TOMSK POLYTECHNIC UNIVERSITY
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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

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

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
Исследование способа переработки отработанных ионообменных смол ядерного реактора путем пиролиза в электромагнитных полях диапазона СВЧ

УДК 661.183.12.092-977:621.039.73

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Томск – 2023 г.

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

MASTER THESIS

Topic of research work
Study of the method of reprocessing spent nuclear reactor ion-exchange resins by pyrolysis in the electromagnetic fields of the microwave range

UDC 661.183.12.092-977:621.039.73

Student

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Section “Social Responsibility”

Position	Full name	Academic degree, academic rank	Signature	Date
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ADMITTED TO DEFENSE:

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Tomsk – 2023

LEARNING OUTCOMES

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

PC(U)-7	Ability to assess risks and determine safety measures applied for new facilities and technologies, draw up and analyze scenarios of potential accidents, develop methods to reduce the risk of their occurrence.
PC(U)-8	Ability to analyze technical and computational-theoretical developments, take into account their compliance with the requirements of laws in the field of industry, ecology and safety, and other regulations.
PC(U)-9	Ability to carry out independent experimental or theoretical research to solve scientific and technical problems using modern equipment, calculation and research methods.
PC(U)-10	Ability to draw up technical assignments, use information technology, standard design automation tools and application software packages in the design and calculation of nuclear facilities, materials and devices, apply knowledge of methods of ecological efficiency and economic-value analysis in the design and implementation of projects.
PC(U)-11	Ability to develop design process documentation, execute engineering design and production projects.
PC(U)-12	Ability to conduct training sessions and develop instructional materials for the training courses within the cycle of professional training programs (bachelor degree programs).

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

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

ASSIGNMENT
for the Graduation Thesis completion

In the form:

Master Thesis

For a student:

Group	**Full name**
0АМ1И	Ilia E. Tutolmin

Topic of research work:

Study of the method of reprocessing spent nuclear reactor ion-exchange resins by pyrolysis in the electromagnetic fields of the microwave range	
Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	№ 30-89/c dated January 30, 2023

Deadline for completion of Master Thesis:	06.06.2023

TERMS OF REFERENCE:

Initial date for research work: *(the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.)*	Method of recycling ion-exchange resins by pyrolysis in the electromagnetic fields of the microwave range for the purpose of recycling was proposed and experimentally investigated.

List of the issues to be investigated, designed and developed *(analytical review of literary sources with the purpose to study global scientific and technological achievements in the target field, formulation of the research purpose, design, construction, determination of the procedure for research, design, and construction, discussion of the research work results, formulation of additional sections to be developed; conclusions).*	– study the information about microwave pyrolysis; – review and compare methods for ion-exchange resin disposal; – carry out experimental studies on microwave pyrolysis method for spent ion-exchange resin disposal; – make analysis of the obtained results.
List of graphic material *(with an exact indication of mandatory drawings)*	

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

Section	Advisor
One: Literature Review	Head of Laboratory Pavel Yu. Chumerin
Two: Experimental Methods	Head of Laboratory Pavel Yu. Chumerin
Three: Results and Discussion	Head of Laboratory Pavel Yu. Chumerin
Four: Financial management, resources efficiency and conservation	Associate Professor Ekaterina V. Menshikova
Five: Social Responsibility	Associate Professor Yuriy V. Perederin

Date of issuance of the assignment for Master Thesis completion according to the schedule	16.01.2023

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

Position	Full name	Academic degree, academic status	Signature	Date
Head of Laboratory	Pavel Yu. Chumerin	Dr. Sc. (Phys.-Math)		

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0АМ1И	Ilia E. Tutolmin		

TOMSK POLYTECHNIC UNIVERSITY — ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Министерство науки и высшего образования Российской Федерации
федеральное государственное автономное
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School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Science and Technology
Specialization: Nuclear Power Engineering

Level of education: Master degree program
Research and Training Centre for International Nuclear Education and Career, School of Nuclear Engineering
Period of completion: spring semester 2022/2023 academic year

Form of presenting the work:

Master Thesis

SCHEDULED ASSESSMENT CALENDAR
for the Master Thesis completion

Deadline for completion of Master's Graduation Thesis:	06.06.2023

Assessment date	Title of section (module) / type of work (research)	Maximum score for the section (module)
16.01.2023	Literature Review	
27.02.2023	Studying the Materials and Methods	
14.04.2023	Conduction of the Experiments	
08.05.2023	Discussion and Analysis of the Experimental Results	
20.05.2023	Defense preparation	

COMPILED BY:
Scientific supervisor:

Position	Full name	Academic degree, academic status	Signature	Date
Head of Laboratory	Pavel Yu. Chumerin	Dr. Sc. (Phys.-Math)		

APPROVED BY:

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

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

To the student:

Group	Full name
0АМ1И	Ilia E. Tutolmin

School	Engineering School of Nuclear Technologies	**Division**	Nuclear Fuel Cycle
Degree	Master	**Educational Program**	14.04.02 Nuclear physics and technologies

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 – 322851 – STR budget – 657131
2. *Expenditure rates and expenditure standards for resources*	– Electricity costs – 5.8 rub per 1 kW
3. *Current tax system, tax rates, charges rates, discounting rates and interest rates*	– Labor tax – 27.1 %; – Overhead costs – 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; – creation of the time schedule of the project; – calculation of scientific and technical research budget;
4. *Resource efficiency*	– integral indicator of resource efficiency for the developed project.
A list of graphic material *(with list of mandatory blueprints):*	
1. *Competitiveness analysis* 2. *SWOT- analysis* 3. *Gantt chart and budget of scientific research* 4. *Assessment of resource, financial and economic efficiency of STR* 5. *Potential risks*	

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

Task issued by adviser:

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

The task was accepted by the student:

Group	Full name	Signature	Date
0АМ1И	Ilia E. Tutolmin		

TASK FOR SECTION
«SOCIAL RESPONSIBILITY»

To the student:

Group	Full name
0АМ1И	Ilia E. Tutolmin

School	Engineering School of Nuclear Technologies	**Division**	Nuclear Fuel Cycle
Degree	Master	**Educational Program**	14.04.02 Nuclear physics and technologies

Initial data for the section "Social responsibility":	
Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application	Tools and methods for improving the quality of practical training for students of nuclear specialties in Russian universities at the TPU level; education of nuclear industry specialists.
The list of subjects to study, design and develop:	
1. Legal and organizational issues to provide safety: – special (specific for the operation of the research object, the projected working area) legal norms of labor legislation; – organizational measures for the layout of the working area.	– Federal law of 09 Jan. 1996 No. 3-F3 "On radiation safety of the population"; – SanPiN 2.2.2 / 2.4.2732-10 "Hygienic requirements for personal computers and work organization; – SanPiN 1.2.3685-21; – other.
2. Work safety: 2.1. Analysis of the identified harmful and dangerous factors 2.2. Justification of measures to reduce probability of harmful and dangerous factor	– Enhanced electromagnetic radiation level; – Insufficient illumination of workplace; – Excessive noise; – Deviation of microclimate indicators; – Electric shock.
3. Safety in emergencies:	– Fire safety.

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

Task issued by adviser:

Position	Full name	Scientific degree, rank	Signature	Date
Associate professor	Yuriy V. Perederin	PhD		

The task was accepted by the student:

Group	Full name	Signature	Date
0АМ1И	Ilia E. Tutolmin		

Abstract

The master thesis contains 108 pages, 14 figures and 20 tables.

Key words: pyrolysis, microwave pyrolysis, ion-exchange resin, nuclear reactor, radioactive waste, disposal of radioactive substances.

The object of the thesis is the methods for spent ion-exchange resin disposal, and the subject is microwave pyrolysis method for ion-exchange resin disposal.

The aim of the thesis is to investigate the feasibility of implementing a microwave pyrolysis process for the disposal of ion exchange resins.

During the research, the microwave pyrolysis of ion-exchange resin was carried, its feasibility was proven. 84% percent mass reduction of ion-exchange resin was achieved. Gas-analysis showed the possibility of the implementation of such a method for radioactive ion-exchange resin.

Scope: nuclear physics waste management.

Content

Abbreviations

CPR – cardiopulmonary resuscitation

DSC – differential scanning calorimetry

DTA – differential thermal analysis

DVB – divinylbenzene

EMF – electromagnetic field

IER – ion-exchange resin

MSW – municipal solid waste

NPP – nuclear power plant

SCWO – supercritical water oxidation

SWOT – strengths, weaknesses, opportunities, threats

TG – thermogravimetry

TPU – Tomsk polytechnic university

VOC – volatile organic components

Introduction

Humankind currently produces two billion tonnes of waste per year between 7.6 billion people [1]. The rate of waste generation only increases, this could be supported by the graph in Figure 1.

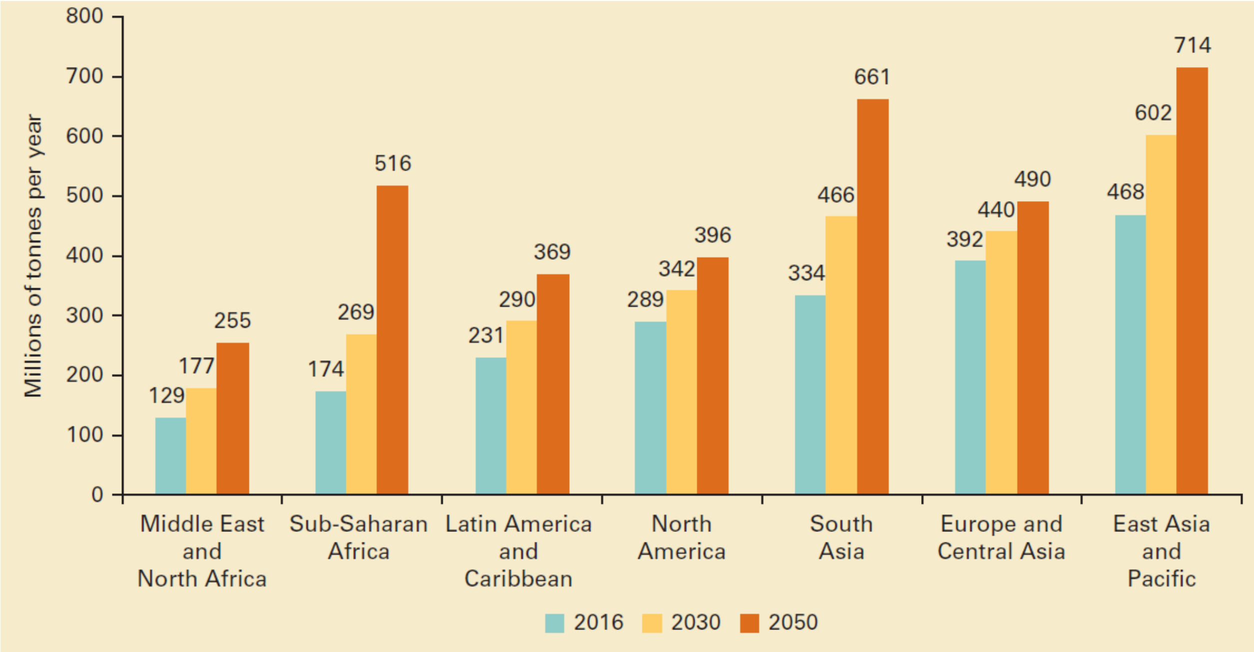

Figure 1 – Projected waste generation, by region [2]

Population increase may be part of the problem, but it’s levels of consumption within a handful of developed nations, and their gross mismanagement of waste, that have led to this environmental catastrophe. The problem of waste disposal is a major international challenge, and new sustainable solutions must be created to satisfy the modern needs.

Things get more complicated when the waste is of industrial type. One of such waste is ion exchange resin. Ion-exchange resins found their application in a lot of spheres of human life, both domestic and industrial. One of such technological spheres is nuclear physics, where it is used in different ways. This resin is applied in radioisotope separation and production, waste treatment, fuel management and spent fuel storage [3].

In nuclear reactor physics ion-exchange resins are used to purify the primary and secondary circuit coolant from radionuclides and water impurities in all water-cooled nuclear power plants. This is done by continuously taking a certain volume of coolant from the main and secondary circuit and passing it through a series of coolers, filters, and layers of ion exchange resins. Depending on the water-chemical regime, the 1300 MW power unit generates 3-10 m^3 of spent ion-exchange resins annually [4].

The disposal of spent ion exchange resins (IER) is an important problem for the nuclear and chemical industry because some of the existing disposal technologies are ineffective or harmful to the environment. Therefore, new process solutions are needed, to address this issue. At the moment, the most popular methods of disposal are incineration, cementation, or withdrawal from the process after several recycling cycles with followed by stockpiling in warehouses [5]. These methods are applicable, but may have a negative impact on components of the biosphere.

Difficulties of utilization of spent IER are that the composition of ion-exchange resins includes organic substances, due to which it is necessary to assess the fire safety of technology, with a high water content, more than 50%, the IES becomes unsuitable for disposal, which requires pre-drying of the resin [4].

At present, pyrolysis units are being developed and used in various countries, which make it possible to decontaminate industrial waste along with domestic waste. What all pyrolysis units have in common is that there is practically no contamination of the air and water environment. The pyrolysis process is the thermal decomposition of materials at elevated temperatures, often in an inert atmosphere [6]. It involves a change of chemical composition. Pyrolysis is most commonly used in the treatment of organic materials.

Microwave pyrolysis is getting more popular recently because it has several distinguishing advantages [7]. First off, the energy transfer to the processing material is instantaneous in all volume, and the conversion of microwave energy to thermal energy is practically 100% [8]. The processed materials possess better properties and the amount of CO_2 significantly decreases [9].

Despite the fact that there are studies on ion-exchange resin disposal methods, none of them suggests the microwave pyrolysis method, that conditions the novelty of the work. The relevance of the thesis is once again connected to the increasing waste generation and deteriorating state of the environment. Problem of research is the absence of sustainable and effective method for ion-exchange resin disposal. Correspondently, the object of the thesis is the methods for spent ion-exchange resin disposal, and the subject is microwave pyrolysis method for ion-exchange resin disposal.

The aim of the thesis is to investigate the feasibility of implementing a microwave pyrolysis process for the disposal of ion exchange resins**.** The following tasks were set to achieve the aim:

– study the information about microwave pyrolysis;
– review and compare methods for ion-exchange resin disposal;
– carry out experimental studies on microwave pyrolysis method for spent ion-exchange resin disposal;
– make analysis of the obtained results.

The first chapter of the thesis is dedicated to the literature review that covers such topics as conventional and microwave pyrolysis, their features and characteristics, further the review is describing the ion-exchange resin, its application and properties, and finally different methods for ion-exchange resin disposal are going to be described, analyzed and compared.

The second chapter contains the information about microwave pyrolysis experiment. There, all the experimental methods are going to be described, along with the experimental materials, experimental setup and procedure and preparation steps.

The third chapter shares the results of how successful the experiments were. An analysis of all the results is done there, considering the experiment itself, the gas-analyzer data and the chemical content of the resin.

The last fourth and fifth chapters contain section of financial management and social responsibility correspondingly. In the financial management section, the project evaluated according to its cost and resource efficiency, compared with analogues like conventional pyrolysis and incineration, also SWOT analysis and competitive analysis is given there. In social responsibility section, the safety precautions for the project are given, also potential risks during the experiments are evaluated.

Chapter 1 Literature review

1.1 Pyrolysis

Talking about materials treatment and specifically disposal, pyrolysis is one of the best technology according to the properties of heating and to the sustainability. Especially if compared with such a method as incineration: lower temperatures are used, even heat distribution and less CO_2 accumulated [10]. Pyrolysis is a thermochemical process that breaks down organic material in the absence of oxygen to produce char, oil, and gas. The conventional pyrolysis process is slow and energy-intensive, requiring temperatures of 400-500 °C and residence times of several hours [11]. The process occurs in three stages: drying, pyrolysis, and char formation. During the drying stage, water and other volatile compounds are removed from the waste material. In the pyrolysis stage, the waste material is heated to a high temperature, causing it to decompose into smaller molecules, which then condense to form the desired products. In the char formation stage, the remaining residue is converted into carbon-rich char.

Pyrolysis can be classified into three types based on the operating conditions: slow pyrolysis, fast pyrolysis, and flash pyrolysis [12,13,14]. Slow pyrolysis is a low-temperature process that takes place between 350 °C and 550 °C. This type of pyrolysis is characterized by long residence times, typically between hours to days, and low heating rates. Slow pyrolysis produces biochar, a solid residue that can be used as a soil amendment, and a low yield of liquid bio-oil and syngas [12].

Fast pyrolysis is a high-temperature process that takes place between 400 °C and 600 °C. This type of pyrolysis is characterized by short residence times, typically between seconds to minutes, and high heating rates. Fast pyrolysis produces a high yield of liquid bio-oil, which can be used as a fuel or feedstock for the production of chemicals, and a small amount of biochar and syngas [13].

Flash pyrolysis is an ultra-fast pyrolysis process that takes place at very high temperatures, typically above 800 °C. This type of pyrolysis is characterized by very short residence times, typically in the order of milliseconds, and very high heating rates. Flash pyrolysis produces a high yield of liquid bio-oil, which can be used as a fuel or feedstock for the production of chemicals, and a small amount of syngas. The type of pyrolysis used depends on the desired products and operating conditions [14].

Pyrolysis has a wide range of applications, including:

- Waste management. Pyrolysis can be used to convert various types of waste, including municipal solid waste, agricultural waste, and plastic waste, into valuable products such as bio-oil, biochar, and syngas [15,16].
- Energy production. Pyrolysis can be used to produce renewable energy in the form of bio-oil and syngas, which can be used to generate electricity or as a fuel for heating applications [17].
- Chemical production. Pyrolysis can be used to produce various chemicals such as phenol, acetic acid, and levoglucosan from biomass [18].
- Soil amendment. Biochar produced from pyrolysis can be used as a soil amendment to improve soil quality and increase crop yields [19].

Pyrolysis has several applications in waste management, including the treatment of municipal solid waste (MSW), agricultural waste, and industrial waste [20]. MSW pyrolysis has been demonstrated to be an effective method for reducing the volume of waste and producing useful products such as bio-oil and biochar. Agricultural waste such as straw, corn stover, and rice husks can also be converted into biochar and bio-oil through pyrolysis. In addition, pyrolysis has been used to treat hazardous waste, including electronic waste and medical waste, by converting them into non-hazardous products [21,22].

Municipal solid waste pyrolysis involves the conversion of mixed waste streams into valuable products such as bio-oil, biochar, and syngas. MSW pyrolysis typically involves shredding and sorting the waste material to remove non-combustible materials such as metals and glass. The remaining waste material is then heated in a pyrolysis reactor to produce bio-oil, biochar, and syngas [23].

Agricultural waste such as straw, corn stover, and rice husks can be converted into biochar and bio-oil through pyrolysis. These waste materials are typically low in moisture and have a high lignocellulosic content, making them suitable for pyrolysis. Agricultural waste pyrolysis can provide a valuable source of biochar and bio-oil for use in soil remediation and as a renewable energy source [24].

Industrial waste such as plastics and tires can also be converted into valuable products through pyrolysis. Pyrolysis of plastic waste can produce a range of products, including liquid fuels, waxes, and carbon black. Pyrolysis of tires can produce oil, carbon black, and steel. Industrial waste pyrolysis can provide a cost-effective and environmentally sustainable method for managing waste streams [25].

The success of the pyrolysis process relies heavily on the design and operation of the pyrolysis reactor. A variety of pyrolysis reactor designs have been developed, each with its own advantages and limitations.

Fixed bed reactors are one of the most commonly used reactor designs for pyrolysis. The waste material is placed on a fixed bed and heated to a high temperature in the absence of oxygen. The products of the pyrolysis process are removed from the bottom of the reactor. Fixed bed reactors are simple in design and operation, but they suffer from poor heat transfer and low process efficiency. They are best suited for slow pyrolysis processes [26].

Fluidized bed reactors are another common design for pyrolysis. The waste material is fluidized by a stream of hot gas, which creates a suspended bed of particles. The particles are heated to a high temperature in the absence of oxygen, and the resulting products are removed from the reactor. Fluidized bed reactors have good heat transfer properties and high process efficiency. They are well suited for fast pyrolysis processes [27].

Rotary kiln reactors consist of a rotating cylindrical chamber that is heated to a high temperature. The waste material is introduced into the chamber and tumbles as it is heated, ensuring uniform heat distribution. The products of the pyrolysis process are removed from the end of the kiln. Rotary kiln reactors have good heat transfer properties and are capable of processing a wide range of waste materials. Like fluidized bed reactors they are also implemented for fast pyrolysis [28].

Microwave pyrolysis reactors use electromagnetic waves to heat the waste material, resulting in fast and efficient pyrolysis. The microwave radiation penetrates the waste material and heats it uniformly, ensuring complete pyrolysis. Microwave pyrolysis reactors are capable of processing a wide range of waste materials and have high process efficiency. However, they are expensive and require specialized equipment [29].

Plasma pyrolysis reactors use plasma arc technology to heat the waste material to a high temperature in the absence of oxygen. The plasma arc generates a high-intensity electromagnetic field that breaks down the waste material into its constituent components. Plasma pyrolysis reactors have high process efficiency and are capable of processing a wide range of waste materials. They are also quite costly and have complicated technology [30].

Despite its many advantages, pyrolysis faces several challenges that limit its widespread adoption. One major challenge is the high cost of the technology, which is largely due to the high energy consumption required to operate pyrolysis plants [31]. In addition, the variability of waste streams makes it difficult to design pyrolysis plants that can handle a wide range of waste materials. The quality of the products produced by pyrolysis can also be highly variable and dependent on the feedstock and operating conditions. Finally, the regulatory environment surrounding pyrolysis is still evolving, making it difficult for companies to navigate the legal requirements for operating pyrolysis plants [32].

1.2 Microwave pyrolysis

As it was mentioned, more attention is getting drawn to the microwave type of pyrolysis as it has significant advantages comparing to the conventional pyrolysis. Microwave pyrolysis (or microwave-assisted pyrolysis) is a relatively new and advanced technique that refers to heating materials with the electric field component of an electromagnetic wave [33, 34, 35].

Microwave pyrolysis involves the use of microwaves to heat organic materials to high temperatures. Microwaves are electromagnetic waves that have a frequency range of 300 MHz to 300 GHz [36]. Most reactors for microwave pyrolysis operate at 2.45 GHz frequency, which corresponds to a wavelength of 12.25 cm. However, 915 MHz and 2450 MHz are two frequencies which are reserved by the Federal Communications Commission for industrial, scientific, and medical purposes [37]. This is in order to avoid any interference with telecommunications and cellular phone frequencies [38].

When microwaves are absorbed by a material, they cause the molecules in the material to vibrate, generating heat. This heat is then transferred to adjacent molecules, leading to an increase in temperature throughout the material. Each material has different absorption of microwave radiation. According to the interaction of microwave irradiation (electric component of microwave field) with materials, there are three ways in which a material may be categorized [39]:

- insulator or microwave-transparent material where microwaves pass through without any losses (e.g., quartz, teflon, etc.);
- conductor where the microwaves cannot penetrate and are reflected (e.g., metals);
- absorber where the microwaves can be absorbed by the material (e.g., water, oils, etc.).

Microwave dielectrics are known as a material which absorbs microwave radiation, thus microwave heating is called dielectric heating [39].

In the case of microwave pyrolysis, the organic material is placed in a reactor chamber and exposed to microwaves. The microwaves cause the material to heat up rapidly, leading to the breakdown of the material into smaller molecules. The absence of oxygen in the reactor chamber prevents the material from burning, which is a common problem with traditional pyrolysis techniques [36].

Heat transfer in microwave pyrolysis occurs directly within the feedstock by convection (not by conduction where heat is transferred from the surface towards the center of the material) and does not require external drying of the feedstock, which is especially relevant when some wet substances are treated. This feature of microwave heating comparing to the conventional one is represented in Figure 2.

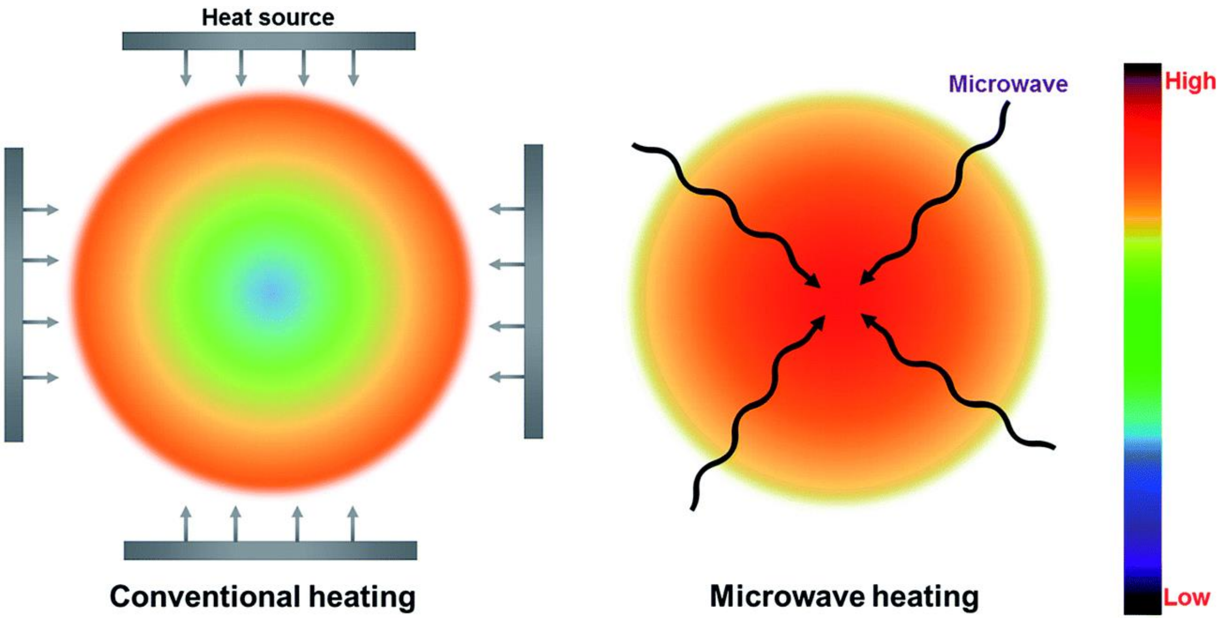

Figure 2 – Difference between microwave and conventional heating [40]

Compared to conventional pyrolysis, which uses electric resistance heating, microwave pyrolysis heating is much more efficient because of rapid volumetric heating [41].

According to the literature, there are three possible ways (combination of two or all three contributions) of chemical reaction enhancement using microwave irradiation technique [42], including thermal effects (the influence of a high reaction temperature which can be rapidly attained when irradiating polar materials in a microwave field), specific microwave effects (can be caused by the unique nature of the microwave irradiation heating mechanism in a microwave field and cannot be achieved by conventional heating), and non-thermal effects (chemical transformation accelerations that cannot be defined in terms of thermal or specific microwave effects) [43].

The process of microwave pyrolysis can be divided into three stages: drying, devolatilization, and char formation. In the drying stage, the moisture content of the organic material is reduced, preparing it for the pyrolysis reaction. In the devolatilization stage, the organic material is rapidly heated to high temperatures, causing the release of volatile organic compounds (VOCs). The VOCs are then condensed into bio-oil, leaving behind biochar and syngas. In the char formation stage, the remaining organic material is converted into char and syngas [44].

Microwave pyrolysis has several advantages over conventional pyrolysis. Firstly, it has a faster reaction rate and can produce higher product yields of better quality due to the homogeneous heating of the organic material [45]. Secondly, microwave pyrolysis can be performed at lower temperatures, resulting in reduced energy consumption and lower carbon emissions, which makes it cost effective. Thirdly, microwave pyrolysis can be used to convert a wide range of feedstocks, including agricultural waste, municipal waste, and forestry residues. Also, it is an environmentally friendly process that reduces the emission of greenhouse gases and other pollutants [46].

However, microwave pyrolysis also has some disadvantages. Firstly, it requires specialized equipment that can be expensive and difficult to maintain. Secondly, the equipment must be designed to withstand high temperatures and pressures, which can add to the cost. Thirdly, the feedstocks used for microwave pyrolysis must be dry, as moisture can interfere with the heating process [47].

Microwave pyrolysis has several applications in various fields. Some of the important applications are the following:

- Waste treatment. Microwave pyrolysis is used for the treatment of various waste materials such as plastic, rubber, biomass, and municipal solid waste. The process can convert these waste materials into valuable products such as biofuels, activated carbon, and pyrolysis oil [48].
- Chemical synthesis. Microwave pyrolysis is also used for the synthesis of various chemicals such as carbon nanotubes, graphene, and metal oxides. The

process provides a fast and efficient way to synthesize these chemicals, which have various applications in electronics, energy storage, and catalysis [49, 50].

– Food processing. Microwave pyrolysis is used for the processing of food products such as cereals, nuts, and spices. The process can improve the quality of the food products by reducing the microbial load and improving the shelf life [51, 52].

– Biofuels. Microwave pyrolysis can be used to convert biomass into biofuels such as bio-oil, biochar, and syngas. Bio-oil is a liquid fuel that can be used as a substitute for diesel fuel, while biochar is a solid material that can be used as a soil amendment or as a source of carbon for industrial processes [53, 54]. Syngas is a mixture of hydrogen and carbon monoxide that can be used as a fuel for power generation [55].

To study how microwave pyrolysis occurs with different substances, it was considered to take a closer look at biomass, as so as it shares some similarities with ion-exchange resin in its properties and functions. First off, both ion-exchange resins and biomass are made up of organic compounds. Ion-exchange resins are typically synthetic polymers, while biomass is composed of natural polymers such as cellulose, lignin, and proteins. Both types of materials have functional groups that can interact with ions in solution [3, 56].

Secondly, they are capable of adsorbing or exchanging ions from a solution. Ion-exchange resins are designed to remove specific ions from a solution by replacing them with other ions of the same charge that are attached to the resin. Similarly, biomass such as plants and microorganisms can take up and accumulate ions from their environment, which can be used for various metabolic functions [3, 56].

Finally, both ion-exchange resins and biomass can be regenerated and reused. Regeneration of ion-exchange resins involves washing the resin with a solution that removes the ions attached to it, allowing the resin to be used again. Similarly, biomass can be treated to remove accumulated ions, or it can be composted and used as a nutrient source for other organisms [3, 56].

Bearing the information above in mind, the process of microwave pyrolysis of biomass was studied in different literature sources. Tabakaev et al. [7] studied effects of microwave pyrolysis on wood shavings and lowland peat. The power of magnetron consisted to be 750 W and the frequency of microwave was 2.45 Hz as usual. Upon finishing the research, it was found that thermal conversion end temperature these types of biomass was around 600-650 °C. It was also mentioned, that comparing to the conventional slow pyrolysis, during microwave pyrolysis there is less solid carbonaceous sludge (9.5-11.7%) and the obtained pyrolysis gas contains less ballast CO_2 which makes the process more efficient. The methodology and the experimental setup of the thesis are going to be based on the ones, that were presented in the article, and it will be described in the next chapter.

In the study of Huang Y. F. et al [57] the heating performance and kinetics of seven lignocellulosic biomass was considered, namely: corn stover, rice straw, rice husk, sugarcane bagasse, sugarcane peel, coffee grounds, and bamboo. The frequency in the experiment was again 2.45 GHz, but this there were different power levels of the magnetron: 200, 300, 400 and 500 W. Most of the materials decomposed at the temperature range of 200–500 °C, after 500 °C, the biomass feedstocks decomposed very slowly. With increase in power level, heating rate and maximum temperature increased as well for all the samples. The maximum temperatures at microwave power levels of 200, 300, and 500 W were approximately 280, 410, and 495 °C, respectively. As an overall conclusion was that, comparing to the conventional pyrolysis, the microwave one is more rapid and efficient.

1.3 Ion-exchange resin

Ion-exchange resins are widely used in various industries, including water treatment, food and beverage, pharmaceutical, and chemical processes. These resins are typically made up of yellowish or whitish polymer beads (0.25–1.43 mm radius) that are designed to selectively remove or exchange ions in a solution [58]. These polymers, such as polystyrene, polyacrylic, divinylbenzene, are cross-linked polymers and have been functionalized with charged groups, such as sulfonic acid or quaternary ammonium. These charged groups provide the resins with the ability to selectively bind or release ions from a solution. The physical properties of the resins, such as particle size and porosity, can also affect their ion-exchange capacity and selectivity [59].

There are two main types of ion-exchange resins: cation-exchange resins and anion-exchange resins [60]. Cation-exchange resins are functionalized with negatively charged groups and are used to selectively remove positively charged ions from a solution, such as calcium, magnesium, and sodium. Anion-exchange resins are functionalized with positively charged groups and are used to selectively remove negatively charged ions from a solution, such as chloride, sulfate, and nitrate. There are also mixed-bed ion-exchange resins that combine both cation- and anion-exchange resins to remove both positively and negatively charged ions from a solution. Other types of ion-exchange resins are of limited use: amphoteric, chelate and redox ion-exchangers, usually in research and experimental processes. Amphoteric ones can be either cationic or anionic, depending on conditions. Chelate resins can be "tuned" for selective extraction of one or two kinds of ions, i.e., they have extremely high single or group selectivity. Redox ion exchange resins can change the charges of the ions in the medium [61].

Ion exchange resins have a finite exchange capacity and, when depleted, hold a finite mass of hardness ions in the softener (if it is about water treatment). They can no longer exchange ions because they are depleted and must be recharged or regenerated to restore them to their original operating state. Substances used for this may include sodium chloride as well as hydrochloric acid, sulfuric acid or sodium hydroxide and are called a regenerating solution. To clean the resin of hardness ions, regeneration - washing the resin beads with a volume of saline solution (8-10 %) must be performed. During the regeneration cycle, the ion-exchange reaction is essentially reversed by using a concentrated regenerant solution. The regenerating $NaCl$ solution enters the softener until the mass of brine has passed through the resin and displaced an equivalent amount of hardness ions. The resin is now in an equilibrium state. The flushing process must then be started and the ion exchange resin is ready for use again [62].

Ion exchange resins are mainly made from cross-linked styrene. Styrene monomer (also known as vinylbenzene) is a water-insoluble liquid. When it is suspended in water and stirred, it forms small droplets or spheres. Monomeric styrene is polymerized, that is, turned into a solid plastic substance by heating it in the presence of a catalyst. It is transparent to water and completely insoluble and takes the form of tiny spheres with a diameter of about 0.2 to 0.8 mm [63].

It is known from chemistry that styrene consists of a benzene ring and a vinyl group. The crosslinking agent has a reactive vinyl group on both sides and is called divinylbenzene (DVB). This structure gives a three-dimensional cross-linking to the polystyrene. The level of DVB reacted in the main chain of the polymer determines the density or strength of the bead. The higher the divinylbenzene content, the lower the moisture content will be when the ball turns into resin [58].

Now the functional groups must be added, which turn the polymer pellet into an ion-exchange resin. When the functional groups are added to the styrene main chain of the polymer, the resins become reactive, and the polymer links function as if they were individual ions suspended in water. The individual units are bound together by DVB, making the pellet insoluble but highly swollen in water [62].

Ion-exchange resins are widely used in various industries for water treatment, food and beverage production, pharmaceuticals, and chemical processes. In water treatment, ion-exchange resins are used to remove impurities, such as dissolved minerals, from drinking water. In food and beverage production, ion-exchange resins are used to remove impurities and improve the taste and quality of products. In the pharmaceutical industry, ion-exchange resins are used to purify drugs and remove impurities. In chemical processes, ion-exchange resins are used to separate and purify chemicals [64, 65, 66].

In nuclear physics, ion-exchange resins are used to separate and purify different elements, isotopes, and compounds, water purification, fuel and waste management [67]. Isotopes are different forms of an element that have the same number of protons but different numbers of neutrons. Isotope separation is important for various nuclear applications, such as the production of nuclear fuel, nuclear medicine, and research. Ion-exchange resins are used for isotope separation because they can selectively bind or release specific isotopes based on their charge and size. For example, in the production of nuclear fuel, uranium isotopes can be separated using ion-exchange resins. The resin is functionalized with negatively charged groups that can selectively bind to the positively charged uranium ions. By controlling the pH and other factors, the desired isotopes can be selectively released, allowing for the separation of isotopes [68].

Another application of ion-exchange resins in nuclear physics is the purification of radioactive materials. Radioactive materials often contain impurities that can affect their properties and increase their radioactivity. Ion-exchange resins can be used to selectively remove these impurities, improving the purity and quality of the radioactive material. For example, in the production of medical isotopes, ion-exchange resins are used to purify the final product. The resins can selectively remove impurities, such as metal ions and organic compounds, from the radioactive material. This improves the quality and safety of the final product, which is used for medical imaging and treatment [68].

Ion-exchange resins are also used in the production of radioisotopes. Radioisotopes are isotopes that are unstable and emit radiation as they decay. They are used in various nuclear applications, such as nuclear medicine, imaging, and research. Ion-exchange resins can be used to produce radioisotopes by selectively binding or releasing specific isotopes. For example, in the production of iodine-131, an important radioisotope used in nuclear medicine, ion-exchange resins can be used to selectively bind and release the iodine-131 isotope. The resins are functionalized with negatively charged groups that can selectively bind the iodine-131 isotope. By controlling the pH and other factors, the desired isotope can be selectively released, allowing for the production of the radioisotope [69].

Nuclear reactors generate radioactive waste, including spent fuel, contaminated materials, and liquids. The treatment and disposal of radioactive waste are critical for ensuring the safety of the environment and human health. Ion-exchange resins are used to treat radioactive waste by selectively removing radioactive ions and isotopes from the waste stream [70].

In the treatment of liquid radioactive waste, ion-exchange resins can selectively remove radioactive isotopes, such as cesium and strontium, from the waste stream. The resins can then be processed or disposed of safely, reducing the risk of contamination and exposure to radiation [70].

The type of ion-exchange resin used for radioactive waste treatment depends on the specific radioactive isotopes present in the waste. For example, strong acid cation exchange resins are used to remove cesium ions, while complexing or chelating ion-exchange resins are used to remove actinide ions, such as plutonium and uranium. The fuel cycle management of nuclear reactors includes various processes, such as fuel enrichment, fuel reprocessing, and spent fuel storage. Ion-exchange resins are used for these processes to improve efficiency and safety [70].

In fuel enrichment, ion-exchange resins are used to selectively bind and release uranium isotopes. The resins can be used to enrich the uranium fuel, increasing its concentration of fissile isotopes and improving its performance.

In fuel reprocessing, ion-exchange resins are used to separate and recover valuable isotopes, such as plutonium and uranium, from spent nuclear fuel. The resins can selectively bind and release the isotopes, allowing for their recovery and reuse in the fuel cycle.

In spent fuel storage, ion-exchange resins are used to remove impurities and radioactive isotopes from the spent fuel before storage or disposal. The resins can selectively bind and remove fission products, such as cesium and strontium, reducing the heat and radiation emissions of the spent fuel.

At last, but not least the water purification which is critical for the safe and efficient operation of nuclear reactors. The water used in nuclear reactors must be of high purity to prevent corrosion, scaling, and contamination of the reactor components. Impurities in the water can also affect the performance of the reactor, leading to reduced efficiency and increased maintenance costs [71].

Ion-exchange resins are used for water purification in nuclear reactors due to their high selectivity and efficiency in removing impurities. Cation exchange resins are used to remove positively charged ions, such as calcium and magnesium, while anion exchange resins are used to remove negatively charged ions, such as chloride and sulfate. By using a combination of cation and anion exchange resins, the water can be purified to a high degree of purity, ensuring safe and efficient operation of the reactor [71].

The type of ion-exchange resin used for water purification depends on the specific impurities in the water. For example, strong acid cation exchange resins are used to remove calcium and magnesium ions, while strong base anion exchange resins are used to remove sulfate and chloride ions. Mixed bed ion-exchange resins are also used to further purify the water to ensure the removal of all impurities.

1.4 Spent ion-exchange resin disposal

Spent ion-exchange resin from nuclear power plant is loaded with radioactive contaminants (except for the one which was extracted from the second circuit of a NPP). That means that the resin must be properly treated and disposed of. The volume of generated spent ion-exchange resin comprises the large part of the whole generated nuclear waste. For example, the contemporary power reactor might generate 3-10 m^3 of spent ion-exchange resins annually [4].

The literature suggests different ways for ion-exchange resin disposal, some of them are: immobilization (such as cementation, bituminization and plastic solidification), advanced oxidation processes (such as incineration, pyrolysis, acid boiling degradation, the Fenton or Fenton-like reaction, supercritical water oxidation and plasma technology) and super compaction. And there also are some supplementary methods, such as acid stripping, microbial conversion treatment and high integrity container [72].

Storage is a common method of disposal not only of spent ion-exchange resin from nuclear reactors, but also of many different other radioactive materials. The resin is stored in specially designed containers, which are then placed in a secure storage facility. This method of disposal is effective in isolating the radioactive isotopes from the environment and preventing their release. However, the long-term safety of storage facilities is a matter of concern, as they require continuous monitoring and maintenance to prevent leaks or breaches [72].

Encapsulation or solidification involves encapsulating the spent ion-exchange resin in a stable matrix, such as cement, bitumen, plastic or glass, to immobilize the radioactive isotopes. The encapsulated resin is then placed in a storage facility. Comparing the encapsulation materials, that cement is probably one of the best due to its low cost and perfect irradiation stability compared with bitumen which is flammable during immobilization. The plastic is relatively expensive material and has the potential to cause corrosion which is inappropriate [73].

This method of disposal is effective in reducing the volume of waste and preventing the release of radioactive isotopes. Encapsulated waste forms can be combined with other waste forms, such as vitrified waste, for storage and disposal. However, the encapsulation process is complex and expensive, and the long-term safety of encapsulated waste is still uncertain. Also, its effectiveness depends on several factors, including the quality of the binder material, the mixing ratio of resin to binder, and the quality control measures during the process [73, 74].

Very often, to prepare resin for the encapsulation the drying process is used. In the patent [75] method was described that includes pretreatment of radioactive waste by drying the resin by electromagnetic field of microwave range. After that, the obtained solid bulk product is immobilized in a polymeric matrix material based on epoxy-dian resin. Humidity of the ion-exchange resin after exposure to microwave radiation is less than 0.4 %. The technical result is reduction of mass, volume and moisture of radioactive waste, increase of degree of filling of polymer matrix by resin during transfer of liquid radioactive waste into solid [75].

Deep geological disposal involves burying the spent ion-exchange resin in deep geological formations, such as stable rock formations, to isolate the radioactive isotopes from the environment for thousands of years. This method of disposal is considered the most effective and long-term solution for the disposal of radioactive waste. However, it requires careful site selection, construction, and monitoring to ensure the safety of the disposal site [76].

For deactivation of ion-exchange resins for enterprises where it is needed to clean technological environment from radionuclides the ultrasonic method is suggested. The use of ultrasound is much more effective than the existing conditioning methods that are used to decontaminate of radioactive waste. Based on the studies conducted, it is possible to conclude that washing, intensified by ultrasonic vibrations, propagated in the medium of aqueous solutions of specially selected reagents, extracts up to 97 % of the activity of ion exchange resins and removes γ-emitting radionuclides. The spent decontaminating solutions can be re used for this method after adjusting the composition [77].

A totally different approach to manage the spent ion-exchange resin is decomposition. Decomposition is a treatment technique for resins prior to solidification, aimed at reducing risks in subsequent processes. It achieves this by lowering the concentration of organic material to decrease the risk of flammability, reducing the concentration of organic acids to minimize corrosion of the container, and converting the resin particles into inorganic residue or liquid that can be easily treated. Additionally, this process facilitates the recovery of transuranium and transplutonium from the resulting residue. All ways for decomposition vary in nature, there are chemical, biological, electrochemical and thermal. The most attention in the work is paid to thermal methods.

Chemical oxidation is a process of decomposing spent ion-exchange resin by treating it with a strong oxidizing agent, such as hydrogen peroxide or ozone. The oxidizing agent breaks down the organic matrix of the resin, reducing its radioactivity. Chemical oxidation is a relatively low-cost method of reducing the volume of radioactive waste, but it requires careful handling of the oxidizing agent. The most popular chemical processes are Fenton or Fenton-like process, supercritical water wet oxidation and acid boiling degradation [78].

The degradation of organic wastes using the H_2O_2-transition metals process, also known as the Fenton or Fenton-like process, relies on the production of OH radicals. This process involves the use of a catalyst such as transition metals, which react with H_2O_2 to produce OH radicals. The OH radicals then react with peroxide and peroxy acid-containing peroxide chains, leading to a chain reaction that breaks down the organic waste into smaller molecules [79].

Supercritical water oxidation SCWO is a process that takes place in water when it reaches temperatures and pressures beyond the critical point of a mixture. This condition transforms water into a fluid that possesses unique characteristics, which can be beneficial in the elimination of persistent and harmful waste. This technique enables water to have enhanced solubility, a rapid transfer of both mass and heat, reduced viscosity, and an increased diffusion coefficient. At a temperature of 374 °C and pressure greater than 22.1 MPa, water can combine with oxygen and nearly all organic materials, forming a homogeneous reaction environment that facilitates the quick decomposition of organic materials due to the high rate of mass transfer [80].

Plasma is a type of ionized gas that includes electrons, ions, neutral particles, and chemically reactive state particles. When O_2 is transferred into a free radical state, it can react with organic materials. Plasma technology can break down waste materials without burning them, instead using thermal equilibrium to heat organic waste to temperatures higher than 1500 °C. This process breaks down the organic materials into CO_2, CO, H_2O, SO_x, and NO_x, while the remaining residues containing radioactive and metallic oxide materials are turned into glass for disposal. These two steps result in a reduction of volume and the fixation of radioactive materials, and no additional fuels are needed for this process. Additionally, the amount of waste gas produced is minimal, allowing for smaller facilities to be used [81].

To sum up all the chemical methods, it could be mentioned that plasma option and supercritical water oxidation decompose the waste completely, but the plasma technology is the most expensive. From the other methods acid boiling degradation has the highest volume reduction, but it causes corrosion and, as well as

Fenton process and supercritical water wet oxidation, has high requirements for the facility materials like temperature and pressure resistance. Supercritical water wet oxidation has the shortest reaction and during Fenton process all radioactive materials are held in the solid part of the product, so they could be easily immobilized. Taking this into account, the method should be chosen depending on the requirements, possibilities, money and etc.

Electrochemical treatment is a method of treating spent ion-exchange resin by passing an electric current through it. The current disrupts the organic matrix of the resin, resulting in a decrease in its radioactivity. While electrochemical treatment is a relatively inexpensive technique for managing radioactive waste, it necessitates careful handling of the electrodes and electrolyte involved [82].

Biological treatment refers to a technique for breaking down spent ion-exchange resin through the use of microorganisms that can break down the organic structure of the resin. These microorganisms have the capacity to transform the organic compounds into carbon dioxide and water, which can significantly decrease the radioactivity of the waste. Although it is a cost-effective and eco-friendly approach to treating radioactive waste, this method requires a meticulous selection and handling process for the microorganisms utilized [83].

Thermal decomposition is a process of decomposing spent ion-exchange resin by heating it to high temperatures in the presence of an oxidizing agent or in an inert environment. The heat breaks down the organic matrix of the resin, while the oxidizing agent oxidizes the organic compounds, reducing their radioactivity. Thermal decomposition is an effective method of reducing the volume of radioactive waste, but it requires high temperatures and may produce secondary waste.

Incineration is typical method of thermal decomposition and is used for different type of materials including ion-exchange resin. The majority of organic waste can be transformed into inorganic ash through incineration, which typically retains 80-95 % of radioactive materials. Incineration is effective in reducing both the volume and weight of waste. However, there are several limitations to using this method. For instance, the need to dehydrate resin before incineration, incomplete combustion, recycled off-gases that may still contain radioactive materials, and the risk of inhaling incineration residue all restrict the use of incineration. Additionally, this method requires specialized facilities, such as those with steel shells and refractory ceramics. The off-gas treatment facilities must also use corrosion-resistant materials like fiberglass, nickel, and titanium [72].

A more advanced option is pyrolysis. Pyrolysis is a process that occurs usually at temperatures between 502-752 °C, during which waste materials are transformed into new gases, liquids, and solids without oxygen or with limited oxygen present due to their thermal instability. This process can significantly reduce the volume of waste, and radioactive materials are primarily retained in the residue, simplifying the subsequent immobilization process. However, residue containing carbon and sulfate deposits can damage the pyrolysis facility's performance and the final waste form's stability. There are two forms of pyrolysis: direct pyrolysis and oxidative pyrolysis. In the former, spent resins are heated without air supply, and the resulting slag is oxidized before immobilization. However, this process requires an additional facility for exhaust gas disposal. The latter method involves partially burning spent resins with a small amount of air to reduce the risk of explosions during incineration [84].

Preliminary tests have shown that the decomposition of ion-exchange resins by pyrolysis gives very good results: it provides an inert and chemically neutral final product without the use of additives [85].

The main component of the final product ("pyrolysate" or ash) is carbon. Supply of water steam into the process - pyrolysis becomes pyrohydrolysis - ensures almost complete removal of carbon, while only inorganic components remain in the ash composition. The results have shown that during pyrolysis/pyrohydrolysis of ion exchange resins, all radioactive elements are completely transferred into the pyrolysate. This is achieved due to the relatively low process temperature, which prevents volatile elements (such as radioisotopes of cesium) from transferring into the gaseous phase. Equipping the pyrolysis unit with ceramic metal filters ensures that even the radioactivity bound to dust particles remains in the pyrolysis. The pyrolysate is a loose solid material, not a melt - accordingly, it is easy to handle and can be compacted or cemented, depending on the requirements for intermediate storage and disposal [86].

NUKEM Technologies has developed a method for the pyrolysis of ion-exchange resin, this method involves heating the resin to high temperatures in a pyrolysis reactor with ball filler, where it breaks down into gas, liquid, and solid components. The process is carried out under controlled oxygen-free conditions to prevent combustion and minimize the formation of hazardous byproducts. During the pyrolysis process, the ion-exchange resin is broken down into a gas mixture consisting mainly of carbon dioxide, carbon monoxide, and hydrogen, as well as a liquid fraction containing organic compounds and a solid residue made up of non-volatile inorganic materials. The gaseous and liquid components can be treated using standard methods for air and wastewater pollution control, while the solid residue can be encapsulated in a stable glass matrix for disposal [84].

NUKEM's pyrolysis method offers several advantages over other waste treatment methods. For instance, it achieves a high level of volume reduction, resulting in lower disposal costs. Additionally, the process produces minimal emissions and hazardous byproducts, making it an environmentally friendly solution. Finally, the solid residue produced by the process is relatively stable, reducing the risk of contamination due to complete localization of cesium radionuclides in the solid residue and facilitating long-term storage [84].

As so as pyrolysis of ion-exchange resin shows good results, and there was no microwave pyrolysis of this material found in any literature sources, it was decided to carry out the experiments in this way.

A conclusion could be made, that a microwave pyrolysis a perspective technology that could be used to dispose of the ion-exchange resin. And this is a very relevant matter, because the amount of the waste is increasing drastically, and there is no universal method that could satisfy meet all the disposal requirements. Also, no researches investigate the implementation of the microwave pyrolysis to the ion-exchange resin.

Chapter 2. Experimental methods

2.1 Research Laboratory of Super High Frequency Technology

All the experiments were carried in the Research Laboratory of Super High Frequency Technology. The laboratory was founded at TPU in 1970 as part of the Research Institute of Nuclear Physics; today it is a part of TPU Engineering School of Nuclear Technologies [87].

Priority areas of work conducted in the laboratory are fundamental and applied research related to the development and creation of unique sources of powerful electromagnetic radiation based on temporal compression and amplification of microwave pulses in waveguide resonant structures, as well as physical substantiation of the application of such sources in nanosecond radars, radioelectronic combat systems and technological installations for processing various materials and media to give them new properties. In the laboratory there are plenty of needed equipment for the thesis such as waveguides, magnetrons of different power levels and other auxiliary equipment.

2.2 Experimental Materials and Equipment

In the thesis the following materials and equipment were used: waveguide circulator, reactor chamber, magnetron of 750 W power along with Samsung microwave, cationite «КУ-2-8 чС» and anionite «АВ 17-8чС» ion-exchange resin, waveguide load, gas analyzer «Тест-1», quartz tube, plastic snap caps, inlet and outlet valves for nitrogen supply and gas removal, gas filters, hoses, nitrogen tank, gas flowmeter, laptop, Pioneer analytical scales, tweezers, screwdriver, gas torch burner, acetone, cleaning cloth, fan coolers, stopwatch.

2.2.1 Ion-exchange resin

The ion-exchange resin was obtained at the TPU IRT-T research reactor. Its photo is represented in Figure 3.

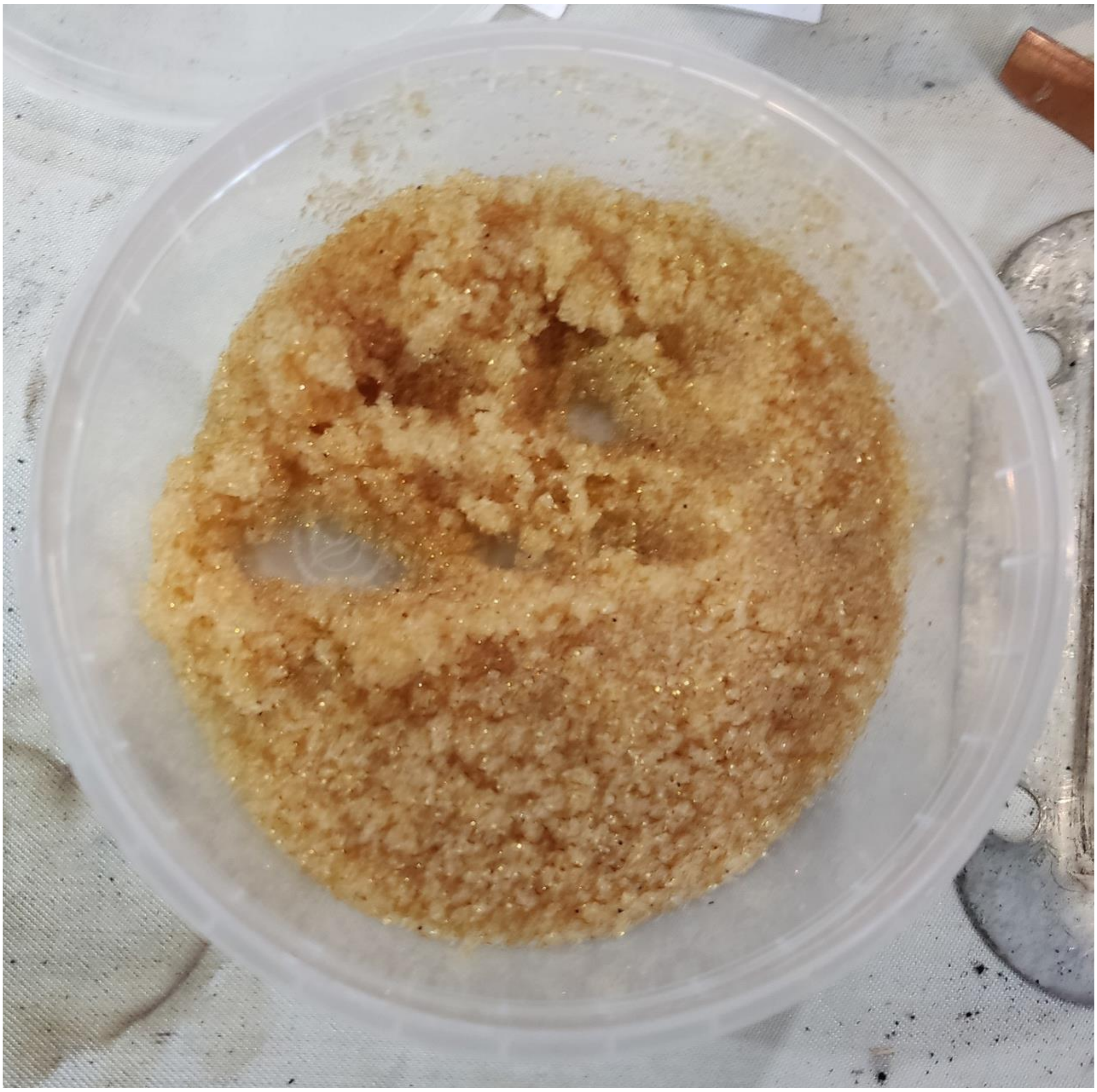

Figure 3 – Spent ion-exchange from IRT-T reactor

This resin was used in the second circuit of the IRT-T reactor, so does not contain radioactive contaminants. It was done for the reasons of safety and precautions. Also, the laboratory equipment is further going to be used in the researches that are not connected with radioactive substances, so it is not allowable to contaminate the facility with radiation.

The ion-exchange taken from the reactor represents a mix of two types of resin: cationite «КУ-2-8 чС» and anionite «АВ 17-8чС», they are used separately and simultaneously for better purification. Cationite «КУ-2-8 чС» is a strongly acidic ion-exchange resin, with high level of purity. It has HSO_3 sulfogroup, whose acidic properties are close to those of sulfuric acid. At present they are represented by sulfopolystyrene resins produced in the following way [88]:

- copolymerization of an emulsion of styrene and divinylbenzene, which allows the formation of perfect microspheres during solidification of the final product;
- sulfation of the obtained resin grains.

It has the appearance of a granular product. Yellow granules, less than 1 mm in diameter, with a microporous, gel structure. The substance contains functional groups, which can react in cation exchange reactions in alkaline, acidic and neutral media. The reagent is of special purity, osmotically stable, resistant to aggressive substances. It is non-water-soluble, does not react with solutions of inorganic acids and bases and organic solvents. Stored in polyethylene and polypropylene containers for bulk products (bags, flasks, containers, etc.). It is not recommended to store at t below -3 °C. It is used for water purification, extraction of some substances from water. It is used in [88]:

- water softening and desalination at thermal and nuclear power plants and boiler houses;
- preparation of water for the food industry;
- softening and desalting of water in filters;
- aquarium water treatment;
- electroplating;
- hydrometallurgy;
- wastewater treatment.

Anionite «АВ 17-8чС» represents itself a loose mass consisting of spherical grains ranging in size from 0.4 mm to 1.25 mm. The color can vary from yellow to dark brown. The structure is gelatinous. The matrix is styrene-divinylbenzene aminated with trimethylamine. The functional groups provide ion exchange reactions with a wide range of organic and inorganic impurities in water. The total number of charged particles in the flow does not change. This resin is used for softening and maximum purification of drinking and technical water. And also in the course of water treatment for food, pharmaceutical, electronic, heat and power industries. The load effectively neutralizes hardness salts (Ca and Ma), heavy metals, weak acids, high-molecular organics. Water must be pre-cleaned of any insoluble contaminants, colloidal particles, oils and petroleum products. The maximum flow temperature is 60 degrees Celsius. Regeneration of the filter bed is done by washing with a 3.5 % to 4.5 % sodium hydroxide (*NaOH*) solution.

Advantages of ion-exchange resin «АВ 17-8чС» [89]:

- High osmotic and chemical stability;
- High exchange capacity;
- Capability to operate in media of different acidity (including slightly alkaline);
- Wear resistance, long service life without degradation of water treatment quality;
- Easy regeneration;
- Price, considerably lower than that of their foreign analogues.

2.3 Experimental procedure

2.3.1 Preparation for the experiment

All equipment required for the experiment must be checked before the experiment, and the whole setup must be assembled and connected. The experimental setup is represented in Figure 4.

First of all, it is necessary to analyze possible technical solutions and choose the best one based on the considered technical and economic criteria. It was chosen to make a competitive analysis between incineration P_i, conventional pyrolysis P_p and microwave pyrolysis P_{mp} for ion-exchange resin disposal. These techniques were chosen as so as they all used or could be used for waste management, and there is enough data about them.

Evaluation map analysis presented in Table 2. The position of the research and competitors is evaluated for each indicator by the student on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators determined by the student in the amount should be 1. Analysis of competitive technical solutions is determined by the formula:

$$C = \sum W_i \cdot P_i, \tag{1}$$

C - the competitiveness of research or a competitor;

Wi– criterion weight;
Pi – point of i-th criteria.

Table 2 – Evaluation card for comparison of competitive technical solutions

Evaluation criteria	**Criterion Weight** *Wi*	**Points**			**Competitiveness** Taking into account weight coefficients		
		P_i	P_p	P_{mp}	C_i	C_p	C_{mp}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Mass and volume reduction	0.15	3	4	5	0.45	0.6	0.75
2. Speed of treatment	0.05	2	3	5	0.1	0.15	0.25
3. Containment of radioactive isotopes	0.15	2	3	4	0.3	0.45	0.6
4. Heating efficiency	0.1	2	3	5	0.2	0.3	0.5

Continuation of Table 2

5. Safety	0.1	2	3	4	0.2	0.3	0.4
6. Simplicity of technology	0.05	5	4	2	0.25	0.2	0.1
7. Sustainability	0.15	1	3	5	0.15	0.45	0.75
Economic criteria for performance evaluation							
1. Installation cost	0.1	5	3	2	0.5	0.3	0.2
2. Cost-efficiency	0.1	3	4	5	0.3	0.4	0.5
3. Maintenance	0.05	4	3	2	0.2	0.15	0.1
Total	**1**				2.65	3.3	4.15

As it could be seen from the analysis, microwave pyrolysis is almost an absolute leader, and it proves to be better according to the score. Incineration loses almost in all criteria, because it is not ecological and a lot of pollutants are released during the process that harm the environment. It is pretty slow, as well as conventional pyrolysis, because heating occurs from the walls of the reactor, it also effects heating efficiency. All radioactive contaminants are going to be released during the incineration which is inappropriate. Though, during microwave pyrolysis part of radioactive contaminants may also be released and it still must be researched, there is data that proves that during microwave pyrolysis gaseous radioactive contaminants stay in the solid phase.

Microwave pyrolysis loses in simplicity, because it is easier to use pyrolysis and incineration technology, plus there are a lot of such industrial installations, so the technologies are widespread, whereas microwave pyrolysis is quite an advanced technology that is not applied industrially. As so as all the equipment for microwave treatment is much more complicated, needed attention should be paid to its maintenance, which may be expensive, as well as its installation. Yet, this technology is believed to be very cost-efficient, because less energy is spent to heat the material and lower temperature could be used, due to properties of microwave radiation and uniform heating. It also allows to treat more material faster, which will increase the flow of the treated material and will increase the overall profit.

4.3 SWOT analysis

Complex analysis solution with the greatest competitiveness is carried out with the method of the SWOT analysis: Strengths, Weaknesses, Opportunities and Threats. The analysis has several stages. The first stage consists of describing the strengths and weaknesses of the project, identifying opportunities and threats to the project that have emerged or may appear in its external environment. The second stage consists of identifying the compatibility of the strengths and weaknesses of the project with the external environmental conditions. This compatibility or incompatibility should help to identify what strategic changes are needed. The swot analysis is represented in the Table 3 down below.

Table 3 – SWOT analysis

	Strengths:	**Weaknesses:**
	S1. Big mass reduction of the resin S2. Cost-effective and energy efficient technology S3. Sustainability *S4.*Real experimental prototype S5 Possibility to use it to treat other types of waste.	W1. This technology has never been implemented on industrial scale W2. Complexity of equipment W3. Relatively expensive technology

Continuation of Table 3

Opportunities: O1. Increase of numbers of nuclear power plants with water cooled reactors O2. Increase of people awareness about deteriorating state of the environment O3. Humanity growth O4. Manufacture growth	The more reactors there are, the more spent resin is produced which is needed to be disposed of. Deteriorating state of the environment will make people to turn to more sustainable ways for disposal and not only. Humanity and manufacture growth will also lead to growth of ion-exchange resin use, because it is implemented in many spheres like water treatment, pharmaceuticals and etc. Of course the rate of industrial and domestic waste generation will increase as well. So, this technology is perfect for treating large amount of waste and resin in particular ecologically.	It is a pioneer method to treat ion-exchange resin like this, and many mistakes might be done and a lot of hardships might appear while implementing this complex and relatively expensive technology on industrial scale. Yet, development of nuclear power industry, increase of humanity and bad current state of our planet will surely make people look for sustainable and effective ways for spent resin treatment along with the overall waste.
Threats: T1. Lack of demand for new production technologies T2. Developed competition of production technologies T3. Tense world situation	Lack of demand for new production technologies and competitors who use old, but checked and trusted technology are a serious problem, but marketing work must be done to attract people to this technology. Marketing must highlight the real working experimental prototype and its advantages like efficiency and sustainability, also it should be pointed out that competitors lack these features. Ecology is a trend now, so it will make people pay their attention to it. Still it is hard to be safe from changing tense situation in the world.	As so as it is a pioneer technology on industrial scale, and it is more complex and expensive than existing one, it will be hard to break into market. It is not known about all possible hardships while implementing this technology, and people would go to the good-old and checked by time technologies. A lot of money might be spent for project implementation, so big investments are in need. So good marketing campaign is required to attract investments. In case of worst scenarios in the world like war, the last thing people are going to think about is ecology and new technologies, so this technology will be irrelevant. So again, a lot of advertising will be a must thing to do, to provide an opportunity for this technology to be implemented industrially.

After the analysis, the project began to see its main strengths, which contribute to the promotion of this work and indicate its competitiveness in the market. Weaknesses were also identified, mainly accounted for by complexity and expensiveness of the technology, but still strengths prevail over the weaknesses, and therefore the project still exists. The project now has clear opportunities and prospects, which are directly related to the strengths, which contribute to the emergence of those very opportunities if the project is successful, and in turn the weaknesses determine the possible absence or non-existence of some of the proposed opportunities. At the end, threats to the project were identified, with the linking of strengths and weaknesses to existing threats showing that the threats were real, some of them like lack of interest or strong competitors might be mitigated due to promoting of this technology, because it really has unique and relevant features, like sustainability, which is a trend nowadays, and overall efficiency. Still, intense world situation is impossible to control, and in case of the worst scenario, the project will not be relevant.

4.4 Project initiation

4.4.1 The purpose and results of the project

The initiation process group consists of processes that are performed to define a new project or a new phase of an existing one. In the initiation processes, the initial purpose and content are determined and the initial financial resources are fixed. The internal and external stakeholders of the project who will interact and influence the overall result of the research project are determined in the Table 4.

Table 4 – Stakeholders of the project

Project stakeholders	Stakeholder expectations
National Research Tomsk Polytechnic University	Realization of such a technology will increase scientific promotion of the university, and allow to create a patent for this method
Rosatom State Corporation	This project could be implemented for all water cooled reactors and decrease the amount of spent ion-exchange resin.

Table 5 provides information about the hierarchy of project goals and the criteria for achieving the goals. The project goals include goals in the area of resource efficiency and resource conservation.

Table 5 – Purpose and results of the project

Purpose of project:	Implementation of the method for disposal of spent ion-exchange resin by microwave pyrolysis
Expected results of the project:	Effective method that potentially could be implemented on industrial scale
Criteria for acceptance of the project result:	Mass reduction of the resin at least by two times
Requirements for the project result:	Significant mass and volume reduction of the resin
	Sustainability of the method
	Safe for people who carry out the process of pyrolysis

4.4.2 The organizational structure of the project

It is necessary to solve some questions: who will be part of the working group of this project, determine the role of each participant in this project, and prescribe the functions of the participants and their number of labor hours in the project. This information is presented in the Table 6.

Table 6 – Structure of the project

№	Participant	Role in the project	Functions	Labor time, hours (working days (from table 7) × 6 hours)
1	Pavel Chumerin, head of laboratory of super high frequency technology, scientific supervisor, PhD	Head of the project	Responsible for the implementation of the project within the specified resource limits, coordinates the the activities of the project participants.	222
2	Ivan Kalinich, teaching assistant, post-graduate student	Project expert	Assistance in conducting the experiments, consultation about topic related materials.	330
3	Ilia Tutolmin, master student	Project executor	Gathering of the information about ion-exchange resin disposal, conduction of the experiments, report preparation.	486

4.4.3 Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members. They are represented in the Table 7.

Table 7 – Project limitations

Factors	**Limitations / Assumptions**
3.1. Project's budget	657131
3.1.1. Source of financing	TPU
3.2. Project timeline:	01.02.2023 – 15.05.2023
3.2.1. Date of approval of plan of project	**13.02.2023**
3.2.2. Completion date	**15.05.2023**

4.5 Planning if scientific and technical project management

As part of planning, project schedule and Gantt chart must be built. The project schedule is represented in the Table 8.

Table 8 – Project Schedule

Job title	Duration, **working** days (without holidays and weekends)	Start date	Date of completion	Participants
Choosing the direction of the research	**10**	01.02.2023	12.02.2023	Head of the project, project expert, project executor
Development of the technical assignment	**6**	13.02.2023	19.02.2023	Head of the project, project executor
Choosing the sample material for the research	**5**	20.02.2023	28.02.2023	Project executor
Theoretical research	**15**	01.03.2023	19.03.2023	Project executor
Experiment execution	**24**	20.03.2023	16.04.2023	Project expert, project executor
Summary and evaluation of results	**21**	17.04.2023	15.05.2023	Head of the project, project expert, project executor

The works from the table 8 are placed into the Gantt chart in the Table 9. A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule. This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The width of the horizontal bars in the graph shows the duration of each activity.

Table 9 – A Gantt chart

№	Activities	Participants	T_c, Days	Duration of the project											
				February			March			April			May		
				1	2	3	1	2	3	1	2	3	1	2	3
1	Choosing the direction of the research	Head of the project, project expert, project executor	**10**												
2	Development of the technical assignment	Head of the project, project executor	**6**												
3	Choosing the sample material for the research	Project executor	**5**												
4	Theoretical research	Project executor	**15**												
5	Experiment execution	Project expert, project executor	**24**												
6	Summary and evaluation of results	Head of the project, project expert, project executor	**21**												

\- Head of the project, project expert, project executor, - head of the project, project executor, - project executor, - project expert and project executor.

4.6 Scientific and technical research budget

The amount of costs associated with the implementation of this work is the basis for the formation of the project budget. This budget will be presented as the lower limit of project costs when forming a contract with the customer. As so as it is hard to imagine what exactly must be done to implement such a technology on an industrial scale, the budget for the experimental setup will be given here.

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

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

- Material costs of scientific and technical research;
- costs of special equipment for scientific work (Depreciation of equipment used for design);
- basic salary;
- additional salary;
- labor tax;
- overhead.

4.6.1 Calculation of material costs

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

$$C_m = (1 + k_T) \cdot \sum_{i=1}^{m} P_i \cdot N_{consi} \tag{2}$$

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

N_{consi} – the amount of material resources of the i-th species planned to be used when performing scientific research (units, kg, m, m^2, etc.);

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

k_T – coefficient taking into account transportation costs.

No additional materials were needed for the experiments, and they all were conducted with the help of the special equipment in the laboratory.

4.6.2 Costs of special equipment

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

But all the experiments were conducted in the laboratory, where there already was all the needed equipment. So this part is dedicated to Calculation of the depreciation. Depreciation is not charged if an equipment cost is less than 40 thousand rubles, its cost is taken into account in full. The equipment which cost is less than 40 thousand rubles is presented in the Table 10:

Table 10 – Costs of special equipment with the price less than 40 thousand rubles

№	Equipment identification	Quantity of equipment	Price per unit, rub.	Total cost of equipment, rub.
1.	Тест-1 gas analyzer	1	35000	35000
2.	Samsung microwave (750 W magnetron)	1	5000	5000
3.	Waveguide circulator	1	30000	30000
4.	Waveguide load	1	30000	30000
5.	Quartz tube	3	300	900
6.	40 liters nitrogen tank	1	22000	22000
7.	Laboratory stand	1	4000	4000
8.	Gas torch burner	1	1000	1000
9.	Gas flowmeter	1	500	500
10.	Fan cooler	1	500	500
Overall price				**128900**

If you use available equipment, then you need to calculate depreciation:

$$A = \frac{C_{перв} * Н_а}{100} \quad (3)$$

A - annual amount of depreciation;

$C_{перв}$ - initial cost of the equipment;

$Н_а = \frac{100}{Т_{сл}}$ - rate of depreciation;

$T_{сл}$ - life expectancy.

The project lasts 81 days, so the period for depreciation is also 81 days:

$$A(scales) = \frac{C_{перв} * Н_а}{100} = \frac{100000 * \frac{100}{5}}{100} * \frac{81}{365} = 4438 \text{ rub;}$$

$$A(w1) = \frac{C_{перв} * Н_а}{100} = \frac{100000 * \frac{100}{7}}{100} * \frac{81}{365} = 3170 \text{ rub;}$$

$$A(w2) = \frac{C_{перв} * Н_а}{100} = \frac{120000 * \frac{100}{7}}{100} * \frac{81}{365} = 3804 \text{ rub};$$

$$A(w3) = \frac{C_{перв} * Н_а}{100} = \frac{80000 * \frac{100}{7}}{100} * \frac{81}{365} = 2536 \text{ rub};$$

$$A(w4) = \frac{C_{перв} * Н_а}{100} = \frac{150000 * \frac{100}{7}}{100} * \frac{81}{365} = 4755 \text{ rub};$$

$$A(laptop) = \frac{C_{перв} * Н_а}{100} = \frac{50000 * \frac{100}{5}}{100} * \frac{81}{365} = 2219 \text{ rub}.$$

Depreciation of the equipment is shown in the Table 11.

Table 11 – Depreciation of special equipment (+software)

№	Equipment identification	Quantity of equipment	Total cost of equipment, rub.	Life expectancy, year	Depreciation for the duration of the project, rub.
1.	Pioneer analytical scales	1	100000	5	4438
2.	Waveguide transition from 90*45 to 72*34, w1	1	100000	7	3170
3.	Waveguide transition from a rectangular section of 72*34 to a round diameter of 90, w2	1	120000	7	3804
4.	Small waveguide 72*34, w3	1	80000	7	2536
5.	Round waveguide with a diameter of 90 mm (reactor chamber), w4	1	150000	7	4755
6.	Laptop	1	50000	5	2219
Overall cost					20924

4.6.3 Basic salary

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

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

$$S_b = S_a \cdot w, \tag{4}$$

where S_b – basic salary per participant;

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

S_d - the average daily salary of an participant, rub.

The average daily salary is calculated by the formula:

$$S_d = \frac{S_m \cdot M}{F_v}, \tag{5}$$

где S_m – monthly salary of an participant, rub .;

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

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

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

Table 12 – The valid annual fund of working time

Working time indicators	
Calendar number of days	365
The number of non-working days - weekend - holidays	 52 14

Continuation of Table 12

Loss of working time - vacation - isolation period - sick absence	48
The valid annual fund of working time	251

Monthly salary is calculated by formula:

$$S_{month} = S_{base} \cdot (k_{premium} + k_{bonus}) \cdot k_{reg}, \quad (6)$$

where S_{base} – base salary, rubles;

$k_{premium}$ – premium rate;

k_{bonus} – bonus rate;

k_{reg} – regional rate.

The results of calculations are represented in the table 13.

Table 13 – Calculation of the base salaries

Performers	S_{base}, rubles	$k_{premium}$	k_{bonus}	k_{reg}	S_{month}, rub.	S_d, rub.	T_p, work days (from table 7)	W_{base}, rub.
Pavel Chumerin, head of laboratory of super high frequency technology, scientific supervisor, PhD	54978			1.3	71471	3189	37	117999
Ivan Kalinich, teaching assistant, post-graduate student	25460				33098	1477	55	81229
Ilia Tutolmin, master student	20064				26083	1164	81	94274

4.6.4 Additional salary

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

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

$$W_{add} = k_{extra} \cdot W_{base}, \quad (7)$$

where W_{add} – additional salary, rubles;

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

W_{base} – base salary, rubles.

$$W_{add}(supervisor) = 0.1 \cdot 117999 = 11799\, rub;$$
$$W_{add}(expert) = 0.1 \cdot 81229 = 8123\, rub;$$
$$W_{add}(student) = 0.1 \cdot 94274 = 9427\, rub.$$

4.6.5 Labor tax

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

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

$$P_{social} = k_b \cdot (W_{base} + W_{add}) \quad (8)$$

where k_b – coefficient of deductions for labor tax.

In accordance with the Federal law of July 24, 2009 No. 212-FL, the amount of insurance contributions is set at 30%. Institutions conducting educational and scientific activities have rate - 27.1%. Labor taxes are presented in the Table 14.

Table 14 – Labor tax

	Project leader	**Project expert**	**Project executor**
Coefficient of deductions	0.271		
Salary (basic and additional), rubles	90768.46, 9076.85	62483.51, 6248.35	72518.17, 7251.82
Labor tax, rubles	27058.08	18626.33	21617.67

4.6.6 Overhead costs

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

Overhead costs account from 30% to 90% of the amount of base and additional salary of employees. So, the overhead rate was taken as 30%. Calculations of the overhead costs are in the Table 15.

Overhead is calculated according to the formula:

$$C_{ov} = k_{ov} \cdot (W_{base} + W_{add}) \tag{9}$$

where k_{ov} – overhead rate.

Table 15 – Overhead costs

	Project leader	**Project expert**	**Project executor**
Overhead rate	30%		
Salary, rubles	99845.30	68731.86	79769.99
Overhead, rubles	29953.59	20619.56	23930.99

4.6.7 Other direct costs

Energy costs for equipment are calculated by the formula:

$$C = P_{el} \cdot P \cdot F_{eq}, \tag{10}$$

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

P – power of equipment, kW;

F_{eq} – equipment usage time, hours.

The first energy consumer was the 750W magnetron. Considering that there were 8 experiments in total and that each of them was occurring for approximately 6 minutes and 30 seconds, the overall usage time of magnetron was 52 minutes. It cost is 3.78 rubles.

$$C(magnetron) = 5.8 \cdot 0.75 \cdot 0.87 = 3.78\,rub$$

Another source was the laptop with 60 W. Approximately, the time of its work was around 1 hour per day, so 81 hours overall:

$$C(laptop) = 5.8 \cdot 0.06 \cdot 81 = 28.19\,rub$$

2 LED lamps were used for lightning during the project with power of 10 W each. The approximate time is 8 hours a day:

$$C(lamp) = 5.8 \cdot 0.01 \cdot 8 \cdot 81 = 37.58\,rub$$

So, for 2 lamps the price is 75.17 rub. The overall price of the direct costs is 107.14 rub.

4.6.8 Formation of budget costs

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

Determining the budget for the scientific research is given in the Table 16.

Table 16 – Items expenses grouping

Name	Cost, rubles
1. Material costs	-
2. Equipment costs	149824

Continuation of Table 16

3. Basic salary	293501
4. Additional salary	29350
5. Labor tax	87493
6. Overhead	96855
7. Other direct costs	107
Total planned costs	**657131**

4.7 Evaluation of the comparative effectiveness of the project

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

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

The integral financial measure of development is defined as:

$$I_f^d = \frac{C_i}{C_{max}}, \qquad (11)$$

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).

$$I_f^d(project) = \frac{657131}{657131} = 1$$

$$I_f^a(pyrolysis) = \frac{550000}{657131} = 0.84$$

$$I_f^a(incineration) = \frac{450000}{657131} = 0.67$$

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

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a \qquad I_m^p = \sum_{i=1}^{n} a_i b_i^p \tag{12}$$

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 17.

Table 17 – Evaluation of the performance of the project

Criteria	**Weight criterion**	**Microwave pyrolysis**	**Pyrolysis**	**Incineration**
1. Mass and volume reduction	0.15	5	4	3

Continuation of Table 17

2. Speed of treatment	0.05	5	3	2
3. Containment of radioactive isotopes	0.15	4	3	2
4. Heating efficiency	0.1	5	3	2
5. Safety	0.1	4	3	2
6. Simplicity of technology	0.05	2	4	5
7. Sustainability	0.15	5	3	1
Economic criteria for performance evaluation				
1. Installation cost	0.1	2	3	5
2. Cost-efficiency	0.1	5	4	3
3. Maintenance	0.05	2	3	4
Total	**1**	4.15	3.3	2.65

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

$$I_e^p = \frac{I_m^p}{I_f^d}, \quad I_e^a = \frac{I_m^a}{I_f^a} \qquad (13)$$

$$I_e^P = \frac{4.15}{1} = 4.15$$

$$I_e^a(pyrolysis) = \frac{3.3}{0.84} = 3.93$$

$$I_e^a(incineration) = \frac{2.65}{0.67} = 3.96$$

$$I_{\text{исп.2}} = \frac{I_{\text{р−исп2}}}{I_{\text{финр}}^{\text{исп.2}}}$$

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

$$E_c = \frac{I_e^p}{I_e^a} \tag{14}$$

.

Thus, the effectiveness of the development is presented in Table 18.

Table 18 – Efficiency of development

№	Indicators	Project	Pyrolysis	Incineration
1	Integral financial measure of development	1	0.84	0.67
2	Integral indicator of resource efficiency of development	4.15	3.3	2.65
3	Integral indicator of the development efficiency	4.15	3.93	3.96
4	Efficiency	1.06	1	1.01

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. As it could be seen from the table 18, the microwave pyrolysis option is the most effective one.

Thus, in this section was developed stages for design and create competitive development that meet the requirements in the field of resource efficiency and resource saving.

These stages includes:

- 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 project.

Table 19 – Hazardous and harmful factors

Factors (GOST 12.0.003-2015 [93])	Regulatory documents
1. Microclimate	GOST 30494-96. Residential and Public Buildings, Parameters of the microclimate in the premises [94].
2. Noise	GOST 12.1.003-83. Occupational Safety Standards System (SSBT). Noise. General safety requirements (with Amendment N 1) [95].
3. Illumination of the working area	SNiP 23-05-95. Natural and artificial lighting (with Amendment N 1) [96].
4. Fire and explosion safety	SP 12.13130.2009. Determination of explosion and fire hazard categories of premises, buildings and outdoor installations (as amended by Order No. 1 of the Ministry of Emergency Situations of Russia dated 09.12.2010, No. 643) [97]. GOST 1 2.1.004-91 System of standards of labor safety. Fire safety. General requirements [98].
5. Electrical safety	GOST 12.1.009-76 System of Occupational Safety Standards (SSBT) [99]. GOST R12.1.019-2017 SSBT electrical safety [100]. GOST R IEC 61140-2000 Protection against electric shock. General provisions for safety provided by electrical equipment and electrical installations in their interconnection [101].
6. Radiation safety	SanPiN 2.6.1.2523-09 Radiation Safety Norms NRB-99/2009 [102].

5.2 Microclimate

Indicators that characterize the microclimate are [103]:

- air temperature;
- relative humidity;
- air velocity;
- the intensity of thermal radiation.

The source of occurrence of deviations of the above parameters is: the heating of the surfaces of technological equipment, the influence of the environment on the working space, the wrong design and/or choice of materials of the working space, the wrong mode of ventilation.

In general, the deviation of microclimate parameters leads to a decrease in human performance, fatigue and risk of disease. Each of the parameters of the microclimate has an impact on the person, and together they can increase the negative impact on the body.

Thus, a decrease in air temperature leads to hypothermia of the organism, an increase in air velocity only intensifies this effect. Increasing the air temperature leads to overheating of the organism, if the air humidity is high, the sweat evaporates less intensively and the faster the overheating of the organism, which leads to a decrease in efficiency. Intense heat radiation leads to excessive heating of the air in the room with all the ensuing consequences.

Each category of work is assigned certain optimal microclimate parameters. Personnel work at the IR is categorized as light physical work (category 1b). Indicators for temperature, humidity and air velocity are presented in Appendix A, Table A.1.

For ease of work in the room should be rationing parameters of the microclimate, i.e., activities to control ways and means of protection from high and low temperatures, heating, ventilation and air conditioning, artificial lighting, etc.

To maintain these sanitary standards, it is sufficient to have natural unorganized ventilation of the room and a local air conditioner of complete air conditioning, which provides a constant temperature, relative humidity, speed of movement and purity of the air.

To calculate the rate of air exchange of a fan in a room with a volume of V = 350 m^3 (S = 100 m^2 , h = 3.5 m), which will ensure the circulation of air masses in the room, we use the formula 15:

$$W = V \cdot k, \tag{15}$$

where k is the normalized air exchange rate - this is the value that indicates how many times during one hour the room is completely replaced with air. (for the laboratory k = 3) [104].

Substituting the data into formula (5.1), we obtain the fan capacity:

$$W = 350 \cdot 3 = 1050 \quad \frac{m^3}{h}.$$

Based on this result, a VARP Alpha 1100×270 fan should be installed in the classroom with a capacity of 1100 m^3 /h [105].

A central heating system is also needed to provide a given level of temperature during the winter period according to [106]. In winter, the central heating system is used in the auditorium to maintain the required temperature. This system is reliable in operation and provides the ability to regulate the temperature within a wide range. The ventilation and air conditioning system in the room must meet certain fire safety requirements. In winter, a heating system should be provided in the room. It must ensure sufficient, continuous and even heating of the air. In rooms with high requirements for clean air, water heating should be used.

To protect the researcher from the effects of the harmful factor of deviation of microclimate indicators, microclimatic conditions are created by heating, exchange ventilation and air conditioning according to [105,106,107].

The TPU Research Laboratory of Super High Frequency Technology has the satisfying conditions of microclimate [103].

5.3 Noise

Excessive noise levels occur with mechanical and electromechanical products.

A numerical characteristic called the sound level (measured in dB) can be used to assess the noise environment. According to [104] the permissible noise level at work requiring concentration, work with increased requirements to observation processes and remote control of production cycles at workplaces in rooms with noisy equipment is 75 dB. Zones with a sound level of 80 dB shall be marked with safety signs according to [108]. In this room, the main source of noise are the fan cooler the microwave which is insignificant.

According to the microwave specification, the noise level of it is 45-50 dB, the noise level of the fan cooling unit is 15-20 dB, the other cooling elements are passive and their noise level is not taken into account. No additional soundproofing is required because the noise level limit is not reached.

To bring the noise level to sanitary standards should be timely preventive maintenance of the experimental unit (cleaning dust and lubrication of moving parts of systems, replacement of excessively noisy components).

Protection against elevated noise levels is carried out by methods to reduce noise at the source and on the path of propagation, the installation of screens and sound-absorbing facings, personal protective equipment according to [109].

No excessive noise levels were found during the analysis, that means that the TPU Research Laboratory of Super High Frequency Technology meets the noise level requirements [104].

5.4 Lighting

Insufficient lighting of the work area is also considered one of the factors affecting human performance. For industrial enterprises, the optimal illumination of the territory and premises is an important and difficult technical task, the solution of which ensures normal hygienic conditions for working personnel. Correctly selected light sources and their design create conditions for productive work, correct execution of technological operations, compliance with rules and safety precautions.

The main task of lighting calculations for artificial lighting is to determine the required power of the electric lighting installation to create a given illumination.

Inside the premises on the method of placement of lighting fixtures and the distribution of illumination distinguish the following systems of artificial lighting: general and combined.

General lighting is lighting that illuminates the entire area of the room, as occupied by equipment or workplaces, as well as auxiliary. Depending on the location of lighting fixtures distinguish uniform and localized general lighting. In general uniform lighting fixtures are located in the upper zone of the room evenly, thus providing equal illumination of the entire room. It is generally used when the arrangement of the work areas is not known in the design or in case of flexible layout. In general localized lighting fixtures are placed taking into account the location of technological equipment, creating the required level of illumination on individual surfaces.

Combined lighting system consists of general and local lighting. General lighting is designed to illuminate passageways and areas where work is not carried out, as well as to equalize brightness in the field of view of workers. Local lighting is provided by fixtures located directly on the workplace. It should be preferred if several work areas of the room are to have different visual tasks and therefore require different levels of illumination. It is also necessary when the workplaces are geographically distant from each other. It should be kept in mind that local lighting alone is not acceptable, because it creates a large difference in the illumination of working surfaces and the environment, which is unfavorable to the vision [96].

When taking into account the peculiarities of the experiment it is allowed to use a system of general uniform lighting.

Gas discharge lamps are used for general lighting: daylight (LD), cool-white (CCW), warm-white (WH) and white (WH).

The laboratory room has the following parameters:

- room height: H = 350 cm;
- distance of the luminaires from the ceiling: h_c = 35 cm;
- Let's calculate the height of the lamp above the floor, the height of the suspension:

$$h_n = H - h_c = 350 - 35 = 315 \ \text{см}; \tag{16}$$

- height of the work surface above the floor: $h_{рп}$ = 75 cm;
- Let's calculate the height of the lamp above the work surface:

$$h = h_n - h_{pn} = 315 - 75 = 260 \ cm. \tag{17}$$

When illuminating the workplace with two-lamp OD luminaires when installed alone or in continuous rows of single luminaires, as required, the lowest permissible height of suspension above the floor is 3.5 m. The calculated value of *h* = 2.6 m does not meet the requirements.

– distance between adjacent lights: *L* = 3.75 cm;

– distance from the outermost lights to the wall: *l* = 0.9 cm.

This distance from the outermost lights to the wall is appropriate, because the required value is equal:

$$\frac{L}{3} = \frac{3,75}{3} = 1,25\ cm. \tag{18}$$

– integral criterion for the optimality of the location of luminaires is a value equal to:

$$\lambda = \frac{L}{h}. \tag{19}$$

This value should be 1.4 with the best and best arrangement of the luminaires. Let's calculate the optimal distance between the luminaires:

$$L = \lambda \cdot h = 1,4 \cdot 2,6 = 3,64\ m. \tag{20}$$

This value is fully consistent with the actual location of the lights.

Calculation of the total uniform artificial lighting of the horizontal working surface is performed by the method of luminous flux factor φ:

$$\varphi = \frac{E_k \cdot S \cdot K_S \cdot Z}{N \cdot n} \tag{21}$$

where *S* - area of the room to be illuminated: *S* = 40 m^2 ; $K_з$ - safety factor that takes into account the pollution of the luminaire, the presence of smoke, dust in the atmosphere: $K_з$ = 1.5 (room with low dust emission); *Z* - coefficient of irregularity of lighting: *Z* = 1.1 (for fluorescent lamps); *N* is the number of lamps in the room: *N* = 5; *n* - coefficient of luminous flux utilization: *n* = 0.49.

$$\varphi = \frac{200 \cdot 40 \cdot 1,5 \cdot 1,1}{5 \cdot 0,49} = 5387,8\ lm.$$

Standardized minimum illuminance, according to [96]: $E_н$ = 200 lm (visual work grade VI: very low precision);

Room index:

$$i = \frac{S}{h \cdot (A+B)} = \frac{40}{2,6 \cdot 10} = 1,54; \qquad (22)$$

ρ_c - wall reflection coefficient (freshly whitewashed walls with windows without curtains): ρ_c = 50%;

ρ_n - ceiling reflectance (freshly whitened ceiling): ρ_n = 70%.

According to the value of the calculated luminous flux φ = 5387.8 lux, the closest fluorescent lamp is a lamp type LHB with an electrical power of the lighting system of 65 W.

To protect against the lack of light in the work area natural light in its spectrum is the most appropriate, but it is not always enough. This is largely due to the mode of work. Usually, it is recommended to use general and combined lighting. Norms of illumination of the workplace correspond to [96].

After light analysis, it was established that the level of lightning in the TPU Research Laboratory of Super High Frequency Technology is the optimal range [104].

5.5 Electromagnetic fields

One of the main harmful factors when conducting the experiment is computer. Norms of harmful permissible levels of electromagnetic radiation of computers, established in the document [110] are shown in Table A.2 of Appendix A.

Electromagnetic fields (EMF) are propagated by electromagnetic waves, which in turn radiate charged particles, molecules and atoms. The harm of electromagnetic radiation has been officially proven and confirmed by relevant studies of scientists, so it is necessary to limit its effect on the human body as much as possible.

The screen and the computer system units also produce electromagnetic radiation. Most of it comes from the system unit and the video cable. The electromagnetic field strength at a distance of 50 cm around the screen in terms of the electrical component must correspond to [111].

Increased levels of electromagnetic radiation can adversely affect the human body, namely lead to nervous disorders, sleep disorders, significant deterioration of visual activity, weakening of the immune system, disorders of the cardiovascular system.

To protect against EMF, it is possible to increase the distance from the source (the screen must be at least 50 cm from the user).

In the TPU Research Laboratory of Super High Frequency Technology the radiation complies with the norms [104].

5.6 Fire and explosion safety

Depending on the characteristics of the substances and materials in the room, rooms are divided into categories «А», «Б», «В», «Г», and «Д» according to the explosion and fire hazard, according to [112]. The room in question belongs to category «В», since it contains solid combustible substances in a cold state. Possible causes of fire:

- working with exposed electrical equipment;
- short circuits in power supply units;
- failure to comply with fire safety rules.

In order to reduce the risk of a fire and minimize the possible damage, preventive measures are taken, which are divided into organizational and technical, operational and regime measures. Organizational and technical activities consist of regular briefings to employees responsible for fire safety, training employees in proper operation of equipment and the necessary actions in case of fire, certification of substances, materials and products in terms of fire safety, production and use of visual aids to ensure fire safety [98]. Operational activities include preventive inspections of equipment. Measures of regime character include the establishment of rules for the organization of work and compliance with fire safety measures. The following fire safety rules must be observed in order to prevent the occurrence of a fire:

- maintaining the premises in accordance with fire safety requirements;
- proper operation of the equipment (proper connection of the equipment to the power supply network, control of the equipment heating);
- Training of production personnel in fire safety rules;
- availability, proper placement and use of fire extinguishing equipment.

In a room with electrical equipment, to avoid electric shock, it is advisable to use carbon dioxide or powder fire extinguishers. These fire extinguishers are designed to extinguish fires of various substances and materials, electrical installations under voltage up to 1000 V, flammable liquids. Chemical and foam fire extinguishers are not allowed. Fire extinguishers shall be located at the site to be protected in accordance with the requirements so that they are protected from direct sunlight, heat flow, mechanical effects and other adverse factors (vibration, aggressive environment, high humidity, etc.). They shall be clearly visible and easily accessible in case of fire. It is preferable to place the fire extinguishers near the places where fire is most likely to break out, along passageways, and near exits from the premises. Fire extinguishers shall not interfere with the evacuation of people during a fire.

5.7 Electrical Safety

Electrical safety is a system of organizational and technical measures and means ensuring protection of people from harmful and dangerous effects of electric current, electric arc, electromagnetic field and static electricity according to [99]. Electric current, passing through the human body, produces thermal, chemical and biological effects, thereby violating the normal vital functions. Employees hired to work in electrical installations must have professional training appropriate to the nature of the work.

Electrical shock occurs when a person comes into contact with an electrical circuit that contains voltage sources and/or current sources that can cause current to flow through the energized part of the body. It is common for a person to be susceptible to the passage of a current greater than 1 mA [99]. In addition, at high voltage installations, electric shock can occur without touching live parts, as a result of current leakage or air gap breakdown with the formation of an electric arc.

There has been no contact with exposed electrical current sources as part of the current work. The current flowing in the computer peripherals (computer mouse, keyboard) does not pose a significant hazard to human health. According to the classification, this classroom fits into Class 1 rooms with operating voltages not exceeding 1,000 V [99].

5.8 Radiation safety

Elevated levels of ionizing radiation in the work area. Hazardous and harmful production factors associated with elevated levels of ionizing radiation include the following types of radiation [102]:

a) Short-wave electromagnetic radiation - X-rays and gamma rays;

b) particle flows:

- beta particles;
- alpha particles;
- neutrons;
- protons, other ions, muons, etc;
- fission fragments.

c) radiation caused by radioactive contamination (above the natural background), including contamination with man-made radionuclides:

– radioactive contamination of the air in the work area (due to the presence of radioactive gases radon, thoron, actinon, products of their radioactive decay, aerosols containing radionuclides);

– radioactive contamination of surfaces and materials in the work environment, including workers' protective equipment and their skin.

As a result of exposure to ionizing radiation on the human body, the normal course of biochemical processes and metabolism is disturbed. Depending on the magnitude of the absorbed dose of radiation and on the individual characteristics of the body. The changes caused may be reversible or irreversible. Any type of ionizing radiation causes biological changes in the body both in external exposure, when the source of exposure is outside the body, and in internal exposure, when radioactive substances enter the body [102].

No work with ionizing radiation sources was carried out in the course of the scientific research, which involved theoretical calculations using a computer and no more.

5.9 Safety in accidents and emergencies

Emergency situation (ES) is the situation in a particular territory resulting from an accident, natural hazard, catastrophe, natural or other disaster, which may cause or have caused human casualties, damage to human health or the environment, significant material losses and disruption of human life [113].

There are two types of emergencies:

– man-made;

– natural.

Man-made emergencies include fires, explosions, sabotage, releases of toxic substances. Natural ES include natural disasters. The most likely man-made ES are fires.

Accident hazards include a sudden and uncontrollable source of energy: a moving object, uncontrollable movement or energy.

Consider possible emergency situations in the laboratory:

- the occurrence of fire;
- electric shock;
- falling from one's own height;

Accidents and emergencies and measures to prevent and eliminate their consequences are presented in Table 20.

Table 20 – Accidents and emergencies and measures to prevent and eliminate their consequences.

№	Accidents and emergencies	Measures to prevent accidents and emergencies	Measures to eliminate the consequences of accidents and emergencies
1	Injury due to a fall from a height corresponding growth	1. Maintaining the premises in proper order. 2. limiting your workspace. 3. Timely briefing.	1. Examine or interview the victim. 2. If necessary - call an ambulance using the number 112. 3. Stop bleeding, if any. 4. If it is suspected that the victim's spine is broken, the victim must be given complete rest in a supine position until qualified medical assistance is given.
2	Injury due to electric shock	1. Grounding of all electrical installations. 2. Limiting your workspace. 3. Ensure that live parts of the equipment are inaccessible. 4. Timely briefing.	1. Quickly free the victim from the action of the electric current [101]. 2. Call an ambulance (112). 3. If the victim has lost consciousness but is still breathing, he should be comfortably laid down, his clothes unbuttoned, a supply of fresh air and complete rest. 4. The victim should be given smelling ammonia, splashing his face with water, rubbing and warming his body. 5. If there is no breathing, CPR and heart massage must be performed immediately.
3	Fire	1. Timely briefing. 2. Installation of automatic fire extinguishing equipment in the premises. 3. Installation of smoke and fire detectors. 4. Provide evacuation routes and maintain them in proper condition. 4. Monitoring the operation of electrical appliances.	1. Turn off the air supply and de-energize the room. 2. Immediately report the fire to the fire department (112). 3. If possible, take measures to evacuate people, extinguish the fire and save property.

In this section about social responsibility the hazardous and harmful factors were revealed:

1. The following factors were analyzed:

– microclimate [94];
– noise [95];
– lighting [96];
– fire and explosion safety [97];
– electrical safety [99];
– radiation safety [102].

2. The laboratory has the following classifications:

– category «B» according to the fire and explosion safety [112];
– class 1 according to the electrical safety [99].

3. The accidents and emergencies were taken into account [113]:

– injury due to a fall from a height corresponding growth;
– injury due to electric shock;
– fire.

To conclude with, the TPU Research Laboratory of Super High Frequency Technology is safe in all the considered aspects and meets all the needed requirements.