantt Chart.

The line graph is presented in the form of table 20.

Table 20 – The project schedule

| Activity code | Description | Duration, active days | Start date | Completion date | List of participants |
|---|---|---|---|---|---|
| Development of technical specifications | | | | | |
| 1 | Drafting and approval of technical specifications | 2 | 01.02.19 | 3.02.19 | Chertkov Y.B. |
| The choice of research directions | | | | | |
| 2 | Selection and study of materials on the topic | 4 | 4.02.19 | 8.02.19 | Chertkov Y.B., Selevich S.V. |
| 3 | Scheduling work on the topic | 2 | 8.02.19 | 10.02.19 | Chertkov Y.B. |
| Theoretical and experimental studies | | | | | |
| 4 | Study of the design features of the reactor under consideration | 11 | 11.02.19 | 22.02.19 | Selevich S.V. |
| 5 | Examination of software required for calculations | 12 | 25.02.19 | 10.03.19 | Selevich S.V. |
| 6 | Development of the calculated model of the reactor under investigation | 16 | 11.03.19 | 28.03.19 | Selevich S.V. |
| 7 | Performing calculations | 20 | 29.03.19 | 21.04.19 | Selevich S.V. |
| Summary and evaluation of results | | | | | |
| 8 | Evaluation of the effectiveness of the results | 2 | 22.04.19 | 23.04.19 | Chertkov Y.B., Selevich S.V. |
| Presentation of a master's thesis. | | | | | |
| 9 | Drafting an explanatory note | 25 | 24.04.19 | 26.05.19 | Selevich S.V. |
| 10 | Checking the work performed on compliance with all state standards | 5 | 27.05.19 | 31.05.19 | Chertkov Y.B., Selevich S.V. |
| **Total:** | | 99 | | | |

Gantt Chart is a type of bar charts (histograms), which is used to illustrate the project schedule, where the work on the topic is represented by lengthy segments, characterized by the dates of the beginning and end of these works.

The calendar schedule in the form of a Gantt Chart is presented in table 21.

Table 21 – The calendar schedule

| № | Description | Participants | $T_c$, days net | The duration of the workx | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | February | | | March | | | April | | | May | | |
| | | | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | Drafting and approval of technical specifications | Project leader | 2 | | | | | | | | | | | | |
| 2 | Selection and study of materials on the topic | Project leader, engineer | 4 | | | | | | | | | | | | |
| 3 | Scheduling work on the topic | Project leader | 2 | | | | | | | | | | | | |
| 4 | Study of the design features of the reactor under consideration | Engineer | 11 | | | | | | | | | | | | |
| 5 | Examination of software required for calculations | Engineer | 12 | | | | | | | | | | | | |
| 6 | Development of the calculated model of the reactor under investigation | Engineer | 16 | | | | | | | | | | | | |
| 7 | Performing calculations | Engineer | 20 | | | | | | | | | | | | |
| 8 | Evaluation of the effectiveness of the results | Project leader, engineer | 2 | | | | | | | | | | | | |
| 9 | Drafting an explanatory note | Engineer | 25 | | | | | | | | | | | | |
| 10 | Checking the work performed on compliance with all state standards | Project leader, engineer | 5 | | | | | | | | | | | | |

– Project leader; – Engineer

### 3.6.2 Research budget

When planning a research budget, a full and reliable reflection of all types of expenses related to its implementation should be provided.

In the process of budgeting a scientific study, the following grouping of expenditures by items is used:

- material costs;
- the cost of special equipment for scientific (experimental) work;
- the base salary of the performers of the topic;
- additional salary of the performers of the topic;
- deductions to extra-budgetary funds (insurance deductions);
- the cost of scientific and industrial travel;
- counterparty expenses;
- overhead.

#### 3.6.2.1 Calculation of material costs

The calculation of material costs is carried out according to the following formula:

$$C_m = (1 + k_T) \cdot \sum_{i=1}^{m} P_i \cdot N_{consi}, \quad (4)$$

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 and procurement costs.

Values of prices for material resources can be set according to data posted on relevant websites on the Internet by manufacturers (or supplier organizations)[19].

The main work for the master's thesis was carried out at a personal computer. The time spent working at the computer, we assume equal to 500 hours. Power is 0.4 kW.

Energy costs are calculated by the formula:

$$C = P_{el} \cdot P \cdot F_{eq}, \tag{5}$$

$$C = 5.8 \cdot 0.5 \cdot 400 = 1160 \text{ rubles}$$

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

$P$ − horsepower of equipment, kW;

$F_{eq}$ − equipment usage time, hours.

Material costs required for this development are presented in table 22.

Table 22 – Material costs

| **Name** | **Unit** | **Amount** | **Price per unit, rub.** | **Material costs, ($C_m$), rub.** |
|---|---|---|---|---|
| 1. Internet access | month | 4 | 250 | 1000.00 |
| 2. Electricity power | kWh | 400 | 5.8 | 1160.00 |
| **Total** | | | | 2160.00 |

#### 3.6.2.2 Base salary

This article includes the base salary of workers directly involved in the implementation of work on this topic. The amount of salary costs is determined on the basis of the labor intensity of the work performed and the current salary system.

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

$$W_{base} = W_d \cdot T_w, \tag{6}$$

where $W_{base}$ – base salary per employee, rubles;

$T_w$ – the duration of the work performed by the research engineer, active days;

$W_d$ – average daily salary, rubles.

The average daily salary is calculated by the formula:

$$W_d = \frac{S_{month} \cdot M}{F_r}, \quad (7)$$

where $S_{month}$ – official monthly salary, rubles;

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

- at holiday in 48 active days, $M$ = 10.4 months for 6-day week;

$F_r$ – the valid annual fund of working time of scientific and technical personnel.

The valid annual fund of working time of scientific and technical personnel is presented in table 23.

Table 23 – The valid annual fund of working time

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

Official monthly salary is calculated by formula:

$$S_{month} = S_{base} \cdot (k_{premium} + k_{bonus}) \cdot k_{reg}, \quad (8)$$

where $S_{base}$ – base salary, rubles;

$k_{premium}$ – premium rate;

$k_{bonus}$ – bonus rate;

$k_{reg}$ – regional premium rate.

The calculation of the base salaries is given in table 24.

Table 24 – Calculation of the base salaries

<table>
<tr><th>Performers</th><th>$S_{base}$, rubles</th><th>$k_{premium}$</th><th>$k_{bonus}$</th><th>$k_{reg}$</th><th>$S_{month}$, rubles</th><th>$W_d$, rubles</th><th>$T_p$, active days</th><th>$W_{base}$, rubles</th></tr>
<tr><td>Project leader</td><td>33664.00</td><td rowspan="2">0.3</td><td rowspan="2">0.2</td><td rowspan="2">1.3</td><td>65644.80</td><td>2719.94</td><td>5</td><td>13599.72</td></tr>
<tr><td>Engineer</td><td>12664.00</td><td>24694.80</td><td>1023.21</td><td>95</td><td>97205.03</td></tr>
</table>

#### 3.6.2.3 Additional salary

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

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

$$W_{add} = k_{extra} \cdot W_{base}, \quad (9)$$

where $W_{add}$ – additional salary, rubles;

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

$W_{base}$ – base salary, rubles.

The calculation of additional salaries is given in table 25.

Table 25 – Calculation of additional salaries

| **Salary** | **Project leader** | **Engineer** |
|---|---|---|
| Base salary, rubles | 13599.72 | 97205.03 |
| Additional salary, rubles | 1359.97 | 9720.50 |
| Salary, rubles | 14959.69 | 106925.53 |
| Total, rubles | 121885.22 | |

#### 3.6.2.4 Labor tax

The labor tax 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.

The amount of labor tax is determined on the basis of the following formula:

$$P_{social} = k_b \cdot (W_{base} + W_{add}) \quad (10)$$

where $k_b$ – coefficient of labor tax (Pension Fund, Federal Compulsory Medical Insurance Fund, etc.).

In accordance with the Federal Law of July 24, 2009 No. 212-FL, the amount of insurance contributions is set at 30%. On the basis of clause 1 of article 58 of Law No. 212-FL, a reduced rate is established for institutions conducting educational and scientific activities – 27.1%.

The labor tax calculations are presented in table 26.

Table 26 – Labor tax calculation

| | **Project leader** | **Engineer** |
|---|---|---|
| Coefficient of labor tax | 0.271 | |
| Salary, rubles | 14959.69 | 106925.53 |
| Labor tax, rubles | 4054.08 | 28976.82 |

#### 3.6.2.5 Overhead

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

Overhead costs account for 30% of the amount of base and additional salaries of employees.

Overhead is calculated according to the following formula:

$$C_{ov} = k_{ov} \cdot (W_{base} + W_{add}) \quad (11)$$

where $k_{ov}$ – overhead rate.

Overhead costs are presented in table 27.

Table 27 – Overhead

| | Project leader | Engineer |
|---|---|---|
| Overhead rate | 0.3 | |
| Salary, rubles | 14959.69 | 106925.53 |
| Overhead, rubles | 4487.91 | 32077.66 |

### 3.6.2.6 Formation of budget costs

The calculated cost of research is the basis for budgeting project costs.

Determining the budget for the cost of scientific research for each version is given in table 28.

Table 28 – Items expenses grouping

| Name | Cost, rubles |
|---|---|
| 1. Material costs | 2160.00 |
| 2. Basic salary | 110804.75 |
| 3. Additional salary | 11080.47 |
| 4. Labor tax | 33030.89 |
| 5. Overhead | 36565.66 |
| **Total planned cost** | **193641.77** |

## 3.7 Project risk register

The identified risks of the project include possible uncertain events that may occur in the project and cause consequences that will entail undesirable effects. Information about this is recorded in the so-called project risk register.

The project risk register is presented in table 29.

Table 29 – Risk Register

| № | Risk | Potential impact | Chance of occurrence (1-5) | Risk impact (1-5) | Risk level | Methods for risk reduction | Trigger event |
|---|---|---|---|---|---|---|---|
| 1 | Theft of technology | Loss of competitive advantage | 1 | 3 | low | The timely receipt of patents, the development of regulations on trade secrets | High competition from Russian and foreign manufacturer s |

Continuation of table 29

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2 | Program failure | The cost of additional time for recalculatio n and verification of results | 1 | 5 | average | Avoid unnecessary system load during calculations | Calculation results are missing or incorrect |
| 3 | Data loss | Inability to continue working | 1 | 5 | low | Storing the results in several copies | Complete loss of accumulated calculation data |

### 3.8 Evaluation of the comparative effectiveness of the research

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

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of the technical problem is taken as the calculation base (as the denominator), with which the financial values for all the options are correlated[11].

The integral financial measure of development is defined as:

$$I_f^d = \frac{C_i}{C_{\max}}, \quad (12)$$

where $I_f^d$ – integral financial measure of development;

$C_i$ – the cost of the i-th version;

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

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

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

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

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a \ , \ I_m^p = \sum_{i=1}^{n} a_i b_i^p \qquad (13)$$

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

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

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

$n$ – number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in the form of table 30.

Table 30 – Evaluation of the performance of the project

| **Criteria** | **Weight criterion** | **Points** |
|---|---|---|
| 1. Energy efficiency | 0.1 | 5 |
| 2. Reliability | 0.25 | 5 |
| 3. Safety | 0.25 | 5 |
| 4. Functional capacity | 0.2 | 4 |
| **Economic criteria for performance evaluation** | | |
| 1. The cost of development | 0.05 | 5 |
| 2. Market penetration rate | 0.03 | 3 |
| 3. Expected life | 0.1 | 5 |
| 4. After-sales service | 0.02 | 5 |
| **Total** | 1 | 37 |

$I_m = 5 \cdot 0.1 + 5 \cdot 0.25 + 5 \cdot 0.25 + 4 \cdot 0.20 + 5 \cdot 0.05 + 3 \cdot 0.03 + 5 \cdot 0.10 + 5 \cdot 0.02 = 4.74$

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

$$I_e^p = \frac{I_m^p}{I_d^f}, I_e^a = \frac{I_m^a}{I_f^a} \text{ and etc.} \quad (14)$$

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

$$E_c = \frac{I_e^p}{I_e^a}. \quad (15)$$

Thus, the effectiveness of the development is presented in table 31.

Table 31 – Efficiency of development

| № | Indicators | Points |
|---|---|---|
| 1 | Integral financial measure of development | 1 |
| 2 | Integral indicator of resource efficiency of development | 4.74 |
| 3 | Integral indicator of the development efficiency | 4.74 |

Comparison of the values of integral performance indicators allows us to understand and choose a more effective solution to the technical problem from the standpoint of financial and resource efficiency. But since the task has rather strict conditions, the solution has only one option.

# 4 Social responsibility

Nowadays one of the main ways to radical improvement of all prophylactic work referred to reduce Total Incidents Rate and occupational morbidity is the widespread implementation of an integrated Occupational Safety and Health management system. That means combining isolated activities into a single system of targeted actions at all levels and stages of the production process.

Occupational safety is a system of legislative, socio-economic, organizational, technological, hygienic and therapeutic and prophylactic measures and tools that ensure the safety, preservation of health and human performance in the work process [6].

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

A dangerous factor or industrial hazard is a factor whose impact under certain conditions leads to trauma or other sudden, severe deterioration of health of the worker [6].

A harmful factor or industrial health hazard is a factor, the effect of which on a worker under certain conditions leads to a disease or a decrease in working capacity.

## 4.1 Analysis of hazardous and harmful factors

The working conditions in the workplace are characterized by the presence of hazardous and harmful factors, which are classified by groups of elements: physical, chemical, biological, psychophysiological.

The main elements of the production process that form dangerous and harmful factors are presented in table 32.

Table 32 – The main elements of the production process, forming hazardous and harmful factors

| Name of the types of work and the parameters of the working process | FACTORS GOST 12.0.003-74 Occupational safety standards system | | Normative documentation |
|---|---|---|---|
| | Harmful | Dangerous | |
| Work on PC, Division for Nuclear-Fuel Cycle | The impact of radiation (HF, UHF, SHF, etc.) | – | SanPiN 2.2.2 / 2.4.1340-03 Sanitary-epidemiological rules and regulations. "Hygienic requirements for personal computers and organization of work" |
| | – | Electricity | GOST 12.1.038-82 Occupational safety standards system.electrical safety |
| | – | Fire | Fire and explosion safety of industrial installations GOST R12.1.004-85 SSBT |

The following factors effect on person working on a computer:

- physical:
  - temperature and humidity;
  - noise;
  - static electricity;
  - electromagnetic field of low purity;
  - illumination;
  - presence of radiation;
- psycho physiological dangerous and harmful factors are divided into:

- physical overload (static, dynamic);
- mental stress (mental overstrain, monotony of work, emotional overload).

The master thesis was written for a personal computer, using the WIMS-5B program for calculations.

The masters working on a computer are affected by the following factors: temperature, noise, low-purity electromagnetic field, light intensity, mental overvoltage, and work monotony.

The layout of the workplace is made with the foreseeing of these impacts. Organized debugging of ventilation and air conditioning. The heating system provides constant and uniform heating of the air. The noise level on the PC at the workplace does not exceed 50 dB. What is required for work is located in the zone of easy reach of the working space.

The height of the working surface of the table is 750 mm. The height of the working surface with the keyboard is 650 mm. The width of the table is 710 mm and the length is 1450 mm. The legroom has a height of 620 mm, a width of 700 mm, a depth at the level of the knees of 550 mm and at the level of the elongated legs of 710 mm.

The work chair is liftable and adjustable in height and angle of inclination of the seat and backrest, as well as the distance of the backrest to the front edge of the seat. Seat height above floor level is 470 mm. The design of the working chair provides a width and depth of the seat surface of 400 mm.

The monitor is located at a distance of 600 mm from the user. The keyboard is located on the table surface at a distance of 100 mm from the edge with a tilt angle to the horizontal plane of 15º. The keys have a concave surface, quadrangular in shape with rounded corners. Since the keyboard is mechanical, the key design provides the operator with a click sensation. The key color is black with white symbols.

## 4.2 Justification and development of measures to reduce the levels of hazardous and harmful effects, and eliminate their influence

### 4.2.1 Organizational arrangements

All personnel are required to know and strictly observe the safety rules. The training of personnel in occupational safety and industrial sanitation consists of introductory briefing and briefing at the workplace by the responsible person.

The qualification commission or by the person responsible for the workplace check the knowledge of safety rules after training at the workplace. After that, commission assign the safety qualification group corresponding to the employee's knowledge and experience of work and issue a special certificate.

Persons serving electrical installations must not have injuries and illnesses that interfere with manufacturing activity. The state of health is established by medical examination before being employed.

### 4.2.2 Technical Activities

The rational layout of the workplace provides for a clear order and permanent placement of objects, means of labor and documentation. Object, what is required to perform the work more often, should be located in the easy reach of the workspace, as shown in fig. 23.

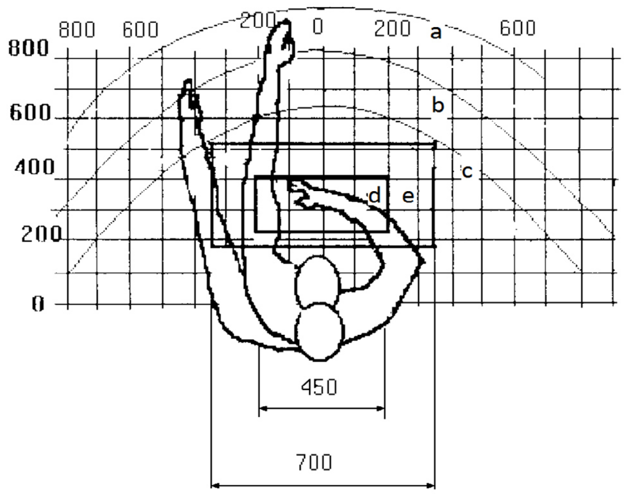


Figure 23 – Hand reach zones in the horizontal plane:
a – zone of maximum reach of hands; b – reach zone of fingers with outstretched arm; c – easy reach zone of the palm; d – Optimum space for fine handmade work; e – the optimum space for rough manual work

Optimal placement of objects of labor and documentation in the reach of hands:

- the display is located in zone a (in the center);
- the keyboard is located in the area of e / d;
- the system unit is located in zone b (on the left);
- the printer is in zone a (right).

The documentation is placed in the easy reach of the palm - in (left) - literature and documentation necessary for work; in the drawers of the table - literature that is not used constantly.

When designing a desk, the following requirements must be taken into account.

The height of the working surface of the table should be within 680-800 mm. The height of the working surface with the keyboard should be 650 mm. The working table must be at least 700 mm wide and at least 1400 mm long. There should be a legroom of not less than 600 mm in height, a width of at least 500 mm, a depth at the knee level of at least 450 mm and at the level of elongated legs – not less than 650 mm.

The work chair must be liftable and adjustable in height and angle of inclination of the seat and backrest, as well as the distance of the backrest to the front edge of the seat. It is recommended that the height of the seat be above the floor level of 420 to 550 mm. The design of the working chair should ensure: the width and depth of the seat surface is not less than 400 mm; Seat surface with recessed front edge.

The monitor should be located at the eye level of the operator at a distance of 500 – 600 mm. According to the norms, the viewing angle in the horizontal plane should be no more than 45º to the normal of the screen. It is better if the viewing angle is 30º. In addition, it should be possible to select the level of contrast and brightness of the image on the screen.

It should be possible to adjust the screen:

- height +3 cm;
- slope from 10 to 20 degrees with respect to the vertical;
- in the left and right directions.

The keyboard should be placed on the surface of the table at a distance of 100 - 300 mm from the edge. The normal position of the keyboard is at the elbow level of the operator with an angle of inclination to the horizontal plane of 15º. It is more convenient to work with keys that have a concave surface, a quadrangular shape with rounded corners. The key design should provide the operator with a click sensation. The color of the keys should contrast with the color of the panel.

It is recommended to choose soft, low-contrast floral shades that do not disperse attention (low-saturated shades of cold green or blue colors) in the case of monotonous mental work requiring considerable nervous tension and great concentration. Shades of warm tones are recommended at work, which requires intense mental or physical tension, due to excitation of human activity.

### 4.3 Safe work conditions

The main parameters characterizing the working conditions are microclimate, noise, vibration, electromagnetic field, radiation, illumination.

The air of the working area (microclimate) is determined by the following parameters: temperature, relative humidity, air speed. The optimum and permissible values of the microclimate characteristics are established in accordance with [22] and are given in table 33.

Table 33 - Optimal and permissible parameters of the microclimate

| Period of the year | Temperature, °C | Relative humidity, % | Speed of air movement, m/s |
|---|---|---|---|
| Cold and changing of seasons | 23-25 | 40-60 | 0.1 |
| Warm | 23-25 | 40 | 0.1 |

The measures for improving the air environment in the production room include: the correct organization of ventilation and air conditioning, heating of room. Ventilation can be realized naturally and mechanically. In the room, the following volumes of outside air must be delivered:

- at least 30 $m^3$ per hour per person for the volume of the room up to 20 $m^3$ per person;
- natural ventilation is allowed for the volume of the room more than 40 $m^3$ per person and if there is no emission of harmful substances.

The heating system must provide sufficient, constant and uniform heating of the air. Water heating should be used in rooms with increased requirements for clean air.

The parameters of the microclimate in the laboratory regulated by the central heating system, have the following values: humidity 40%, air speed 0.1 m/s, summer temperature 20-25 °C, in winter 13-15 °C. Natural ventilation is provided in the laboratory. Air enters and leaves through the cracks, windows, doors. The main disadvantage of such ventilation is that the fresh air enters the room without preliminary cleaning and heating.

Noise and vibration worsen working conditions, have a harmful effect on the human body, namely, the organs of hearing and the whole body through the central nervous system. It result in weakened attention, deteriorated memory, decreased response, and increased number of errors in work. Noise can be generated by operating equipment, air conditioning units, daylight illuminating devices, as well as spread from the outside. When working on a PC, the noise level in the workplace should not exceed 50 dB.

The screen and system blocks produce electromagnetic radiation. Its main part comes from the system unit and the video cable. According to [22], the intensity of the electromagnetic field at a distance of 50 cm around the screen along the electrical component should be no more than:

- in the frequency range 5 Hz - 2 kHz: 25 V/m;
- in the frequency range 2 kHz - 400 kHz: 2.5 V/m.

The magnetic flux density should be no more than:

- in the frequency range 5 Hz - 2 kHz: 250 nT;
- in the frequency range 2 kHz - 400 kHz: 25 nT.

There are the following ways to protect against EMF:

- increase the distance from the source (the screen should be at least 50 cm from the user);
- the use of pre-screen filters, special screens and other personal protective equipment.

When working with a computer, the ionizing radiation source is a display. Under the influence of ionizing radiation in the body, there may be a violation of normal blood coagulability, an increase in the fragility of blood vessels, a decrease in immunity, etc. The dose of irradiation at a distance of 20 cm to the display is 50 μrem/hr. According to the norms [22], the design of the computer should provide the power of the exposure dose of x-rays at any point at a distance of 0.05 m from the screen no more than 100 μR/h.

Fatigue of the organs of vision can be associated with both insufficient illumination and excessive illumination, as well as with the wrong direction of light.

### 4.4 Electrical safety

Depending on the conditions in the room, the risk of electric shock to a person increases or decreases. Do not operate the electronic device 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 metal components connected to the ground and the metal casing of electrical equipment. The operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

- with direct contact with current-carrying parts during computer repair;
- when touched by non-live parts that are under voltage (in case of violation of insulation of current-carrying parts of the computer);
- when touched with the floor, walls that are under voltage;
- short-circuited in high-voltage units: power supply and display unit.
- Measures to ensure the electrical safety of electrical installations:
- disconnection of voltage from live parts, on which or near to which work will be carried out, and taking measures to ensure the impossibility of applying voltage to the workplace;
- posting of posters indicating the place of work;
- electrical grounding of the housings of all installations through a neutral wire;
- coating of metal surfaces of tools with reliable insulation;

- inaccessibility of current-carrying parts of equipment (the conclusion in the case of electroporating elements, the conclusion in the body of current-carrying parts) [9].

### 4.5 Fire and explosive safety

According to [7], depending on the characteristics of the substances used in the production and their quantity, for fire and explosion hazard, the premises are divided into categories A, B, C, D, E.

The room belongs to category B according to the degree of fire and explosion hazard. It is necessary to provide a number of preventive measures.

Possible causes of fire:

- malfunction of current-carrying parts of installations;
- work with open electrical equipment;
- short circuits in the power supply;
- non-compliance with fire safety regulations;
- presence of combustible components: documents, doors, tables, cable insulation, etc.

Activities on fire prevention are divided into: organizational, technical, operational and regime.

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

The technical measures include: compliance with fire regulations, norms for the design of buildings, the installation of electrical wires and equipment, heating, ventilation, lighting, the correct placement of equipment.

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

- elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);
- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials;
- the correct operation of the equipment (proper inclusion of equipment in the electrical supply network, monitoring of heating equipment);
- correct maintenance of buildings and territories (exclusion of the source of ignition - prevention of spontaneous combustion of substances, restriction of fireworks);
- training of production personnel in fire safety rules;
- the publication of instructions, posters, the existence of an evacuation plan;
- compliance with fire regulations, norms in the design of buildings, in the organization of electrical wires and equipment, heating, ventilation, lighting;
- the correct placement of equipment;
- well-time preventive inspection, repair and testing of equipment.
- In the case of an emergency, it is necessary to:
- inform the management (duty officer);
- call the Emergency Service or the Ministry of Emergency Situations - tel. 112;
- take measures to eliminate the accident in accordance with the instructions.

## 4.6 Workplace health and safety compliance

In order to make sure that the workplace complies with sanitary-epidemiological rules and regulations, it is necessary to compare its characteristics with existing standards. This comparison is shown in table 34.

Table 34 – Comparison of conditions with standards

| | Working conditions | Requirements |
|---|---|---|
| The height of the working surface of table | 750 mm | from 680 to 800 mm |
| The height of the working surface with keyboard | 650 mm | 650 mm |
| The width of the table | 710 mm | > 700 mm |
| The length of the table | 1450 mm | > 1400 mm |
| The height of legroom | 620 mm | > 600 mm |
| The width of legroom | 700 mm | > 500 mm |
| A depth at the knee level | 550 mm | > 450 mm |
| The level of elongated legs | 710 mm | > 650 mm |
| The height of the seat above the floor level | 470 mm | from 420 to 550 mm |
| The width of the seat surface | 400 mm | > 400 mm |
| The distance from the eye level to the monitor | 600 mm | from 500 to 600 mm |
| The distance from the edge of the table to the keyboard | 100 mm | from 100 to 300 mm |
| Temperature | 23 $^{o}$C | from 23 to 25 $^{o}$C |
| Noise level | ≈ 35 dB | < 50 dB |

As can be seen from table 34, all conditions are met and the workplace fully complies with sanitary-epidemiological rules and regulations.

# Conclusion

As a result of this master's thesis, a design model of a fuel assembly of a gas-cooled reactor with unified thorium fuel was created.

The initial reactivity margin of the reactor with the considered fuel assembly base composition is 10.47%. The burnup depth is 126.21 GWd/t. The campaign duration is 986 effective days.

Adding 6, 12 and 18 fuel channels to the basic design, the initial reactivity decreases by 3.45%, 5.73% and 7.24%, and it is equal to 10.11%, 9.87% and 9.71%, respectively. This increases the duration of the campaign for 1, 9 and 38 days and it is equal to 987, 995 and 1024 effective days, respectively, due to the lower rate of loss of reactivity. The burnup depth decreases to 118.32, 112.44 and 108.54 GWd/t.

With an increased fuel load of 10% and 20%, there is an increase in the campaign for 65 and 157 days and it is equal to 1051 and 1143 effective days, respectively, by reducing the rate of loss of reactivity. In addition, the initial reactivity margin of a gas-cooled thorium reactor remains at 10.47%, which makes this option of reactor loading the safest from the point of view of reactor control.

With an increase in fuel loading by 10%, the production of secondary fissile nuclides and burnout of Pu-239 and Th-232 isotopes decreases. The burnup depth decreases to a value of 121.92 GWd/t.

With an increase in fuel loading by 20%, the production of secondary fissile nuclides increases by 2.6% and the burnout of Pu-239 and Th-232 isotopes increases. The burnout depth is 121.16 GWd/t.

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